UTILIZATION OF HARDWOODS GROWING ON SOUTHERN PINE SITES

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Southern Forest Experiment Station

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Volume III of three volumes:

I The Raw Material
II Processing
III Products and Prospective

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CONTENTS

VOLUME III—PRODUCTS AND PROSPECTIVE

PART V—PRODUCTS

22

Solid Wood Products

Eight sections or subsections in chapter 22 are condensed from other work as follows:

	Section	Source
22-1	STRUCTURAL COMMODITIES—WOOD AND NONWOOD	Boyd et al. (1976)
22-2	WOOD AND NONWOOD MATERIALS IN HOUSE CONSTRUCTION	Boyd et al. (1976)
22-6	TOYS	International Trade, Centre, UNCTAD/GATT (1976)
22-7,	subsection STIFFNESS AND RIGIDITY OF 28- BY 40-INCH NAILED PALLETS of 22 PINE-SITE HARDWOODS	Stern (1978)
22-10,	subsections TRUCK TRAILER FLOORING and RAILCAR FLOORING	Fergus et al. (1977)
22-15	ENERGY WOOD	U.S. Department of Agriculture, Forest Service (1980)
22-16,	subsection METALLURGICAL CHIPS	Wartluft (1971)
22-16,	subsection EXCELSIOR	U.S. Department of Agriculture, Forest Service (1956)

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CHAPTER 22
Solid Wood Products

CONTENTS

CHAPTER 22

Solid Wood Products

As used in this chapter the term "solid wood products" includes not only lumber, but most products except pulp and paper (chapter 25), fiberboards (chapter 23), and reconstituted wood (chapter 24) such as particleboard, flakeboard, and composite board having veneer faces over a flake or particle core. Furniture, plywood, glue-laminated beams, glue-laminated veneer, pulp chips, and energy wood are considered solid wood products under this definition.

Mulches and soil conditioners of both wood and bark are discussed in chapter 13.

Analysis of materials flow from forest to mill (figs. 2-1 and 2-2) indicates that the largest portion of hardwood roundwood harvested in 1970 in the United States was converted into solid wood products—principally lumber; by the year 2000, however, consumption of pulp and fiberboard will predominate, as follows (Boyd et al. 1976):

Commodity	Hardwood barky roundwood consumed in 1970	2000
	Million tons, ovendry	
Sawlogs for lumber	24.51	42.16
Veneer logs for plywood	2.28	3.09
Veneer logs for lumber laminated from veneer	—	1.59
Roundwood for structural flakeboard	—	1.22
Roundwood for pulp and fiberboard	19.70	78.14
Miscellaneous industrial wood and fuel wood	11.56	7.21
Total	58.05	133.41

As industry progresses toward more complete utilization, products such as energy wood, chips for fiber, and wood for structural flakeboard will significantly increase commodity recovery per tree and per acre. Solid-wood products recovered from hardwoods considered culls in the 1970's will also increase.

Trends in consumption of species and products, and product prices, are graphed in chapter 29. In chapter 28, economic feasibility studies of enterprises manufacturing solid wood products are abstracted.

Some of the key processes by which hardwood is converted to solid wood products are discussed at length in preceding chapters, as follows:

Process	Chapter
Harvesting	16
Bark removal	17
Milling and machining	18
Bending	19
Drying and storage	20
Treating	21

Not completed in time for incorporation in these volumes, but supplemental to them, are three comprehensive reviews on **gluing** and **finishing,** as follows (titles are tentative):[1]

- Sellers, T. Gluing eastern hardwoods—with emphasis on southern hardwoods. (A review intended for 1986 publication; for publication details consult the author, at Mississippi State Forest Products Laboratory, Mississippi State, Miss.) See also: Sellers, T. and J.R. McSween, 1983. Glueing structural plywood from medium-density southern hardwoods. Plywood Research Foundation, Tacoma, WA. 15p.
- Hse, C.-Y. Technology of phenolic resins. (A text intended for publication in about 1986 as a General Technical Report of the Southern Forest Experiment Station, USDA Forest Service, New Orleans, La.)
- Carter, R. (ed.) 1983. Finishing eastern hardwoods. Proceedings No. 7318. Forest Products Research Society, Madison, Wisconsin. 241 p.

Mechanical fastening is discussed at length in chapter 24 of Koch (1972). More recently, Stern et al. (1974) provided a state-of-the-art review, and the Forest Products Research Society (1976) described recent research with mechanical fasteners. Also in 1976, the U.S. Forest Products Laboratory listed their publications on the subject[2]. Some references published since these reviews include the following:

Reference	Subject
Eckleman (1978a)	Withdrawal strength of sheet-metal-type screws in hardwoods
Eckleman (1979)	Withdrawal strength of dowel joints
Ehlbeck (1979)	Nailed joints in wood structures
Jung and Day (1981)	Strength of fasteners in parallel-laminated veneer
Stern (1964)	Nail and spikes in hickory
Stern (1975a)	Performance of 14-gauge sencote staples
Stern (1975b)	Performance of 15-gauge pas-kote staples
Stern (1976)	Performance of pallet nails and staples in 22 pine-site hardwoods (summarized in sec. 22-7)
Stern (1977a)	Toughness of pallet nails
Stern (1977b)	Mibant tests of pallet staples
Stern and Franco (1979)	Predrilling pallet deckboards of very dense hardwoods

[1]All were funded by the Southern Forest Experiment Station as part of an overall effort to advance the technology for utilization of hardwoods that grow among southern pines.

[2]U.S. Department of Agriculture, Forest Service. 1976. Forest Products Laboratory list of publications on joints and fastenings in wood. 6 p. U.S. Dep. Agric. For. Serv., For. Prod. Lab., Madison, Wis.

Yields of solid wood products are given in chapter 12, in section 18-12 (see figs. 18-126 through 18-129), and in chapter 27. Chapter 27 also contains conversion factors useful in yield studies of solid wood products. For page references, see the index heading *Yields and measures, products*.

The balance of the present chapter discusses classes of solid wood products, including, where appropriate, manufacturing procedures and references to product standards. These are preceded by comparisons of wood construction materials with nonwood commodities in terms of energy, manpower, and capital inputs. Most of the products described are important in commercial production, but some have been made only on a laboratory or pilot-plant scale.

22-1 STRUCTURAL COMMODITIES—WOOD AND NONWOOD[3]

Wood as a structural material competes with aluminum, concrete, steel, brick, and petrochemical derivatives. Within the wood sector, solid wood products of both hardwood and softwood may compete with reconstituted products.

On an ovendry basis, structural wood commodities require from 1 to 3½ tons of woody furnish per ton of commodity manufactured (table 22-1); reconstituted boards have highest product yield, and lumber the lowest. Veneer products are intermediate.

ENERGY REQUIREMENTS FOR WOOD-BASED COMMODITIES

Energy expended during harvesting and manufacture is comprised of three major components:

- Diesel fuel and gasoline for forest activities and logging
- Mechanical energy (horsepower-hours) expended in the mill
- Process heat consumed in the mill

Additionally, energy is consumed in manufacture of resin and wax additives to reconstituted commodities. Also diesel fuel and gasoline are consumed delivering the commodities to the construction site.

To achieve a uniform mode of expressing energy consumed and available from residues, the unit *million Btu thermal (oil)* has been used. For example, a gallon of diesel fuel contains 138,336 Btu or 0.138 million Btu thermal (oil). A mechanical horsepower-hour was assumed equivalent to $7,825/10^6$ million Btu thermal (oil); this equivalency is based on the assumption that oil can be converted to mechanical power with about 32.5 percent efficiency. A pound of process steam was assumed to contain 1,200 Btu which, if generated with an oil-fired boiler at 82.5 percent efficiency, would require about $1,455/10^6$ million Btu thermal (oil).

[3]Text under this heading is condensed from Boyd et al. (1977) and Koch (1976a), both based on Boyd et al. (1976).

TABLE 22-1—*Input of woody furnish required to yield a ton (ovendry basis) of product* (Koch 1976a)

Commodity	Form of woody furnish	Input of woody furnish
		Tons, ovendry
Insulation board	50-50 mix of bark-free and barky chips of mixed species	0.96
Underlayment particleboard	Planer shavings, sawdust, and plywood trim	1.02
Wet-formed hardboard	50-50 mix of bark-free and barky chips of mixed species	1.15
Medium-density fiberboard	50-50 mix of bark-free chips and barky roundwood of mixed species	1.16
Structural flakeboard and pallet lumber	Mixed-species barky logs	1.24
Lumber laminated from veneer	Barky logs	2.13
Softwood sheathing plywood	Barky logs	2.22
Softwood lumber	Barky logs	2.86
Hardwood plywood paneling	Barky logs	3.33
Oak flooring	Barky logs	3.57

In computing energy credits for manufacturing residuals (e.g., green bark and sawdust), it is assumed that exhaust steam from turbines or steam engines will be used for process steam. Thus, a non-condensing turbine connected to an AC generator should consume about 16.3 pounds of high-pressure steam to deliver one brake horsepower-hour of mechanical work. The 16.3 pounds of spent steam at low pressure is then available for process heat. It has additionally been assumed that 1 pound of green bark (half water by weight) will generate about 2.6 pounds of high-pressure steam.

Production of hardwood flooring, softwood lumber, or decorative hardwood plywood—including logging and transport to construction site—calls for net expenditure of about 3 million Btu of oil equivalent per ton (ovendry basis) of product if mill residuals are credited against energy demand of the milling process. Reconstituted boards, i.e, fiberboards and particleboards, require 8½ to 21 million Btu per ton produced (table 22-2).

ENERGY REQUIREMENTS FOR NONWOOD-BASED COMMODITIES

Production of structural commodities from nonrenewable resources and transport to building site requires net energy inputs ranging from less than 4 to as much as 200 million Btu oil equivalent per ton (table 22-2).

TABLE 22-2—*Energy needed to extract, manufacture, and transport to building site—selected primary commodities* (Boyd et al. 1977)

Commodity	Logging	Gross manufacture: Electricity	Gross manufacture: Heat	Transport	Gross total	Available residue energy	Net total[1]
	Million Btu (oil equivalent) per OD ton						
Wood-based commodity							
Softwood lumber	0.943	0.786	4.060	1.966	7.755	8.313	2.909
Oak flooring	1.073	.844	4.847	1.977	8.741	11.388	3.050
Lumber laminated from veneer	.740	.144	6.443	1.966	9.293	3.540	5.753
Softwood sheathing plywood	.747	.145	6.726	2.081	9.699	3.697	6.002
Structural flakeboard	.956	.578	6.933	1.314	9.781	8.616	2.270
Medium-density fiberboard	.783[2]	3.748	5.555	1.146	11.232	2.741	8.491
Insulation board	.622[3]	4.920	5.619	1.243	12.404	.667	11.737
Hardwood plywood	1.041	.244	9.998	1.977	13.260	10.629	3.018
Underlayment particleboard	4.617[4]	2.503	5.598	1.198	13.916	1.529	12.387
Wet-formed hardboard	.743[3]	9.919	9.743	1.146	21.551	.797	20.754
Total	12.265	23.831	65.522	16.014	117.632	51.917	76.371
Percent of total (gross)	10.4	20.3	55.7	13.6			
Mean	1.23	2.38	6.55	1.60	11.76	5.19	7.64

	Extraction	Processing	Transport	Total
	Million Btu (oil equivalent) per ton			
Nonwood-based commodity				
Gravel	0.05	.00	0.40	0.45
Gypsum board	.14	2.73	.65	3.52
Liquid asphalt	.00	3.20	.73	3.93
Tar paper	.20	5.00	.73	5.93
Asphalt shingles	.03	5.70	.73	6.46
Concrete slab	.52	7.60	.40	8.52
Concrete block	.52	7.60	.65	8.77
Clay brick	.57	7.73	.76	9.06
Vermiculite	.04	14.20	.92	15.16
Glass fiber	.62	26.70	.92	28.24
Plastic vapor barrier	4.49	25.10	.75	30.34
Carpet and pad	6.60	28.69	1.90	37.19
Steel nails	2.45	46.20	1.48	50.13
Steel studs	2.45	46.20	1.67	50.32
Steel joists	2.45	46.20	1.67	50.32
Aluminum siding	26.80	172.00	1.67	200.47
Total	47.93	444.85	16.03	508.81
Percent of total	9.4	87.4	3.2	
Mean	2.99	27.80	1.00	31.80

[1]Assumes residue energy can be offset *only* against gross manufacturing energy (but not against logging or transport energy).
[2]Includes logging plus preparation of bark-free chips input.
[3]Includes logging plus preparation of chips.
[4]Includes energy input in logging plus preparation of particleboard furnish in form of planer shavings, plywood trim, and sawdust.

MAN-HOUR REQUIREMENTS FOR STRUCTURAL COMMODITIES

Man-hours needed to extract, manufacture, and transport a ton of wood-based commodities to the building site varied from a low of 8.37 for medium-density fiberboard to a high of 19.52 for wet-formed hardboard (table 22-3). Oak flooring and hardwood decorative plywood required about 15 man-hours per ton. The high labor input into wet-formed hardboard is in part attributable to prefinishing operations usual for this product.

TABLE 22-3—*Man-hours needed to extract, manufacture, and transport to building site—selected primary commodities* (Boyd et al. 1977)[1]

Commodities	Logging or extraction	Manufacture	Transport (mill to bldg. site)	Total
		Man-hr/OD ton		
Wood-based commodities				
Medium-density fiberboard	3.43	2.86	2.08	8.37
Underlayment particleboard	5.04	2.64	1.99	9.67
Softwood lumber	3.92	3.06	3.06	10.04
Structural flakeboard	3.97	3.99	2.14	10.10
Lumber laminated from veneer	3.08	4.53	3.06	10.67
Insulation board	2.28	6.54	2.13	10.95
Softwood sheathing plywood	3.10	4.55	3.31	10.96
Hardwood plywood	4.33	8.03	2.67	15.03
Oak flooring	4.46	8.07	2.67	15.20
Wet-formed hardboard	2.72	14.72	2.08	19.52
Total	36.33	58.99	25.19	120.51
Percent of total	30	49	21	
Mean	3.6	5.9	2.5	12.05
		Man-hr/ton		
Nonwood-based commodities				
Gravel	0.08	.00	1.03	1.11
Concrete slab	.09	.79	1.03	1.91
Concrete block	.09	1.75	1.24	3.08
Gypsum board	.34	1.74	1.24	3.32
Clay brick	.08	2.93	1.36	4.37
Liquid asphalt	.10	4.30	1.33	5.73
Asphalt shingles	.18	4.40	1.33	5.91
Tar paper	.64	4.00	1.33	5.97
Vermiculite	.08	10.70	1.71	12.49
Steel nails	.89	10.10	2.18	13.17
Steel studs	.89	10.10	2.25	13.24
Steel joists	.89	10.10	2.25	13.24
Glass fiber	1.12	17.50	1.71	20.33
Aluminum siding	.62	50.10	2.25	52.97
Carpet and pad	1.61	93.70	2.98	98.29
Plastic vapor barrier	.82	96.70	1.48	99.00
Total	8.52	318.91	26.70	354.13
Percent of total	2	90	8	
Mean	0.5	19.9	1.7	22.1

[1]Man-hour requirements for erection of structure are not included.

CAPITAL DEPRECIATION ASSOCIATED WITH COMMODITIES

To extract, manufacture, and transport structural commodities to the building site requires large investments of capital in physical facilities. As these facilities depreciate with use, a dollar amount can be assigned per ton of commodity produced and delivered (table 22-4). For wood-based commodities these amounts (1972 basis) vary from about $10 per ton to nearly $55 per ton, ovendry basis. Capital depreciation assignable per ton of decorative hardwood plywood is $25; that for oak flooring about $33. Of nonwood-based commodities, the greatest capital depreciation is associated with aluminum siding ($53.47/ton), carpet and pad ($114.88), and plastic vapor barrier ($125.33).

22-2 WOOD AND NONWOOD MATERIALS IN HOUSE CONSTRUCTION[3]

Boyd et al. (1977) analyzed a number of alternative designs for floors, walls, and roofs to determine weights of commodities per 100 square feet of construction. With knowledge of the weight of each commodity in each 100-square-foot section, it was possible to compute (primarily through use of the data in tables 22-2, 22-3, and 22-4) the manpower, energy, and capital depreciation requirements of each design erected in place on the house site. Data on man-hours required to erect the constructions at the house site, while not indicated in table 22-3, were obtained from the homebuilding industry and incorporated in the manpower column of table 22-5 (for details, see Boyd et al. 1976).

Thus table 22-5 compares manpower, energy, and capital depreciation required to build 100-square-foot sections of houses incorporating wood- and nonwood-based materials, including extraction or logging, manufacture, transport to house site, and erection. Table 22-5 does not include data on maintenance, nor does it include data on heating. All constructions were provided with acceptable (and comparable) levels of insulation, however.

Substantial differences in energy requirements between alternative constructions are evident. In roofs, a design incorporating steel rafters required approximately twice as much energy as wood truss or rafter constructions. Exterior walls sided with brick or constructed of concrete block required seven to eight times the energy of all-wood constructions, and walls framed with metal required approximately twice the energy of counterpart wood-framed constructions. In floors, constructions with concrete slabs or with steel supporting members required approximately 10 times more energy than wood floor systems. Manpower and capital costs, however, were in most cases not appreciably different for wood-based and nonwood-based systems.

TABLE 22-4—*Capital depreciation associated with extracting, manufacturing, and transporting to building site—selected primary commodities* (Boyd et al. 1977)[1]

Commodities	Extraction	Manufacturing	Transport	Total
	Dollars/ovendry ton			
Wood-based commodities				
Softwood lumber	3.09	3.91	3.25	10.25
Structural flakeboard	3.13	11.37	2.36	16.86
Lumber laminated from veneer	2.42	11.98	3.25	17.65
Softwood sheathing plywood	2.44	12.09	3.43	17.96
Underlayment particleboard	6.72	13.74	2.20	22.66
Hardwood plywood	3.41	18.37	3.14	24.92
Insulation board	3.84	24.06	2.29	30.19
Oak flooring	3.51	26.07	3.14	32.72
Medium-density fiberboard	3.21	27.89	2.18	33.28
Wet-formed hardboard	4.59	48.08	2.18	54.85
Total	36.36	197.56	27.42	261.34
Percent of total	14	76	10	
Mean	3.64	19.76	2.74	26.13
	Dollars/ton			
Nonwood-based commodities				
Gravel	.19	.00	1.17	1.36
Concrete slab	.19	.80	1.17	2.16
Concrete block	.19	.80	1.47	2.46
Clay brick	.19	.80	1.61	2.60
Liquid asphalt	.77	4.90	1.57	7.24
Gypsum board	.37	6.23	1.47	8.07
Tar paper	1.16	5.80	1.57	8.53
Asphalt shingles	.82	7.40	1.57	9.79
Steel nails	4.78	16.60	2.68	24.06
Steel studs	4.78	16.60	2.73	24.11
Steel joists	4.78	16.60	2.73	24.11
Glass fiber	.96	33.00	1.86	35.82
Vermiculite	.08	34.50	1.86	36.44
Aluminum siding	2.14	48.60	2.73	53.47
Carpet and pad	8.11	103.80	2.97	114.88
Plastic vapor barrier	6.29	117.40	1.64	125.33
Total	35.80	413.83	30.80	480.43
Percent of total	8	86	6	
Mean	2.24	25.86	1.93	30.03

[1]1972 basis.

TABLE 22-5—*Manpower, energy, and capital costs of homebuilding—per 100-square-foot section—including logging (or extraction), manufacture, transport to house site, and erection* (Boyd et al. 1977)

House portion and construction type	Manpower	Net Energy[1]	Capital Depreciation
	Man-hr	Million btu	Dollars
Roofs			
1. W-type wood truss with wood shingles	8.96	2.44	6.14
2. Same but with asphalt shingles	9.04	3.22	6.72
3. Steel rafters (flat roof)	9.17	5.11	6.38
4. Flat roof with LVL[2] rafters and flakeboard[3]	9.36	2.45	6.59
Exterior walls			
1. Plywood siding (no sheathing), 2 x 4 frame	7.99	1.99	4.15
2. Medium-density fiberboard siding, plywood sheathing, 2 × 4 frame	9.86	2.54	6.41
3. Medium-density fiberboard siding, ½-inch insulation board, and plywood corner bracing	9.26	2.69	6.71
4. Concrete building block, no insulation	18.45	16.53	5.56
5. Aluminum siding over sheathing	9.83	4.95	4.61
6. MDF siding, sheathing, steel studs	9.89	4.79	7.20
7. MDF siding, sheathing, aluminum framing	11.26	5.53	6.91
8. Brick veneer	22.00	17.89	8.37
Interior walls			
1. Wood framing	3.87	0.95	2.17
2. Aluminum framing	3.99	2.25	2.13
3. Steel framing	3.53	1.88	2.25
Floors			
1. Wood joist, plywood subfloor, and particleboard underlayment	9.15	2.85	7.58
2. Wood joist, plywood subfloor, oak finish floor	8.51	1.19	6.40
3. Wood joist, "single-layer floor"	7.77	2.09	6.32
4. Concrete slab	11.62	22.06	11.81
5. Steel joist, 2-4-1 plywood	11.97	23.26	16.34
6. LVL joist and flakeboard	7.76	2.05	7.23

[1]Energy from wood residues credited *only* against gross energy requirements of *manufacturing* phase, not against logging or transport of wood components.

[2]Laminated veneer lumber.

[3]Erection costs unavailable. Approximations based on similar construction were used.

22-3 LUMBER, MILLWORK, FLOORING, AND DIMENSION STOCK

LUMBER

Because the oaks predominate on southern pine sites, perhaps half the lumber volume sawn is oak. Other species cut in major quantities from pine sites for lumber include sweetgum, yellow-poplar, black tupelo, and red maple. Less hickory and post oak lumber volumes are cut than tree volumes would suggest; hickory lumber markets are limited, and much of the post oak is of low quality.

Data on lumber production from hardwoods growing on southern pine sites are not available, but total hardwood lumber production in the South has been declining slowly (fig. 29-15B bottom).

Sawmills cutting high-quality eastern hardwood trees derive most of their profits from random-length, random-width 4/4 to 8/4 lumber sawn and graded according to rules of the National Hardwood Lumber Association (1978). Millwork, flooring, and dimension stock for furniture are manufactured from such lumber. Because hardwoods growing on southern pine sites are small in diameter and frequently have short, crooked or defective stems, the yield of the upper commercial grades in desired lumber lengths and widths is frequently too low to support a conventional sawing operation.

The lumber proportion sawn in each grade, as graded by National Hardwood Lumber Association rules, is related to log grades (tables 12-11 through 12-33) and tree grades (tables 12-34 and 12-40).

Sawmills appropriate for high-quality, long hardwood logs are described in section 18-10. Chipping headrigs particularly suited to hardwoods are discussed in section 18-9. For conversion of short small logs see section 18-11.

Time to saw a thousand board feet of lumber depends on mill equipment as well as log diameter, length, and quality (tables 18-54 and 18-55).

Lumber yields.—Because lumber recovery factors (board feet recovered per cubic foot of log) are generally less than 7 in hardwood sawmills, volumetric recovery of rough green lumber, as a percentage of green log volume, is generally less than 50 percent (figs. 18-112 and 22-1). Lumber yield is related to species, sawing accuracy, board thickness, and saw kerf as discussed in the text accompanying figure 18-112 and tables 18-57 through 18-62.

Lumber recovery factors in hardwood mills are less than in softwood mills partly because hardwood lumber is cut thicker than softwood lumber. Rough dry hardwood lumber can be only slightly less than 1 inch thick to yield moderately long cuttings planed on two sides to a thickness of 13/16-inch; rough dry thickness of panels should be slightly over 1 inch to plane to 13/16-inch. Green 4/4 red oak lumber shoud be ⅛-inch thicker than required rough size to allow for shrinkage (Freese et al. 1976). Hardwood 4/4 lumber must therefore be cut about 1-⅛ inches thick, whereas 4/4 softwood lumber is frequently sawn only 15/16-inch thick.

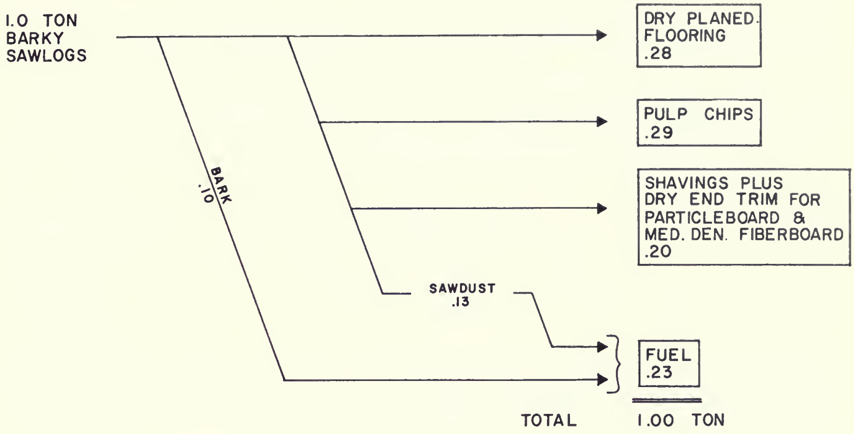

Figure 22-1.—Materials balance for manufacture of ¾-inch-thick, tongue-and-groove oak flooring, based on ovendry weight. Sawlog weight includes bark. (Drawing after Koch 1976a.)

Hardwood lumber varies substantially in thickness. Applefield and Bois (1966) measured lumber in 16 furniture plants at 12 locations in North Carolina and found that 19.7 percent had miscuts, 16.0 percent was too thin, and 1.7 percent was oversize for a total of 37.4 percent mismanufactured. Sawing variation cannot be eliminated, but it can be reduced. Besides the cost in loss of lumber recovery, oversizing increases the cost of kiln-drying by decreasing the number of boards in a kiln charge, shortening sticker life, and increasing kiln time required for drying. Simpson and Tschernitz (1978) computed that an increase in red oak thickness of 3/32-inch increases drying time more than a day and drying cost for 4/4 lumber by about $5 per thousand board feet.

Higher lumber recoveries can be attained through training, improvement of equipment to reduce sawing kerfs and tolerances, change in sawing patterns, and improvement of cutting accuracy. New sawmills should incorporate reliable thin-kerf sawing equipment and proved automated saw and log positioning equipment. To aid mill managers in evaluating the economic feasibility of sawmill improvement, Harpole (1977) provided a procedure to estimate the break-even point at which costs equal anticipated benefits.

Sawlog values.—Martens (1967) commented that if the value of hardwood lumber had increased at the same rate as the cost of producing it, abandoned sawmill sites would be less common; in the Appalachian region some 2,800 sawing and planing mills (about 40 percent of the operating plants) went out of business between 1948 and 1958 and the trend continues. In general, the very large and the very small mills are disappearing, and surviving intermediate-size mills are becoming more automated.

Success in the hardwood sawmill operation requires good estimation of true sawlog value and knowledge of how changing hardwood lumber prices affect it. Martens (1967) computed these changes for the period 1955–1965; in general, increases in prices for hardwood lumber in the Appalachian region resulted in only slight increases in the value of sawlogs (see tables 22-6 and 29-38).

By 1980, lumber cut from red oaks in the Midsouth more than doubled in value over that indicated by Martens for 1964 in the Appalachian region; lumber from upland oaks was significantly more valuable than that for southern lowland oaks, as follows (data from veteran lumber manufacturer H. M. Vick):

Log grade	Upland red oaks	Lowland red oaks
	----Dollars/thousand bd ft of lumber sawn, FOB sawmill----	
1	*310*	*233*
2	*246*	*207*
3	*220*	*191*

How much can a sawmill operator afford to pay for his sawlogs? Adams (1970) developed a computer program that can provide the operator with the answer to this question. Adams (1972) also published a detailed illustration of this SOLVE computer program to derive dollar values for sawlogs delivered to the yard for individual milling situations. Improved procedural guides for the SOLVE technique, including analysis design, data collection, and computer card preparation and use were provided by Adams and Dunmire (1978).

Mill operators frequently have opportunities to sell sawlogs for some higher-value product such as veneer. For operators faced with pricing wood sold in such transactions, Screpetis (1979) provided a procedure for examining the economic benefits of selling versus sawing.

Hardwood lumber price history is shown in figure 29-43ABC; predicted price to 2005 is graphed in figure 29-44. Readers interested in an econometric model of the hardwood lumber market should read Luppold (1982).

A mill manager with decades of sucessful experience sawing hardwood lumber for the furniture trade cautions that concern with log grades should begin while the trees are still growing in the forest; his recommendations follow; in brief, do not wait until a log arrives at the sawmill to start emphasis on grade recovery:

- Prior to purchase, determine the grade of logs each timber tract will yield.
- Compute value of the timber on the basis of log grade.
- Conduct harvesting operations with log grade as focal point.
- Saw, yard, and ship the lumber to maximize value recovered.

Drying and planing.—Lumber drying procedures are described in chapter 20 in text sections as follows:

Section	Subject
20-2	Air-drying
20-3	Forced-air fan predrying
20-4	Heated low-temperature drying
20-5	Low-temperature drying with dehumidifiers
20-6	Drying in conventional heated kilns
20-7	High-temperature drying

Storage of dry lumber is discussed in section 20-13.

TABLE 22-6—*Average lumber recovery values from sawlogs of six hardwood species and three log grades in the Appalachian region during 1955 and 1964* (Martens 1967)

Species groups and log grades	1955	1964
	-----Dollars per thousand board feet of lumber sawn------	
Ash		
Log grade 1	133	148
Log grade 2	102	111
Log grade 3	75	79
Hickory		
Log grade 1	78	90
Log grade 2	59	69
Log grade 3	46	49
Soft maple		
Log grade 1	119	149
Log grade 2	103	130
Log grade 3	75	89
Red oak		
Log grade 1	130	135
Log grade 2	93	92
Log grade 3	68	65
White oak		
Log grade 1	141	146
Log grade 2	95	92
Log grade 3	70	66
Yellow-poplar		
Log grade 1	128	133
Log grade 2	98	105
Log grade 3	75	80

Planing of lumber is described in figures 18-138 through 18-144 and in sections 18-4 through 18-7 and 18-13; for procedures to control planing defects, see text related to tables 18-32 through 18-35.

What future developments are likely in the manufacture of hardwood lumber? Because of the skill required and labor cost to visually grade lumber, it is possible that the process will be computerized. Also, decreasing availability of high-quality sawlogs may cause mills to laminate hardwood lumber to obtain the sound furniture cuttings needed.

Grading lumber by computer.—The mathematical basis of the grading system of the National Hardwood Lumber Association involves estimates of the amount of clear cuttings available from each board. To group boards into grade classes with similar proportions, the grading rules prescribe minimum width and length, maximum wane allowance, maximum knot size, and extent of splits for each grade. Grading also requires decisions on ripping to two boards of differing grades with more value than the single board.

Decisions made at edger and trimmer are largely two-dimensional, involving length and width. Hallock and Galiger (1971) described the problems associated with making two-dimensional decisions as requiring development of a computer program using the description of a flitch or board as input; as output, the program must develop the position of edging cuts, possible rip cut, trimming cuts, and possible crosscut to yield a board or boards of highest quality and value.

Grading by computer therefore requires two developments:

- A system that can scan a board and mathematically describe its shape and defects.
- A computer program that, from the mathematical description of the board, can almost instantly give the grade and value of the board.

The second problem seems easier to solve than the first, as computer capabilities are advancing rapidly. Hallock and Galiger (1971) developed a program that they believe to be nearly 100-percent accurate. Grades established by the program should in all cases be correct, or at most one grade low; overgrading did not appear to be possible. Programming language used was 3600 Fortran; processing can be done on Control Data Corporation 3600, UNIVAC 1108, or IBM 360 computers.

The first problem, mathematical description of the board, seems more difficult. Progress in locating lumber defects by ultrasonics has been reported by McDonald et al. (1969). In the opinion of some researchers digitized image analysis seems a more promising route to board description. McMillin[4] is studying this possibility.

Laminated lumber.—Lumber can be laminated for appearance or structural grades. For structural purposes timbers can be built up into heavy sections by flatwise lamination, narrow boards can be edgewise laminated and ripped to standard wider widths, or rotary-cut veneers can be parallel-laminated to desired thickness thereby randomizing strength-diminishing effects. These three procedures are discussed in section 22-10.

When appearance-grade dimension stock for furniture parts is cut from hardwood lumber, the removal of defects in the rough mill may result in loss of half the lumber volume (see section 18-12). Future abundance of small-diameter hardwood logs, and scarcity of large-diameter logs will increase these yield losses unless alternative manufacturing procedures are developed.

Suchsland (1980) proposed such an alternative procedure and observed that most defects in a 4/4 hardwood board extend throughout its thickness and appear on both faces so that a portion of the board is unusable. Manufacturing a 4/4 board from two laminae, randomly paired, would limit each defect to only one face; in such laminated wood the defect in one face need not be removed because the opposing face may be clear, allowing the manufacture of one-clear-face cuttings. If, in addition, the defects in the laminae are repaired by plugging, the entire board can be converted to furniture cuttings of three qualities, as follows:

- Clear both sides
- Clear one side, other side repaired (sound)
- Repaired both sides (sound)

[4]McMillin, C. W. 1980. A problem analysis and research approach for cutting wood parts with a laser under digital control of an optical image analyzer. Study Plan FS-SO-3201-17 dated June 1, 1980 on file at the Southern Forest Experiment Station, Pineville, La. See also McMillin (1982) and Huber et al. (1982).

Such 2-ply boards could be run through a rough mill to make dimension stock without need to recognize and remove defects, and yields would increase significantly if at least two—if not all three—qualities of cuttings could be utilized.

Suchsland's (1980) computer analysis contains graphical data on yields of cuttings of four sizes from two-ply boards variously constructed of laminae containing one to five defects each. He found that greatest yield gains are obtained when low and high quality laminae are paired. With such pairing in which one laminae had four defects and the other, one, yields of 4- by 24-inch cuttings were as follows (laminae measured 96 inches long and 8 inches wide):

Description	Yield
	Percent
Clear both sides	13
Clear one side	75
Repaired both sides	12
Total yield	100

From solid lumber boards with four defects, yield of this size cutting, clear on both faces was 38 percent (fig. 22-2).

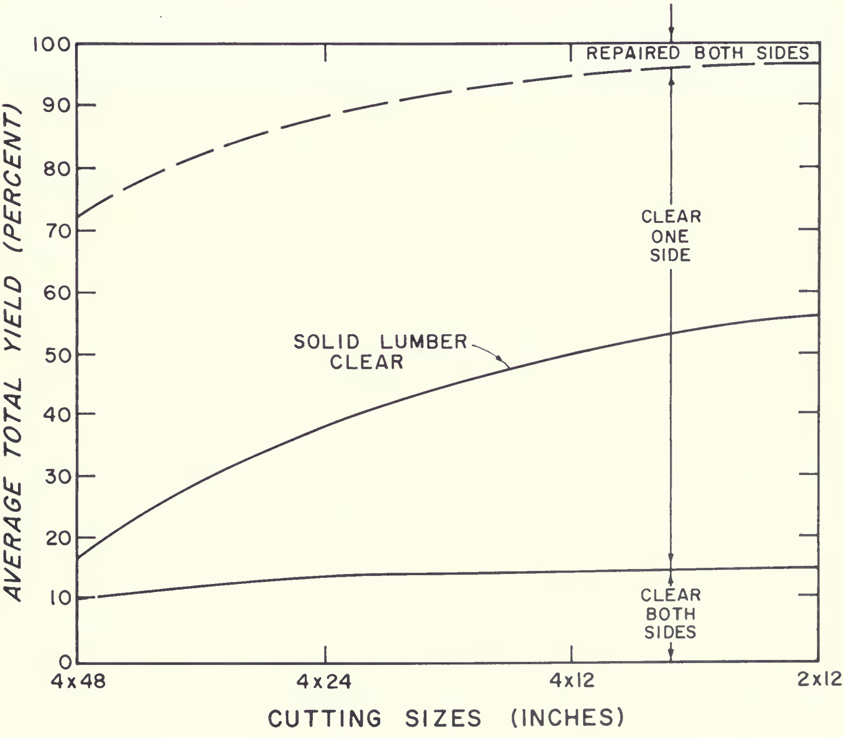

Figure 22-2.—Yield of two-ply furniture cuttings of four sizes and three qualities compared to clear-both-sides cuttings from solid lumber with four defects. The two-ply lumber had four defects in one lamina and one defect in the other. The 4/4 boards measured 96 inches long and 8 inches wide. (Drawing after Suchsland 1980.)

Some obstacles to implementing this concept include cost of matching laminae lengths and widths prior to lamination, loss of wood in surfacing interfaces to be glued, and cost of lamination.

MILLWORK

The scarcity of clear hardwood lumber in lengths and widths traditionally used for hardwood millwork has sharply restricted its use in residences. The magnificent hardwood solid panellings and mouldings popular in homes built in the 19th and early 20th Century have largely been replaced by plywood panelling and painted or overlayed softwood mouldings of smaller dimensions. Use of hardwood millwork in the 1930's dropped sharply from that in 1928, but has since increased somewhat (fig. 29-25).

In these final decades of the 20th Century, hardwood millwork is largely confined to church architecture (oak pews, for instance), executive offices, bank lobbies, luxurious architect-designed homes, and top-grade store fixtures. Prefinished, tongue-and-groove, end-matched panelling of thin solid hardwood is still sold commercially, but competition from foreign and domestic plywood is intense.

Various ideas have been advanced to utilize low-grade hardwood logs for panelling, but few have proven commercially successful. For example, Heebink and Compton (1966) made panelling (fig. 22-3) from low-grade oak logs by sawing thin unedged boards at the headsaw, planing them to 0.6-inch thickness, press-drying (figs. 20-32 and 20-33) and double-surfacing them to 7/16-inch thickness, and then machining matching tongues and grooves on ends and sides to yield face widths of 2, 3, 4, and 6 inches and lengths of 2, 4, 6, and 8 feet. They found that press-drying of oak produces a color about the shade of chestnut or light walnut and accentuates character marks.

Peter and Page (1957) experimented with character-marked interior panelling made from low-grade logs of several southern hardwoods and found that sandblasting produced a pleasing visual effect; the red oaks were easiest to treat by this method. Open knots or defects were backed with heavy black paper and boards were treated with various fillers and tinted finishes. They concluded that the panelling, while attractive, still looked like what it was—a low-grade board. Surface treatment or color blending is needed to subdue defects. Such an effect can be obtained by hammering or pressing indentations into wood that has been previously filled and finished.

More recently, Hansen and Gatchell (1978) and Gatchell and Peters (1981) showed that joints in hardwood lumber end-joined in a sine-wave pattern are stable and virtually undetectable by most people if grain patterns are matched. This serpentine end matching technology, described by Gatchell et al. (1977) and Coleman (1977) shows promise for utilization of short clear cuttings in high quality millwork. The sine-wave joint is not structural, however; it is best suited for application in panels (fig. 22-4)

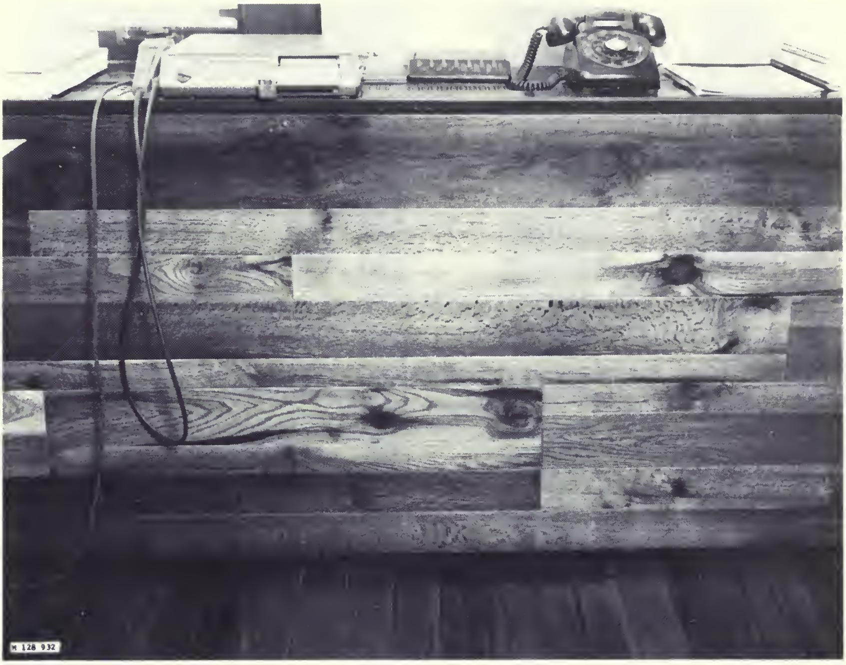

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Figure 22-3.—Panel of press-dried, end-matched oak. (Photo from Heebink and Compton 1966).

Millwork machining technology is described in chapter 18, as follows:

Subject	Figure no.
Panel planing	18-133 through 18-138, 18-143 top
Panel sanding	18-167
Moulding	18-145 though 18-149
Sanding of mouldings	18-170 and 18-174
Tenoner applications for millwork	18-221

Standards and grading rules for hardwood interior trim, mouldings, and stair treads and risers have been published by the Hardwood Dimension Manufacturers Association (1961).

FLOORING

As late as 1955, hardwood flooring was installed in 68 percent of the floor area of new construction; the hardwood flooring industry was relatively free of competition from other flooring materials, and for the most part operated under semi-stable market conditions. By 1963, however, the amount of floor area being covered by hardwood had declined to 34 percent (Martens 1965; Large et al. 1971), principally because of competition from vinyl-asphalt tile and wall-to-wall carpeting. For graphical data on current hardwood flooring production trends, see figure 29-24.

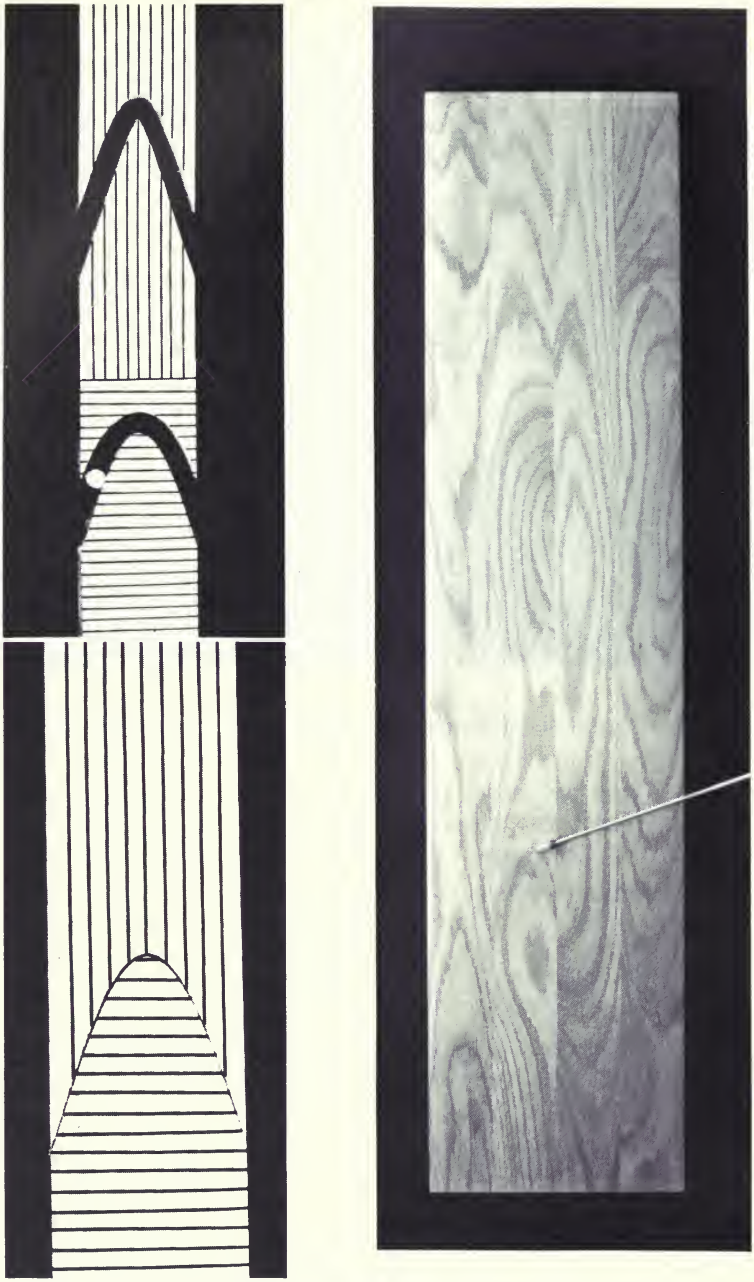

Figure 22-4.—Serpentine end-matched joints. (Left) Two router-bit paths must be used if the pieces are to fit. (Right) A nine-piece oak panel with five joints. (Drawing after Coleman 1977; photo from Hansen and Gatchell 1978.)

Factors affecting changes in markets for hardwood flooring were studied by Martens (1971). He concluded that regardless of room type (living room, dining room, or bedroom), hardwood floors cost less than floors covered with composition tile or carpet. This is true both in terms of yearly cost and long-term cost. Hardwood floors also have a wear life much longer than that of other flooring materials. Wall-to-wall carpet, although two to three times as expensive as hardwood, has the advantage of requiring less time to maintain; but the difference is not large. Composition tile is the cheapest floor material for an apartment owner to have in his building; but tenant maintenance costs are high, and tenant preferences indicate that tile is not as well received as hardwood, which is only slightly higher in total cost. Wall-to-wall carpet is by far the most expensive to the apartment building owner, although it is well received by the tenants. Overall, in yearly cost, long-term cost, wear life, maintenance time, and preference, hardwood floors appear to be the most practical for the single-family-home owner, the apartment tenant, and the apartment building owner (Martens 1971).

In view of this, why have sales of hardwood flooring diminished? Nevel (1975) found that contractors were reluctant to use hardwood flooring because it is difficult for them to obtain necessary quantities in the grades desired, at the time needed, at a stable price. Also, hardwood flooring installation requires skilled labor and more time than vinyl asbestos tile or carpet; these factors combine to upset tight building schedules.

Most hardwood flooring manufactured is ¾-inch thick with 2-¼-inch-wide face and matching tongues and grooves machined on edges and ends. Some flooring, particularly that sold on the West Coast, is only 5/16-inch thick with square edges and ends. A third class is parquet, preassembled in square mosaics from short, thin, narrow strips.

Recommendations for laying, sanding, finishing, and maintaining hardwood floors of all types are found in Anderson (1970, p. 134-139), in USDA Forest Service, Forest Products Laboratory (1961), and in current publications of the National Oak Flooring Manufacturers' Association, Memphis, Tenn.

Species preferences.—Hardwoods most commonly used for flooring include numerous species of oak, maple (principally *Acer saccharum* Marsh.), beech (*Fagus grandifolia* Ehrh.), birch (*Betula* sp.), and pecan (*Carya* sp.). While both white and red oaks are processed into flooring, most is produced from the red oaks, principally southern red oak, northern red oak, and black oak.

¾-inch-thick tongue-and-groove strip flooring.—The predominant hardwood flooring is ¾-inch thick, with 2¼-inch-wide face and matching tongues and grooves on edges and ends (fig. 22-5 top). The pattern has a hollow back to make it rest securely on the floor substructure, and it has tapered edges to insure a tight face joint. The tongue is machined at a set distance from the face to support the strip flush with adjacent strips in case of underthickness. Normally such flooring is machined face down on a planer-matcher to insure correct positioning of tongue and groove. Flooring must be run on planer-matchers with opposed sideheads to insure constant face width (fig. 18-139). Strips are random length and the ends are also machined with tongues and grooves on end-matchers (fig. 18-223).

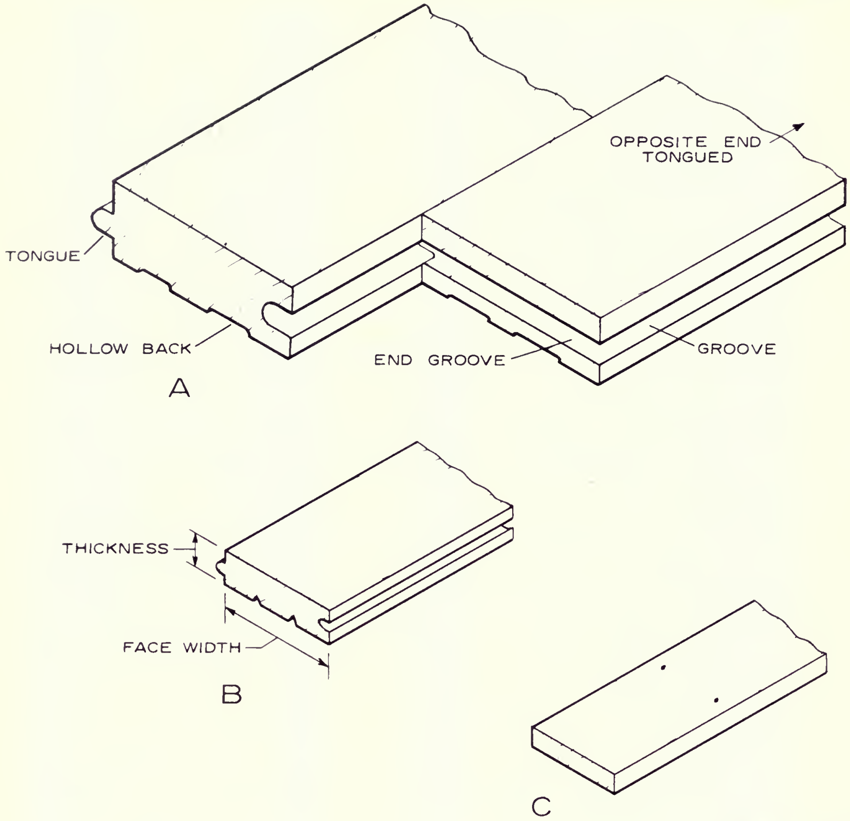

Figure 22-5.—Types of strip flooring. (A) Side and end matched, ¾-inch thick. (B) Thin flooring strips, matched. (C) Thin flooring strips, square-edged. (Drawing after Anderson 1970.)

If oak flooring were manufactured from the entire product of the log, yield of dry planed product would be about 28 percent of log weight, ovendry basis, including bark (fig. 22-1). Normally, however, hardwood flooring manufacturers buy specified common grades of lumber—usually 2 and 3A—which they rip and crosscut to yield flooring grades desired. Flooring is graded according to rules published by the National Oak Flooring Manufacturing Association (1977).

Large et al. (1971) provided data on flooring yields from northern red oak kiln-dried lumber of three grades: 1, 2, and 3A Common. Each of the three lumber grades was subdivided into four width-length classes. The lumber was converted to tongue-and-groove flooring with 2¼-inch face and graded into 2 Common, 1 Common, Select or Clear flooring grades. Lumber grade had a significant effect on both percent yield and the grade distribution of flooring. One Common (1C) lumber had an overall yield of 75.5 percent followed by 2C and 3AC with yields of 68.5 percent and 62.7 percent, respectively. With respect to flooring grade distribution, most flooring from 1C lumber was in the Clear and Select flooring grades, while most flooring from 3AC lumber was graded 2C and 1C. Flooring yield from 2C lumber was more evenly distributed among the four flooring grades. Percent yield of flooring varied considerably with board width. Wide lumber had an average yield of 75.3 percent, while narrow lumber averaged 62.6 percent. Lumber length had little effect on flooring yield, but its grade noticeably affected length distribution; 79 percent of the flooring from 1C lumber was longer than 45 inches as compared to 51 percent from 3AC lumber.

Miller (1971) studied manufacturing and distribution patterns in the oak strip flooring industry in 1969 (fig. 22-6); his conclusions were based on manufacturers' reports on shipments of 363.2 million board feet, about 85 percent of the volume shipped. Most of the **production** was in the southern and Appalachian hardwood forest areas of the United States. The South Atlantic, East South Central, and West South Central Regions produced 88 percent of the oak strip flooring sold in 1969; the Middle Atlantic, East North Central, and West North Central Regions produced the remainder.

Total consumption of oak flooring also varied considerably from region to region throughout the United States. Most of the consumption was in the New England, Middle Atlantic, East North Central, and South Atlantic Regions. The highest consumption was in the South Atlantic Region, which accounted for about 23 percent of the total United States consumption. It was followed closely by the Middle Atlantic Region, which consumed 22 percent of the total. In contrast, the West South Central, Pacific, and Mountain Regions accounted for only a little more than 6 percent of the total consumption. Generally speaking, the dividing line in the concentration of oak strip flooring markets is the Mississippi River—about 90 percent of the markets are found to the East, and about 10 percent to the West.

Wholesalers were the main **distributors of flooring** throughout the United States, handling about 33 percent of all oak strip flooring shipped in 1969. Nonstocking wholesalers ranked second as distributors of flooring, and retailers ranked third. Builders ranked last as distributors, indicating that few of them buy directly from the manufacturer. Even though wholesalers dominated the distribution patterns in most regions, in the three largest producing regions—South Atlantic, East South Central, and West South Central—most volume of shipments was received by retailers (Miller 1971).

5/16-inch-thick face-nailed strip flooring.—Thin, 2-inch-wide, face-nailed hardwood strip flooring (fig. 22-5C) is much used on the West Coast. The 5/16-inch-thick, square-edge strips have planed top and bottom surfaces, but edges are left as they come from straight-line ripsaws. They are random-length, and do not have tongues and grooves on the ends.

Youngquist (1952) described installation procedures. The thin strips are usually laid over a substantial subfloor with a layer of building paper between subfloor and finished floor. The strip flooring is cut and fitted for each room

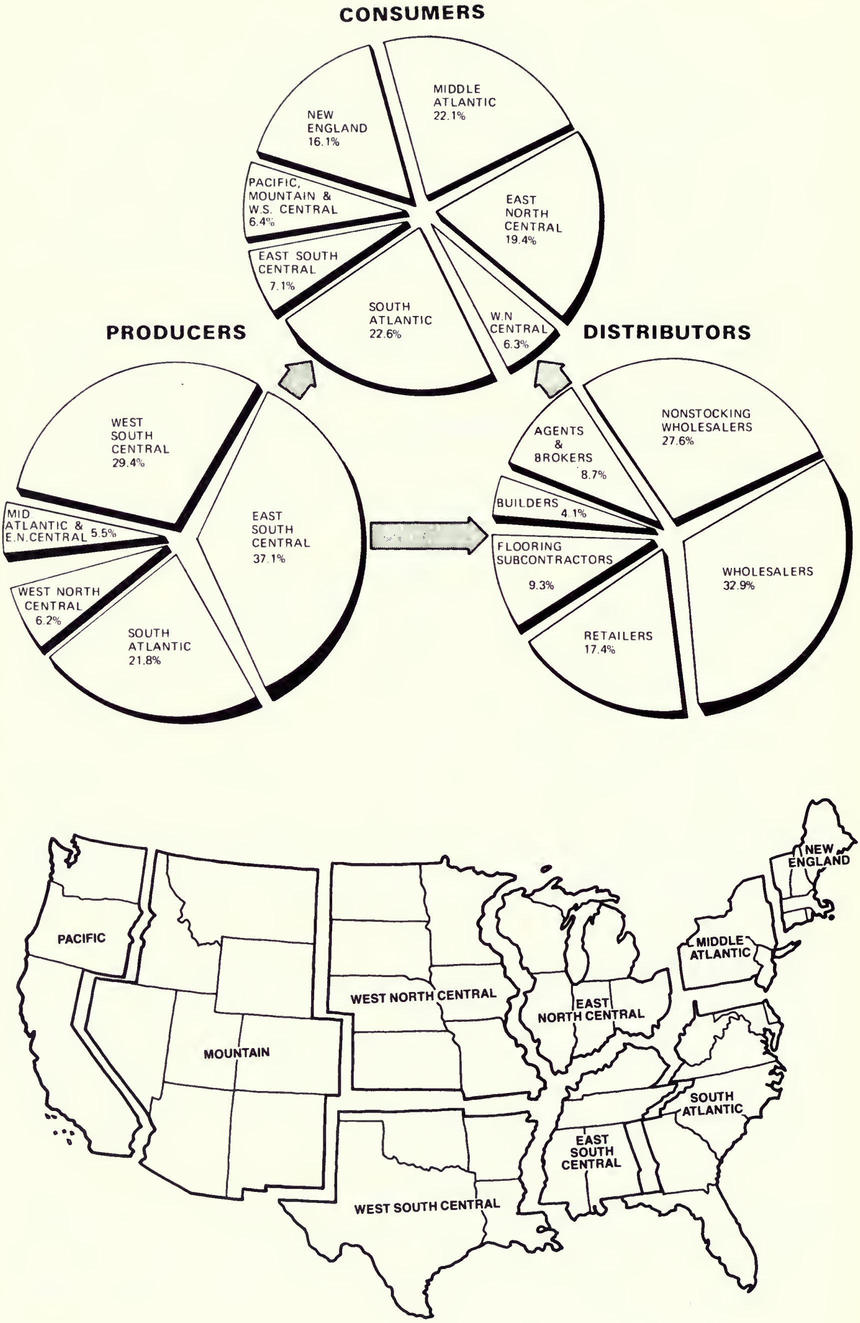

Figure 22-6.—(Top) Producers, consumers, and distributors of oak strip flooring in 1969. (Bottom) Geographic divisions. (Drawings after Miller 1971.)

when laid; ends of strips are butt-jointed. It is common practice to lay about six strips of flooring parallel with the wall around the room to form a border; the rest of the strips are arranged lengthwise in the room. Each strip is face-nailed with 1-inch brads on each edge, about 6-½ inches apart, along the length of the strip (fig. 22-7). The nails are set about 1/16-inch below the face surface, the holes filled with putty. Floors are given a light sanding, and finished with sealer, wax, or varnish.

The thin-strip flooring uses less wood per unit area covered, is easier to manufacture, requires less kiln time, and permits a greater diversity of floor patterns than the thicker tongue-and-groove flooring. Also, the thin strips reach equilibrium moisture content quickly, and because they have square edges, are easy to remove and replace. Because the strips are only 5/16-inch thick, the floor can be sanded and refinished only a few times. As strips are flexible and have no tongue and groove to share loads, the subfloor must be a continuous flat plane.

Parquet flooring.—Mosaic-parquet oak flooring consists of thin slats about an inch wide and 4 to 12 inches long, assembled into squares (fig. 22-8) or planks. Much of the success in marketing parquet flooring is attributable to good finishing techniques employed by the industry.

Manufacturing sequences vary greatly; one procedure for making prefinished parquet planks is shown in figure 22-9. Parquet squares and planks can be bonded directly on a concrete slab using mastic adhesives, hot-melt asphalt, or

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Figure 22-7.—Thin-strip, square-edge, face-nailed oak flooring over plywood subfloor. (Photo from Youngquist 1952.)

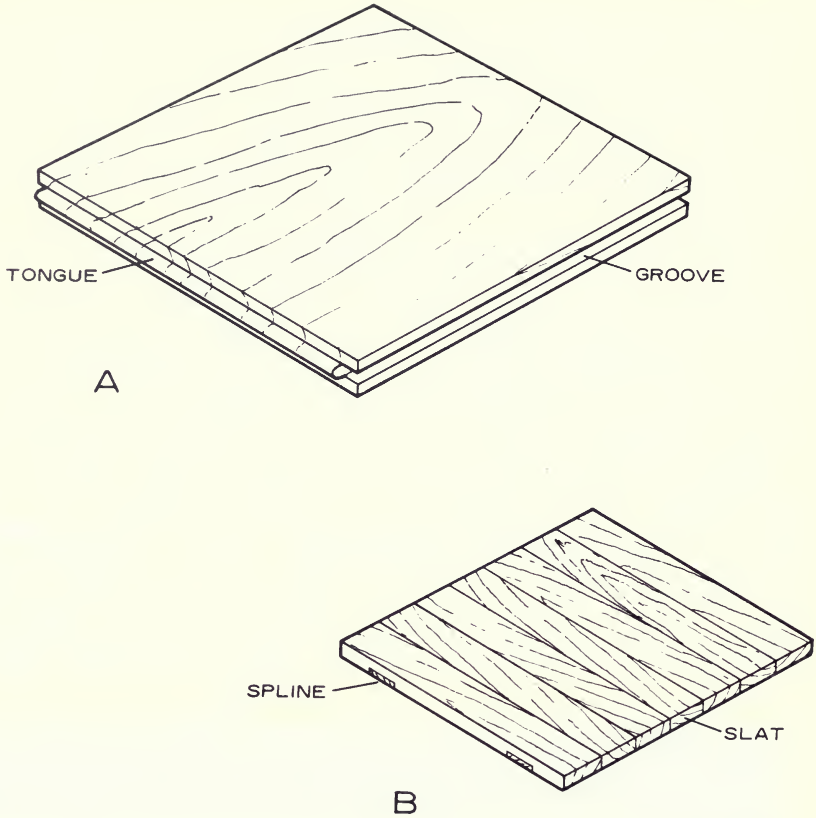

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Figure 22-8.—Parquet flooring. A, tongued and grooved; B, square-edged and splined.

cold setting binders. (See U.S. Forest Service, Forest Products Laboratory 1961, p. 24, for a discussion of mastics.) Finish flooring applied directly over a concrete slab lacks both heat and impact-sound insulation.

Either parquet or strip flooring may be applied over particleboard (5/8-inch) or fiberboard (0.215 inch) underlayment which is nailed or glue-nailed to 5/8-inch plywood sheets glue-nailed to floor joists. If the plywood glue-nailed to the joists is sanded, has tongue-and-groove edges and ends, and is 3/4-inch thick, the strip flooring can be applied directly to the plywood subfloor.

When parquet flooring is mastic-bonded to a fiberboard underlayment, solvent-based mastics are preferable, as water-based mastics tend to swell the underlayment.

Miller (1972) polled 16 parquet flooring manufacturers to determine product distribution patterns existing in the industry in 1969. Geographic regions identified are those shown in figure 22-6 (bottom). Data were obtained on shipments of about 22.21 million square feet of flooring, or 82 percent of total 1969 shipments estimated at 27.20 million square feet. An additional 1.44 million square feet were imported into the United States in 1969.

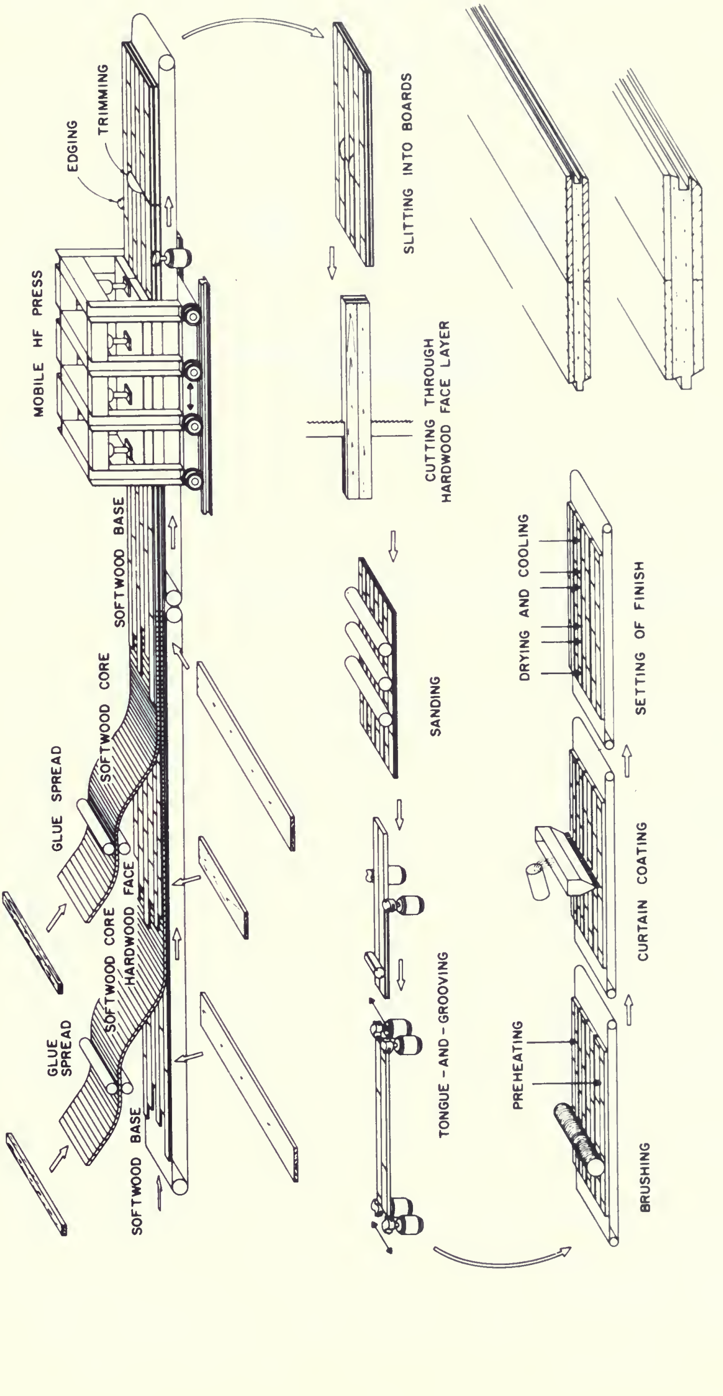

Figure 22-9.—Production of a three-layer prefinished parquet plank by the method of Robert Hildebrand Machinenbau GmbH, West Germany. (Drawing after Kubler and Lempelius 1972.)

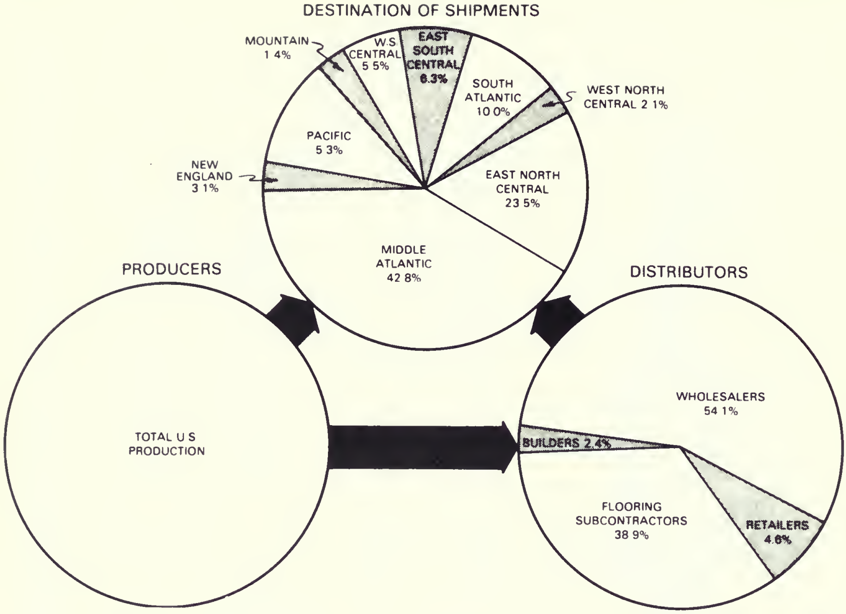

Figure 22-10.—Producers, distributors, and destination of parquet flooring in 1969. See figure 22-6 (bottom) for geographic divisions. (Drawing after Miller 1972.)

Miller found that essentially all of the parquet flooring is produced in the southern and Appalachian hardwood areas of the United States. The Middle Atlantic, East North Central, and South Atlantic Regions were first, second, and third, respectively, in total shipments; and the Mountain Region was last.

The channels of distribution (fig. 22-10) are dominated by wholesalers and flooring subcontractors; however, wholesalers are stronger in the New England, East South Central, Mountain, and Pacific Regions; and wholesalers and flooring subcontractors are about equal in the Middle Atlantic, East North Central, and South Atlantic Regions.

According to most parquet manufacturers, the geographic market area and channels of distribution for parquet flooring have changed since 1960 and will change even more. From 1960 to 1969, increases in shipments to regions east of the Mississippi River and decreases in shipments to regions west of the Mississippi River accounted for most of the geographic distribution changes.

The economics of parquet flooring manufacture are examined in section 28-15.

Parquet manufacturers reported that from 1960 to 1969, distribution shifted from retail lumber yards to flooring subcontractors because flooring subcontractors provide better consumer service. Manufacturers also reported more direct sales to specialty flooring distributors, larger purchasers, mobile home manufacturers, and builders of modular or unitized units. Manufacturers expect to channel a greater proportion of the flooring through the distributors who have both the expertise and the facilities to offer consumers a complete floor system (Miller 1972).

DIMENSION STOCK

Hardwood **dimension stock** includes almost any cut-to-size wood component, usually in the kiln-dried condition, produced for resale to a manufacturer. The term is principally used with reference to furniture components, handle blanks, and squares or rounds; it may include parts for caskets, toys, and specialty items. Flooring and pallet parts are not considered dimension stock. The term includes lumber core stock and laminated components, however, and is sometimes expanded to include flat or moulded plywood components (Flann 1963).

Dimension stock is sold in three classes, depending on degree of processing. **Rough dimension stock** consists of blanks sawed and ripped to specific sizes, and possibly planed hit-and-miss on one side to eliminate excessive thickness variation. **Semi-finished dimension stock** is rough dimension stock further processed by edge- or face-gluing, surfacing, moulding, tenoning, boring, sanding, or other machining; such stock is not, however, completely fabricated and ready for assembly. **Finished dimension stock** is completely machined or fabricated; no additional machining is required by the customer, with the possible exception of a light sanding operation.

Grading rules for dimension stock have been published by The Hardwood Dimension Manufacturers Association (1961) and by the National Hardwood Lumber Association (1978, p. 52).

Text sections 18-11 and 18-12 discuss in considerable detail the rationale for bucking low-grade hardwood logs to short lengths, e.g., 6-foot-long, and then sawing these short logs into lumber for direct conversion to dimension stock—thereby bypassing the manufacture of graded lumber in lengths and widths acceptable to the graded-lumber trade. These text sections describe cutting patterns, cutting procedures and costs, cutting yields, and sawing equipment. Also discussed are cutting-length requirements of the furniture industry. For example, Bingham and Schroeder (1976, 1977) found that the average cutting length in one furniture factory was 24 inches, a second averaged 23 inches, and a third averaged 31 inches. These findings are a strong argument for manufacturing dimension stock directly from short logs.

The technology of sawing rounds is illustrated in figure 18-91; drying data for rounds are graphed in figure 20-26.

Drying of squares is described in chapter 20, as follows:

Subject	Text
Air-drying	Figure 20-6
Kiln-drying hickory handle blanks	Tables 20-23 and 20-24
Kiln-drying 10/4, 12/4, and 16/4 squares of 10 hardwood species or species groups	Tables 20-25

Equipment to turn and sand squares and other shapes is shown in figures 18-175 through 18-190.

The economic feasibility of hardwood dimension manufacture is examined in sections 28-4, 28-8, and 28-13. Consumption of hardwood lumber used to manufacture furniture in 1960, 1965, and 1977 is graphed in figures 29-26 and 29-27.

Edge-glued core stock.—Core panels, a class of dimension stock, are used as center fill material for laminated products. High-grade lumber core cuttings for use in tops, shelves, doors, and drawer fronts can contain only minor defects such as stain, small bird pecks, small burls, pin knots, and pinworm holes (Araman 1978). Yellow-poplar has traditionally been favored in manufacture of such cores.

Araman (1978) observed that in recent years, yellow-poplar has become abundant, especially in the lower grades. Because of this increase in availability, continued use of yellow-poplar as furniture core material should be assured if cost of the lumber core is maintained or lowered. Failure to control cost will result in loss of the furniture core market to other materials, principally particleboards and fiberboards.

From his analysis of alternative production procedures, Araman (1978) concluded that 2A Common lumber is the most economical grade when converting low-grade yellow-poplar lumber into furniture core material; ideally, a combination of 2A Common and 2B Common lumber should be used. In the most economical manufacturing procedures, narrow strips from a gang-ripping operation are sent to a defecting station where objectionable defects are removed by crosscutting. From this point, one of two procedures should be employed, as follows:

- Each random-length, defect-free piece is cut to the longest needed length that the piece will yield
- Or, resulting random-length pieces (minimum of 8 inches) are sent to a finger jointing station where the ends are machined and glued to yield a continuous strip which is then cut to required lengths. Finger jointing results in a loss in usable length of about 7/8-inch per joint; because edges must be remachined prior to edge gluing into panels, this procedure also results in a width loss of about ⅛-inch.

With either system, Araman found that yield from 2A Common lumber is about 70 percent when cutting strips 2.25 inches wide.

A persistent problem in panel manufacture is sunken glue joints, caused by surfacing the panels too soon after gluing. The wood adjacent to the joint absorbs water from the glue and swells. If the panel is surfaced before the excess moisture is distributed, more wood is removed along the joints than at intermediate points. Then during subsequent equilization of moisture, greater shrinkage occurs at the joints than elsewhere, and permanent depressions are formed. These depressions are visible on the surfaces of veneer laminated to such cores.

Selbo (1952) suggested use of one of the following conditioning periods, before planing edge-glued panels, to preclude formation of sunken joints visible in panels that will be given a high gloss finish without veneering:

- 7 days at 80°F and 30 percent relative humidity
- 4 days at 120°F and 35 percent relative humidity
- 24 hours at 160°F and 44 percent relative humidity
- 16 hours at 200°F and 55 percent relative humidity

For edge-glued furniture panels that are subsequently covered with crossbands (usually 1/16- or 1/20-inch) and face veneers (usually 1/28-inch), Selbo thought that the conditioning times shown above could be shortened—perhaps reduced in half. In his experiment, Selbo used urea resin and animal glue.

Use of hardwood dimension stock by the southern furniture industry.— Anderson and Sendak (1972) queried 635 manufacturers of wooden furniture in the 16 States comprising the three southern regions established by the United States Department of Commerce (fig. 22-6 bottom). Of these firms, 544 (87.5 percent) used hardwood lumber or dimension stock in their plants; average consumption in 1967 was 1,465,000 board feet per firm. Of the 544 firms that used hardwood lumber or dimension stock, 372 firms (67 percent) purchased hardwood dimension stock. Types most frequently purchased and dollars expended per type, were as follows in 1967:

Type	Firms purchasing	Expenditure
	Number	*Dollars*
Turnings and carvings	173	8,584,204
Rough flat stock	142	12,839,294
Partially machined stock	116	13,147,102
Squares	107	6,379,926
Fully machined parts	78	11,442,328
Mouldings and trim	73	1,977,176

Most of the furniture firms produce in their own plants the majority of hardwood parts they need. Only 33 percent indicated they manufactured none of the hardwood dimension they used.

Anderson and Sendak (1972) concluded from a survey that total use of hardwood dimension stock would increase in the future, but independent dimension manufacturers' share of the market may not. They expect increases mainly in within-plant production by furniture manufacturers. Over half the furniture manufacturers now produce more than half of their dimension requirements in their own plants; four furniture manufacturers planned within-plant increases for every one planning decreases.

Most manufacturers' decisions were based primarily upon cost factors, but other factors mentioned included: (1) inability to obtain timely delivery; (2) unavailability of hardwood parts of the desired species; and (3) lack of reliability of some suppliers of dimension parts.

An independent dimension manufacturer must aim to be reliable and timely, and to supply parts of acceptable quality, species, and moisture content at a lower cost than the buyer can make them in his own plant.

22-4 TOOL HANDLES

The tool handle industry, while not one of the larger segments of the hardwood trade (fig. 29-35B), is particularly important in the utilization of ash and hickory. White ash is favored for handles of lifting and pulling tools (and for baseball bats). Hickory and white ash are the premium woods for handles of other tools such as cant hooks, peavies, scythes, crosscut saws, and chisels—and for ladder rungs. For handles of striking tools such as axes and mauls, hickory is the favored wood.

WHITE ASH SELECTION FOR HANDLE STOCK

The text associated with figures 7-3 through 7-6 and 10-7 discusses selection of white ash for maximum toughness and strength. In brief, upland ash on well-drained hillside coves produces wood that is strong, stiff, and suitable for long, heavy handles for lifting tools. Creek-bottom trees and suppressed trees produce as heavy wood, but it is low in stiffness. White ash trees grow wood of uniformly high specific gravity when they grow rapidly in diameter throughout their life. Baker (1970) found that white ash sapwood does not vary from heartwood in mechanical properties if growth rates are equal; he also observed that ash loaded on the tangential face is tougher than that loaded on a radial face.

Pillow (1950) concluded that ash trees of adequate toughness and specific gravity for handle stock have relatively large, upward-tapering, generally well-shaped crowns without large dead branches. Vigorous trees producing desirable wood have tight bark with low ridges and shallow depressions, showing light-colored streaks of inner bark.

Non-destructive tests have not been particularly successful in selecting ash handles for lifting and pulling, but handle blanks with highest modulus of elasticity in static bending tend to have highest strength in such service.

HICKORY SELECTION FOR HANDLE STOCK

Hickory is the premium wood for handles of striking tools such as axes, hammers, hatchets, picks, mauls, and sledges because of its impact resistance, toughness, resilience, stiffness, and hardness. A high degree of hardness in handle stock makes possible accurate machining and smooth finishing and polishing during manufacture; during tool use, hard handles resist abrasion. Stiff handles resist flexure under stress and when flexed are resilient and return immediately to original form after relief. Hickory handles are tough and absorb impact forces that would break most other woods; when hickory handles do break, the failure is progressive fiber by fiber rather than sudden and abrupt as in brash woods. (See figs. 10-7 and 19-1 for illustration of fiber-by-fiber failures compared to brash failures.) Brash failures in hickory are almost always associated with tension wood.

There has been considerable controversy over the relative quality of red (heartwood) and white (sapwood) hickory. Specifications frequently call for all white wood, causing much good red hickory to be left in the woods or scrapped at the mill. Tests by the U.S. Department of Agriculture, Forest Service (1936) showed conclusively that weight-for-weight, red, white, and mixed red and white sound hickory all have the same strength, toughness, and resistance to shock.

Lehman (1958) explained the basis of discrimination against red hickory. He noted that red hickory is the heartwood and is in the inner part of the tree. On trees from virgin forests this wood may be 100 or more years old and was formed under forest conditions which produced slow growth. Slow growth in hickory produces low-density, lower-strength wood (fig. 7-7). As the virgin forests were cut, and when many of these hickory trees were released by partial cutting, the growth rate increased and the white sapwood in the outer portions was denser and stronger than their red heartwood.

Now that much of the virgin old-growth hickory has been cut and the hickory in managed forests is growing at a fairly rapid rate, the heartwood and sapwood should not differ appreciably in density, and red hickory is generally as strong as the white. True hickories, on the whole, shrink more, but tend to have greater shock resistance than the pecan hickories (Lehman 1958).

Paul (1947) observed that scrubby hickory trees from poor sites will not supply much defect-free, fast-grown wood for high-class handle stock; moreover, limby trees on poor sites produce cross-grain wood and display more bird peck and insect damage than more thrifty trees grown on sites better suited to hickory. He found that the bark of hickory trees offered clues to wood quality. On slowly growing trees, there are few of the light-colored streaks at the bottom of bark furrows which are evidence of rapid diameter growth. On shagbark hickory instead of light streaks between ridges, fast growing trees shed more bark than those which are stagnating.

No non-destructive test has been devised that accurately predicts impact resistance of hickory. Such parameters as static or dynamic modulus of elasticity, or velocity of sound in longitudinal transit, seem not strongly correlated with impact strength. Old-time craftsmen, however, found that stiff and resilient handle stock, when dropped endwise onto a concrete floor, produces a clear ringing sound. A dull thudding sound, or even a low-pitched tone, indicates it is likely low in stiffness and probably will not straighten readily after being bent under load (Heck 1949). Paul (1947) proposed that the best grades of striking tool handles should have less than 17 rings per inch *or* weigh at least 55 pounds per cubic foot at 12 percent moisture content. Crossgrain in handles, resulting from sawing at an angle to the grain, is the major cause of handle breakage.

REQUIREMENTS FOR HICKORY BOLTS

Grades for hickory bolts (fig. 22-11) representative of those used by midwestern and southern handle companies are given in table 22-7.

Figure 22-11.—Hickory bolts in yard of a handle factory. (Photo from Lehman 1958.)

TABLE 22-7—*Typical grades and specifications for hickory handle bolts* (Herrick 1958)

Statistics	Description
Species accepted	Shagbark, mockernut, and pignut; bitternut hickory not accepted
Minimum top diameter inside bark	7 or 8 inches; varies with company
Length	38, 40, or 42 inches; varies with company
Grade No. 1 (or A)	Strictly clear bolts with at least 3 inches (or 3½, or 4 inches depending upon the company) of white wood (sapwood) on the small end of the block
Grade No. 2 (or B)	Generally clear bolts with less than the depth of white wood required of Grade No. 1
Grade 3 (or C)	Red blocks with less than 2 inches of white wood, or reasonably clear blocks but permitting small defects such as slight pecks and streaks. Light weight may place bolts in this grade.

TYPES OF HANDLES

Striking tools.—Striking tool handles include those for axes, adzes, picks, mattocks, mauls, sledges, hammers, and hatchets; all are made almost exclusively of hickory. Blanks for striking tool handles are generally graded Extra, No. 1, No. 2, or No. 3. The Extra and No. 1 grades are the same for axe, pick, and sledge handle blanks, but the other grades vary some. Lehman (1958) listed the following specifications as typical for striking tool handles:

- Extra: Must be all white, heavy timber, free from all defects, perfect, full size, and straight grain.
- No. 1: Must be good weight timber, ⅓ red wood permitted the entire length of the blank. All white blanks of good weight not sufficiently heavy for extra grade. Two light hair streaks running full length, or their equivalent in shorter streaks permitted. Must be full size, straight grained and free from defects.
- No. 2: Must be fair weight timber permitting red, white, or mixed red and white wood (for axe handle blanks not more than 2/3 red permitted). Light streaks permitted. All white blanks can have not more than three small pin knots not to exceed ⅛-inch in diameter. Reasonably straight grain required.
- No. 3: Includes blanks that will produce serviceable handles but are not admissable to the higher grades because of defects.
- Reject: Blanks containing open knots greater than ⅜-inch in diameter, worm holes or windshake, or ones that are brashy and not admissable to any grade.

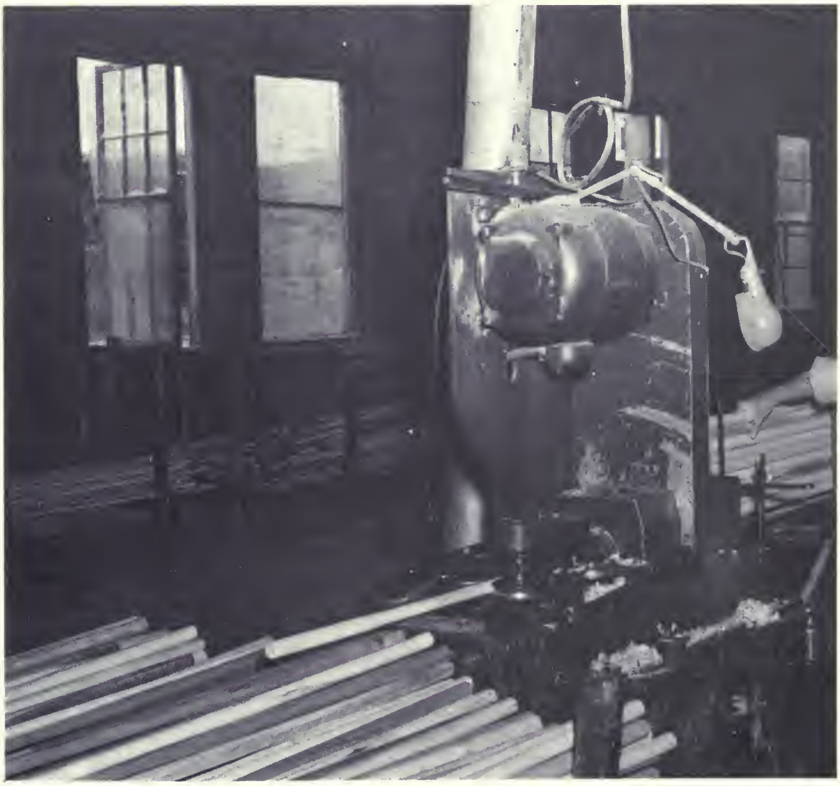

Figure 22-12.—Sanding hickory tool handles. (Photo from Tennessee Valley Authority.)

The size of handle blanks varies according to the tool for which the handle is designed. Thicknesses are generally at least 1-¾ inch at the head end, with widths up to 3-½ inches and lengths to 40 inches (table 22-8).

Most companies use standard grade specifications for striking-tool handles. Table 22-9 describes six handle grades taken from standard practice recommendation No. R77-45, U.S. Department of Commerce (1945). Note that the grading of handles is based on visual inspection of each handle and on the judgement of the grader. It is not expected that the grader will determine the weight per cubic foot or number of rings per inch for each handle. In case of question, however, one or both of these characters may be measured for conformance with the requirements given in the table for each grade (Lehman 1958).

TABLE 22-8—*Length, width, and thickness of hickory handle blanks commonly used in the manufacture of axe, pick, hatchet, sledge, and hammer handles* (Lehman 1958)

Tool	Length	Cross section	
		Head end	Eye end
	Inches	*Inches*	
Axe	33-36 and 40	3½ x 2⅛	3½ x 1⅛
Axe	29-32	3⅛ x 2	3⅛ x 1
RR pick	40	2 x 1¾	3½ x 2½
Coal pick	40	2 x 1¾	3½ x 1¾
Hatchet	19-28	2⅞ x 1¾	2⅞ x 1
Sledge	29-32, 33-36 and 40	1⅝ x 1¾	1⅝ x 1¾
Hammer	15-28	1⅝ x 1¾	1⅝ x 1¾

Lifting and pulling tools.—Lifting and pulling tools include hoes, rakes, forks, spades, and shovels. Toughness is a main requirement, but handles for these tools do not have to meet the rigid requirements for striking tools. While ash is preferred for such handles, hickory is also used.

Other tools.—Handles for cant hooks, peavies, scythes, crosscut saws, and chisels should be tough and stiff. Cant hooks and peavies, in particular, are subjected to sudden stresses. Specifications for these handles are not, however, as rigid as for striking tool handles. The top-grade cant hook and peavy handles are red or red and white wood of medium weight (46 to 55 pounds per cubic foot). They can have up to 27 rings per inch; some blemishes and defects are allowed. Grades BW, or in some cases AR, are top grades for these handles (Lehman 1958).

MANUFACTURE

Sawing.—Hickory and ash bolts are usually sawn into handle blanks on a bolter saw (fig. 18-123). One method commonly used by handle sawyers calls for first halving and then quartering the bolt. Tapered long blanks for axe handles may then be sawn. Smaller pieces are salvaged for sledge and hammer handle blanks.

Longer bolts for industrial products such as textile picker sticks, pitman rods, and handles for garden tools or brooms may be sawn on short-carriage headrigs equipped with a 54-inch circular saw.

Drying.—Air-drying of handle stock is described in text related to figure 20-6. Kiln-drying schedules for ash squares are shown in table 20-25. Special kiln schedules to avoid pinking in hickory handle stock are shown in tables 20-23 and 20-24.

Machining, bending, and finishing.—Rough shaping is usually accomplished with a circular saw. Irregularly shaped handles, such as those for a single-bit axe are turned on a copying lathe (fig. 18-188). Cylindrical handles can be produced on a dowel machine (fig. 18-189AB). Handles for certain lifting and pulling tools, e.g., shovel handles, may be soaked in hot water and formed by bending (fig. 19-13). After trimming to length with circular saws, handles are smoothed with coarse abrasive belts, polished with finer abrasives (fig. 22-12), and waxed or lacquered. Painting is usually limited to low-grade cheap handles. As one of the final operations, handles are usually labelled or stamped with the name of the manufacturer and the trade name.

YIELDS

Hickory handle bolts are commonly bought and sold on the basis of estimated handle yield for various diameters. Based on data collected by the Purdue University Agricultual Experiment Station, handle yield from 40-inch hickory bolts is approximately as follows (Herrick 1958; Lehman 1958).

Top diameter of bolt inside bark	Handle yield
Inches	*Number*
7	3
8	4
10	7-8
12	10-12
14	14-16
16	18-19
18	20-22
20	28
22	34
24	40

22-5 FURNITURE AND FIXTURES

The furniture industry is the largest user of hardwood lumber in the United States (fig. 29-26 and 29-27). Veneer, plywood, particleboard, and hardboard are also used in large quantities to make furniture and fixtures (table 22-10 and fig. 29-36A).

Spelter et al. (1978) found that in 1972 the furniture and fixtures industry consisted of over 9,000 establishments employing 462,000 workers, and used

TABLE 22-9—*Grades for hickory handles* (Smith 1952; Lehman 1958)

Grade symbol[1]	Color of wood	Number of annual rings/inch of radius	Weight[2]	Admissable blemishes[3]	Admissable defects[4]
			Lb/cu ft		
AAW	All white	Not more than 17	Over 55 (heavy)	None	None
AW	All white	Not more than 22	Over 46 to 55 (medium)	Not exceeding 2 small streaks or their equivalent in shorter streaks	None
AR	Red or red-and-white	Not more than 22	Over 46 to 55 (medium)	Medim streaks	None
BW	White except for red extending from the eye end not more than 2 inches beyond the shoulder, or 3 inches from the grip end, or both.	Not more than 27	Over 46 to 55 (medium)	Not exceeding 4 medium streaks or their equivalent in shorter streaks. Light stain.	One or 2 bird pecks, or tight, sound knots the sum of whose average diameter does not exceed ¼ inch in the eye end or first third of the grasp end. Slight dip grain.
BR	Red or red-and-white	Not more than 27	Over 46 to 55 (medium)	Medium streaks Light stain	One or 2 bird pecks, or tight sound knots the sum of whose average diameter does not exceed ¼ inch. Slight dip grain.

TABLE 22-9—*Grades for hickory handles* (Sith 1952; Lehman 1958)—Continued

Grade symbol[1]	Color of wood	Number of annual rings/inch of radius	Weight[2]	Admissable blemishes[3]	Admissable defects[4]
C.	Red or red-and-white	No requirement	38 to 46 (fair)	No requirement	Any or all those listed on footnote 4, provided none of them seriously impairs the serviceability of the handle.

[1]Grade marking: If handles are grade marked it is recommended that the grade symbol be impressed in the wood.

[2]These weights are based on a moisture content not exceeding 12 percent.

[3]Blemishes include: Small streaks, threadlike discoloration extending not more than 1/3 the length of the handle; medium streaks, discoloration extending more than 1/3 the length of the handle, but not over 1/32-inch in width; mismanufacture which does not impair the serviceability; and light stain, slight difference in color which will not seriously impair the appearance of the handle.

[4]Defects include: Knots, bird pecks, splits, holes, decay, stain, cross grain—deviation of the fibre out of parallel with the axis of the handle in excess of 1 in 20; abrupt dip grain—deviation of the fibre out of parallel with the axis of the handle in excess of 1/8 the minimum diameter of the handle at the point where the dip grain occurs; slight dip grain—deviation of the fibre out of parallel with the axis of the handle not in excess of 1/8 of the minimum diameter of the handle at the point where the dip grain occurs; heavy stain—discoloration of the wood occurring in specks, spots, streaks or patches of varying intensities of color (generally bluish black); and large streaks—discoloration more than 1/32 inch in width.

2.6 billion board feet of hardwood lumber. In 1977 this industry shipped $16.97 billion worth of goods (table 22-11). Broken into five classes, household furniture accounted for two-thirds of the total value of shipments. Next was the partitions and fixtures sector (15 percent of shipments for (1977), followed by office furniture (13 percent), miscellaneous furniture (8 percent), and public buildings and related furniture (5 percent). The industry is highly regionalized with 46 percent of the work force located in the South, 24 percent in the Midwest, 18 percent in the Northeast, and 12 percent in the West.

The industry is vulnerable to business cycles. It suffered deep recessions in 1974-1975 and in 1980. In general, however, furniture production is expected to be at high levels during the last decade of the 20th century and early decades of the 21st century.

TABLE 22-10—*Use of seven wood commodities in the furniture and fixtures industry during the years 1960, 1965, 1967, 1972, and 1977*[1] (Spelter et al. 1978)

Commodity	1960	1965	1967	1972	Estimated 1977
	Billion feet				
Hardwood lumber[2]	1.59	1.98	2.26	2.59	2.59
Softwood lumber[2]	.37	.61	.49	.73	.67
Hardwood plywood[3]	.33	.44	.62	1.09	1.05
Softwood plywood[3]	.38	.26	.31	.59	.63
Particleboard[4]	.09	.33	.38	1.27	1.16
Hardboard[5]	.33	.51	.44	.96	.88
Hardwood veneer[6]	.80	1.22	1.31	1.39	1.30

[1]Data include those for kitchen cabinets.
[2]Billion board feet.
[3]Billion square feet (⅜-inch).
[4]Billion square feet (¾-inch).
[5]Billion square feet (⅛-inch).
[6]Billion square feet (surface measurement).

TABLE 22-11—*Value of 1977 shipments of the furniture industry, by sector*

Sector and sub-sector (with Standard Industrial classification numbers used in Census of Manufacturers)	Value of shipments
	Million dollars
251 Household furniture	
2511 Wood household furniture	4,140.3
2512 Upholstered household furniture	2,931.0
2514 Metal household furniture	1,307.1
2515 Mattresses and bedsprings	1,398.5
2517 Radio and TV cabinets	304.8
2519 Household furniture not elsewhere classified	301.9
Sub-total	10,383.6
252 Office furniture	
2521 Wood office furniture	612.0
2522 Metal office furniture	1,397.4
Sub-total	2,009.4
253 Public building furniture	787.4
254 Partitions and fixtures	
2541 Wood partitions and fixtures	1,105.8
2542 Metal partitions and fixtures	1,303.0
Sub-total	2,408.8
259 Miscellaneous furniture and fixtures	
2591 Draperies, blinds, and shades	675.1
2599 Furniture and fixtures not elsewhere classified	705.2
Sub-total	1,380.3
Grand total for SIC number 25 (Furniture and fixtures)	16,969.5

KITCHEN CABINETS

Kitchen cabinets represent an important segment of the furniture and fixture market. Lindell and Klippel (1972) estimated that in 1969 sales of kitchen cabinets totalled $1.4 billion and involved some 3.9 million kitchens, of which only 1.5 million were in new houses. About 71 percent of these cabinets were wood and built in factories, and another 16 percent were factory built of plastic or steel. Mobile-home manufacturers produced about 10 percent; only 3 percent were built on site. Most kitchen cabinet manufacturing plants serve a local market; of the larger firms that market regionally or nationally, many are located in states adjoining the Great Lakes (fig. 22-13).

Use of plastics, hardboard, and particleboard have steadily increased. Plastics in 1963 accounted for less than 1.7 percent of total expenditures for materials, but in 1970 for 6.6 percent (fig. 22-14). The use of particleboard core stock for plastic overlays increased from 0.6 percent in 1963 to 4.5 percent in 1970, while hardboard purchases increased from 2.2 percent to 3.7 percent. During this

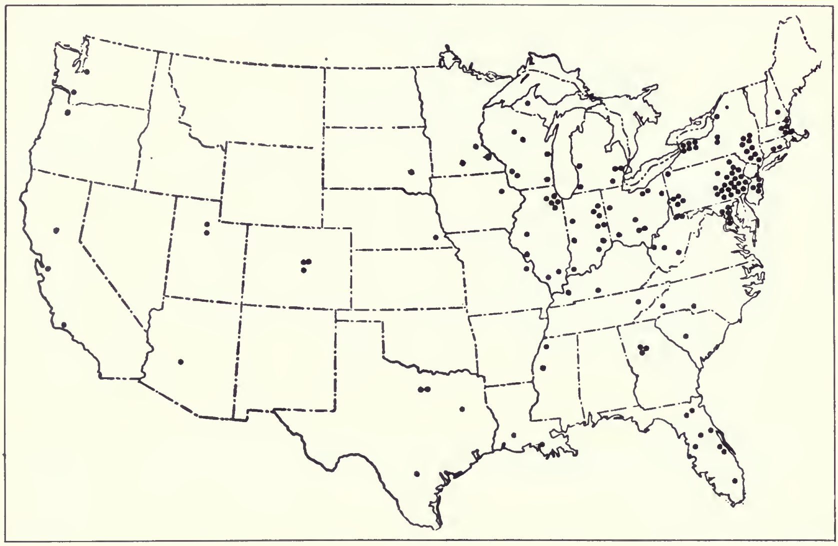

Figure 22-13.—Location of principal kitchen cabinet manufacturers in the United States. (Drawing after Lindell and Klippel 1972.)

period, purchases of hardwood lumber and plywood decreased from 53 to 43 percent of total raw material cost (fig. 22-14).

Purchases of cabinet doors and door skins were about 17 percent of total purchases in 1970. (A door skin is the outer visible sheet of material on a panel door.) Hardwood plywood doors were dominant, accounting for nearly two-thirds (by value) of all cabinet door purchases. Plastic and plastic-overlaid doors made up another fourth; the rest were of softwood plywood and miscellaneous materials. About 42 percent of the purchased hardwood plywood doors were birch, and nearly 30 percent were oak. Maple, cherry, walnut, and other hardwoods made up the remainder.

FURNITURE PLANT LOCATION

As noted previously, 46 percent of the workforce in the furniture industry is in the South. From a poll of furniture manufacturing firms in Virginia and North Carolina, Brock and Hilliard (1977) found that the primary consideration in locating new plants was availability of skilled and unskilled labor. Other important requirements included transportation facilities, accessibility to regional markets, and availability of raw materials. Many furniture plants, particularly small ones in West Virginia, were located in a particular place because that place was the owner's home.

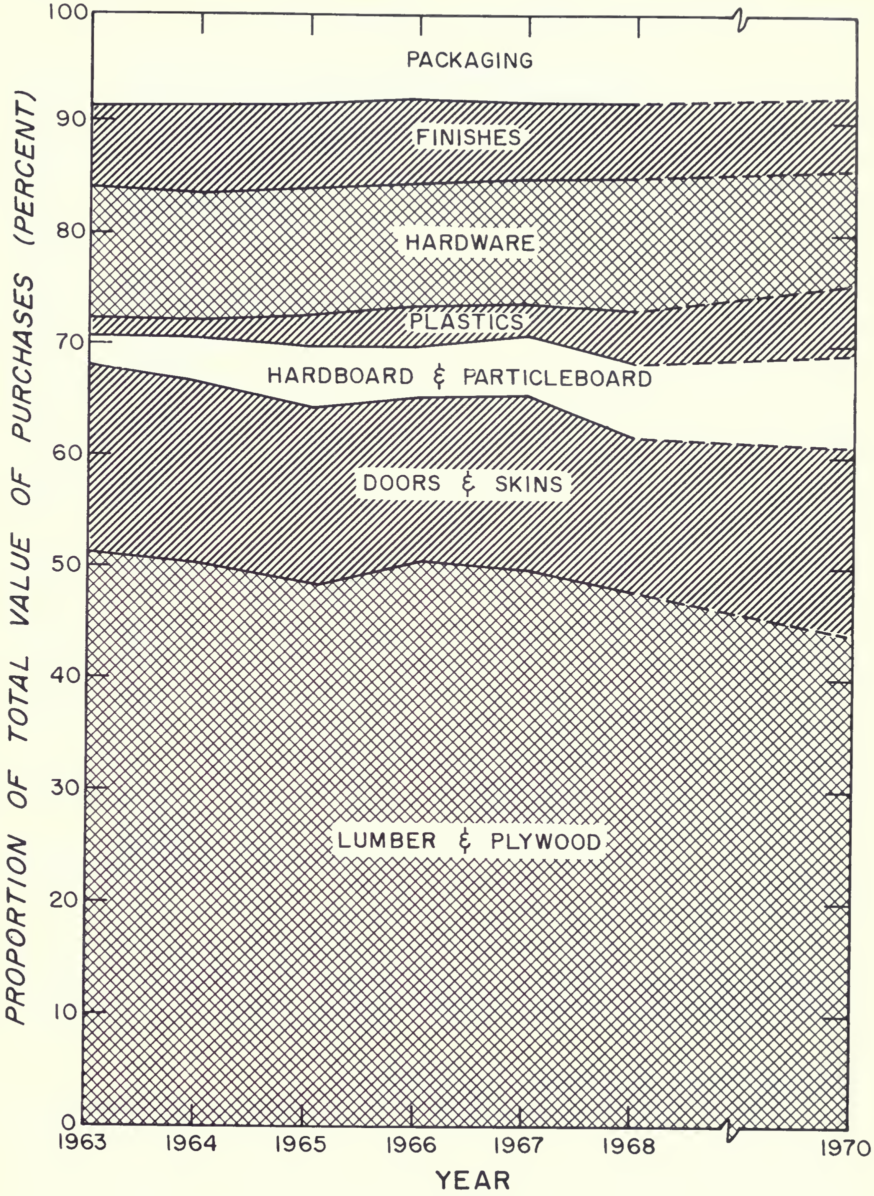

Figure 22-14.—Distribution of dollar value of raw material purchases by members of the National Kitchen Cabinet Association during the years 1963-1970. Data for the year 1969 are not available. (Drawing after Lindell and Klippel 1972.)

WOOD SPECIES FAVORED FOR FURNITURE

Blomgren (1965) concluded that wood has a depth of psychological meaning to people that other materials do not possess. Subconsciously, people feel that wood represents the natural process of life and growth. The tree is a symbol of life; its grows in the earth—and light, air, and water are vital to its growth. Wood suggests strength and security. It is sensuous and intriguing; even the smell of wood is sensuous and suggestive of romantic and idyllic imagery. Wood suggests productive human activity—a man building something, a boat sailing, or a tree growing. Wood is distinctive and evokes memories. It is seen as natural, solid, and reliable.

In Blomgren's survey of people's image of wood, he found that men and women have different images of some wood species. Oaks emerged as the wood with the most specific personality. Men and women both viewed oak as masculine wood and agreed that it is durable, strong, practical, and associated with security. Most men see oak as old fashioned, but only half the women interviewed viewed it this way.

Much of the furniture industry of the United States is concentrated in North Carolina, and species preferences of the North Carolina furniture plants are perhaps representative of most southern plants. Applefield (1971) determined percentages of total lumber volume purchased by North Carolina plants according to species and year of purchase (fig. 22-15). He found that in 1953 yellow-poplar purchases were greatest, with gums (sweetgum and black tupelo) second, oaks third, and maples fourth. By 1968, oaks were first, slightly ahead of yellow poplar, and the maples were in third place. A decade later oak furniture dominated the market (Anonymous 1976a), the popularity of oak continues.

Figures 29-16A through 29-16H show long-term trends in hardwood lumber manufacture by species. Not all of this lumber went into furniture, but the furniture industry is the largest user.

Luppold* found that demand by furniture manufacturers for particular species is price responsive, with demand for open-grain species being more price responsive than the demand for close-grain species.

FIBERBOARDS AND PARTICLEBOARDS

Multi-layer particleboards with fine particles on the faces have become strong competitors of lumber in furniture and fixtures. Medium density fiberboard—because it can be edge-machined, filled, finished, and printed—is capturing a steadily increasing share of the furniture market at the expense of lumber and plywood. The technology of manufacturing medium-density fiberboard, and a description of its properties, are discussed in chapter 23. Particleboards are discussed in chapter 24. Because of increasing costs of high-quality lumber of premium furniture species, it is likely that use of particleboards and fiberboards in furniture will continue to increase.

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* Luppold, William G. The effect of changes in lumber and furniture prices on wood furniture manufacturers' lumber usage. Res. Pap. NE-514. Broomall, PA: U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station; 1983. 8 p.

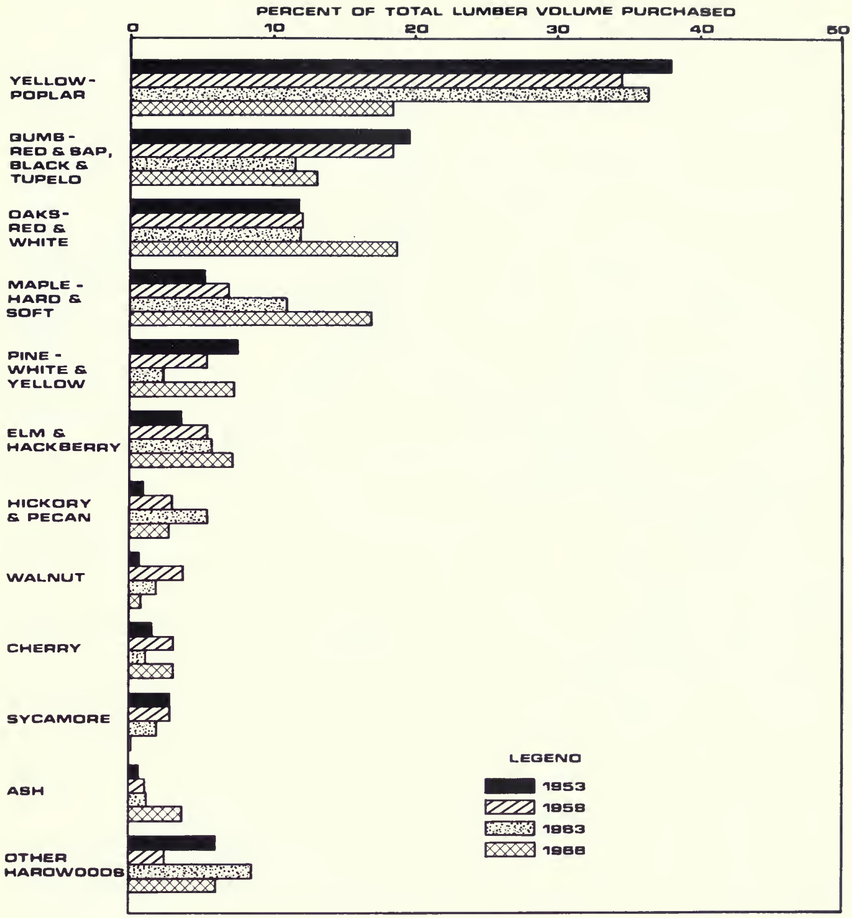

Figure 22-15.—Percent of total volume for domestic species purchased by furniture plants in North Carolina during 1953, 1958, 1963, and 1968. (Drawing after Applefield 1971.)

FURNITURE FRAMESTOCK OF PARALLEL-LAMINATED VENEER

Particleboards and fiberboards have become major competitors of lumber cores and plywood for the flat surfaces of furniture and fixtures. Structural frames for upholstered furniture (fig. 22-16 top), however, require the strength generally found only in lumber. Upholstered-furniture frames are generally produced from No. 2 Common or frame-grade mixed hardwood lumber. Although oak is preferred by many manufacturers because of its greater strength, weaker species such as yellow-poplar are also commonly used. Appearance is not a factor since the frame is hidden by upholstery. Defects included, however, must not reduce structural adequacy.

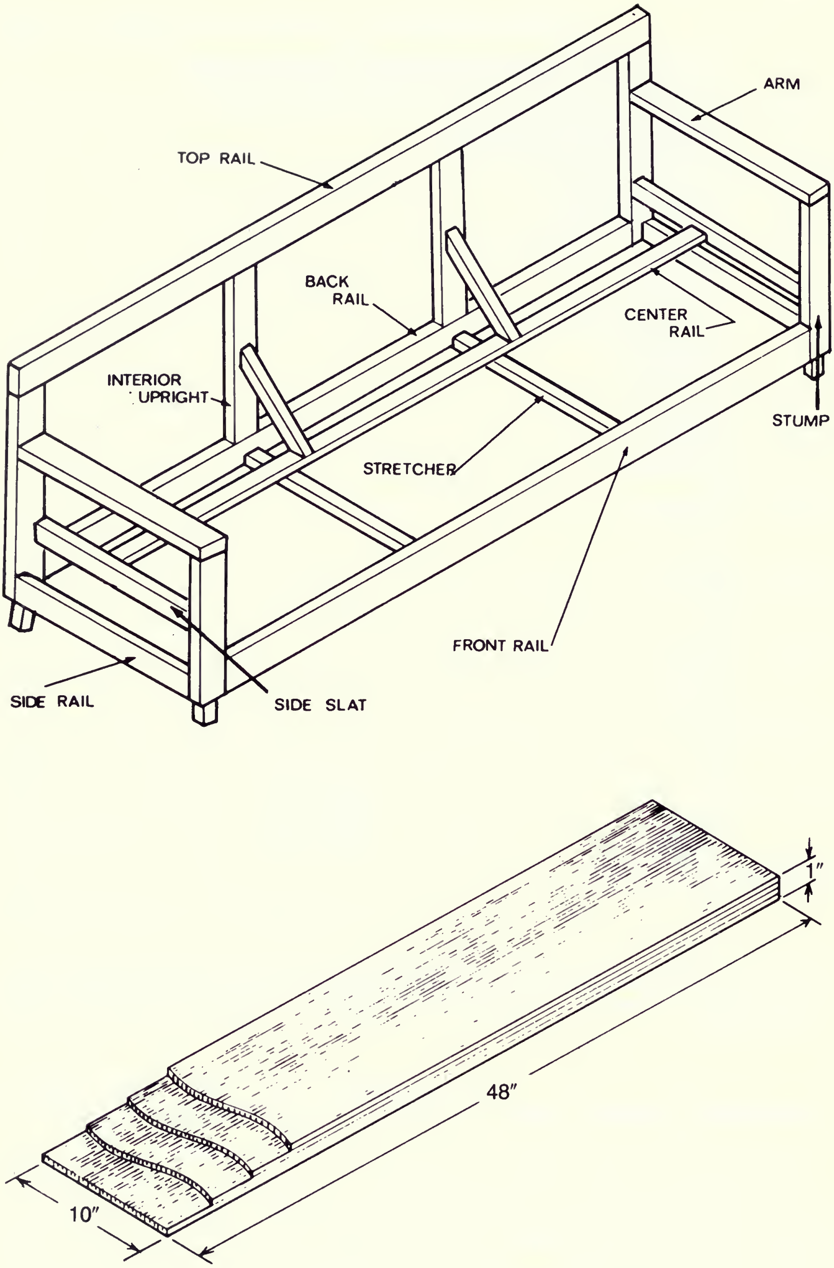

Figure 22-16.—(Top) Wood structural frame for an upholstered sofa. (Bottom) Laminar construction of lumber made from parallel-laminated veneer. (Drawing after Hoover et al. 1978.)

Hoover et al. (1978) found that in the United States there are about 1,308 manufacturers of upholstered household furniture who consume nearly 300 million board feet of lumber annually for frame stock. A frame-stock mill located in northeastern Georgia would be within 350 miles of about 50 percent of the nation's manufacturers of upholstered furniture (fig. 22-17).

Section 18-12 describes the technology of ripping and cross-cutting lumber to yield furniture parts such as those shown in figure 22-16 (top). To more completely use plentiful low-quality oak logs for furniture frames, the U.S. Forest Products Laboratory proposed using thick veneer parallel-laminated into lumber. To accomplish this, they rotary-peeled northern red oak veneer 0.29 inch thick, and press-dried it (fig. 20-32) at 375°F. Subsequently the sheets were reheated at 320°F for 3½ minutes, and passed through a glue spreader which applied phenol-resorcinol adhesive, 60-65 percent solids extended 10 percent with water, at the rate of 60 pounds per thousand square feet. The sheets were then laid up into blanks or boards and cold-pressed until cured. All of the boards were of 4-ply construction with the loose faces of the veneer turned toward the center of the board (fig. 22-16 bottom).

Eckelman et al. (1979) found that this parallel-laminated northern red oak veneer, termed Pres-Lam, splintered slightly more than solid northern red oak when machined, but tests indicated there should be no serious problems in cutting parts from the laminated material. The laminated veneer was not as strong as solid red oak, but because of reduced variability, design stresses for the laminate would likely be nearly as high as those for yellow-poplar. (See Eckelman 1978b for a discussion of the strength of solid wood parts in furniture frames.) Shear strength, about 53 percent of northern red oak, would be adequate for most frame designs. Screw- and dowel-holding strength of the parallel-laminated veneer, less than that of northern red oak, was about the same as that of yellow-poplar. With metal-toothed connector plates, structural-quality joints may be formed in the laminated wood. In general, no problems were encountered that would prevent the laminated wood from being used as frame stock.

Studies indicate that manufacture of parallel-laminated oak veneer for frame stock should be economically feasible. (See section 28-16 and also Hoover et al. 1978 and 1979.)

22-6 TOYS[5]

The world retail market for all types of toys was \$7 to \$8 billion in 1975; wooden toys accounted for about \$250 million for about 3 percent of the total, but this share has been growing rapidly. The prinicpal markets for toys in 1974 were the United States, the Federal Republic of Germany, the United Kingdom, and France, in that order. These countries also appear to be the largest importers of toys.

[5]Text under this section is condensed from International Trade Centre, UNCTAD/GATT (1976).

Figure 22-17.—Estimated markets for framestock for upholstered furniture, 1972 basis. Values below state names indicate volumes in million board feet of lumber used. Shading indicates major market areas. The circle encompasses about 50 percent of the market. (Drawing after Hoover et al. 1978.)

Domestic production of all toys (U.S. Standard Industrial Classification numbers 3942 and 3944) in the United States for the years 1971-1976 with projection to 1985 is as follows (based on value of 1971 dollars):

Year	Value at shipment	Index
	Millions of dollars	
1971	1,594	100
1972	1,779	112
1973	1,956	123
1974	2,090	131
1975	2,390	150
1976	2,570	161
1985	4,670	293

Expert sources indicate that the United States is the world's leading producer of wooden toys, with production estimated at 2 percent of total toy production, i.e., about $50 million (shipment value) in 1975. Hardwood lumber consumed annually in the United States for the manufacture of toys and games was about 30 million board feet and is increasing (fig. 29-33).

Toy sales at the retail level are not evenly distributed geographically across the United States; more than half of total toy sales are made east of the Mississippi River, as follows:

Region	Percentage of retail toy sales
East north central	20.9
Middle Atlantic	17.3
South Atlantic	15.4
Pacific	14.0
West South Central	9.0
West North Central	8.2
New England	5.6
East South Central	5.5
Mountain	4.1
	100.0

TRADE CHANNELS

The distribution system for toys in the United States emphasizes direct dealing between manufacturers and retailers with minimum use of middlemen. Approximately 52 percent of U.S. manufacturers' sales are made directly to the retailer. Retailers requiring small quantities frequently buy through middlemen. Distribution channels are about as follows:

Route and outlet	Proportion of market
	Percent
Manufacturer to retailer (usually)	
Discount stores	33.3
Variety stores	14.7
Mail order houses	11.1
Department stores	10.1
Manufacturer to wholesale jobber to retailer (usually)	
Specialized toy stores	7.9
Grocery markets and supermarkets	5.0
Others	17.9
	100.0

The principal retail outlets for wooden toys are department stores or toy stores that cater to higher income groups. Other stores, such as variety stores, supermarkets, and specialty shops may carry small quantities of lower-priced wooden toys for pre-school children.

DEMAND STRUCTURE

Over 90 percent of total world production of wooden toys are destined for children of pre-school age (fig. 22-18 top). The balance consists of puzzles, toys that have more decorative than play value (fig. 22-18 bottom), and games or game pieces that are bought primarily for or by older children and adults.

Retailers estimate that over 95 percent of the wooden toys for pre-school children are purchased by women either unaccompanied by the child for whom the toy is bought or who are otherwise not influenced by the child's choice. Wooden toys are little advertised and television coverage of them is minimal;

Figure 22-18.—Wooden toys. (Top) Representative of those for children of pre-school age. (Bottom) Representative of those that have more decorative than play value.

with a couple of notable exceptions, brand names appear to be relatively unimportant. Wooden toys are made known mainly through magazines directed to parents, principally mothers. Those most likely to purchase wooden toys have higher incomes and education levels, but smaller families; urban families are more apt to purchase wooden toys than those from rural areas.

More than 50 percent of all retail sales of toys take place in the two months before Christmas. Remaining sales are spread fairly uniformly throughout the year and are frequently associated with birthdays of the recipients.

COMMON TYPES OF TOYS

The most common wooden toys are blocks and other geometric shapes, hammer and peg sets, wooden push-and-pull devices, wooden vechicles such as trucks and trains, miniature people made of wood, dolls' houses and furnishings, farmyard and Noah's ark sets, toy boats, puzzles, and construction sets.

Wood species.—Wood for toys should be of medium density. Very hard woods are more likely to hurt a child than softer woods; very soft woods, however, may be chewed and ingested by a small child. The wood selected should resist splintering. Color tone should be uniform. Generally, light-colored woods are preferred, although darker woods may be used for parts and for decorative toys. Woods of more than one color should be used consistently; i.e., the four wheels of a wooden toy car should match, even if the body of the car is another color.

Finish.—All burrs must be removed from wooden toys. Designs that require nails and screws should be avoided, unless the fasteners are rust proof and attractive. If glue is used, all traces of it must be removed from surfaces. Wooden toys should be finished with a non-toxic oil or wax to yield a natural matte surface. Occasionally, parts of a wooden toy may be painted a bright color attractive to children.

SPECIFICATIONS AND SAFETY

Toys are subject to stringent health and safety regulations, contained in the Federal Hazardous Substance Act of 1964 and the Consumer Product Safety Act of 1973. Under the latter act, the Consumer Product Safety Commission became responsible for enforcing the regulations contained in the Federal Hazardous Substances Act of 1964.

Common sense suggests that wooden toys should display no cracks or insect holes, and that bark should be used only for decorative purposes. Surfaces should be smooth and free of burrs, and pointed ends of fasteners should not be accessible. Toys, and detachable parts of toys should be large enough to prevent ingestion. Cords of pull toys should not include slip knots. Toys designed to bear the weight of a child should be designed so as not to break or tip over. Paints, varnishes, and lacquers used must be non-toxic.

22-7 PALLETS

Strobel and Wallin (1969) observed in their study of the food industry that not many years ago finished goods were handled in case units, moved with two-wheel hand trucks and "stair-stepped" to ceiling heights of 10 to 14 feet. Orders were selected onto four-wheel flat trucks or two-wheel hand carts, moved to the shipping area, loaded case by case into the carrier's equipment, and secured for transit with lumber dunnage. At intermediate warehouses, the goods were again handled case by case—loading, unloading, storing, selecting, and shipping to the retail outlet. Whether the order was for a few or a few thousand cases, the handling system was the same.

Forklift trucks and haul jacks, together with wooden skids, bases, and pallets, have mechanized handling to move and store multiple cases of product as a single unit. The unit-load concept originated within the warehouse. After World War II, traffic men realized that extension of unit-load handling throughout the shipping and receiving cycles could reduce distribution costs substantially. In the late 1940's the building-materials industry, oil refineries, the chemical industry, breweries, meat packers, and steel fabricators began shipping their products on expendable wooden skids or pallets; reusable pallets were commonly used only within the plant.

Skids preceded pallets in development and general use (Bond and Sendak 1970). A **skid** (fig. 22-19) is differentiated from a pallet primarily by its lack of bottom boards. Skids for shipping purposes take many forms; design procedures are given in Anderson and Heebink (1964, p. 68-73). **Pallets** have bottom boards, the deck may or may not be solid, the stringers are less deep than runners on most skids, and they are generally two to five in number (fig. 22-20 top). Some pallet designs do not employ stringers but rather have blocks separating the deck and bottom boards (fig. 22-20 bottom).

Schuler and Wallin (1979) found that the pallet industry in the United States is composed of approximately 1,300 pallet manufacturing firms; about 50 percent employ less than 10 persons and fewer than 5 percent employ more than 50 (U.S. Bureau of the Census 1954-1977). Additionally, there are numerous

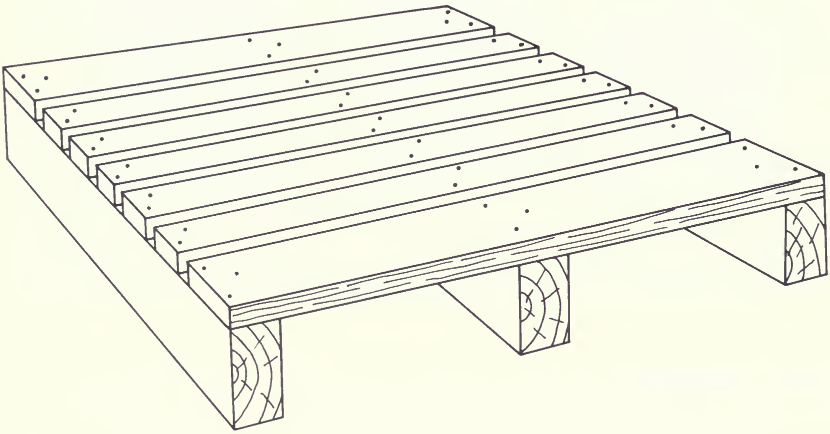

Figure 22-19.—Skid or Type I pallet is single-faced, non-reversible, and customarily made only in two-way design (i.e., forklifts approach parallel to stringers). Typically such skids are used for bricks, concrete, cinder blocks, and heavy materials in wooden boxes or crates.

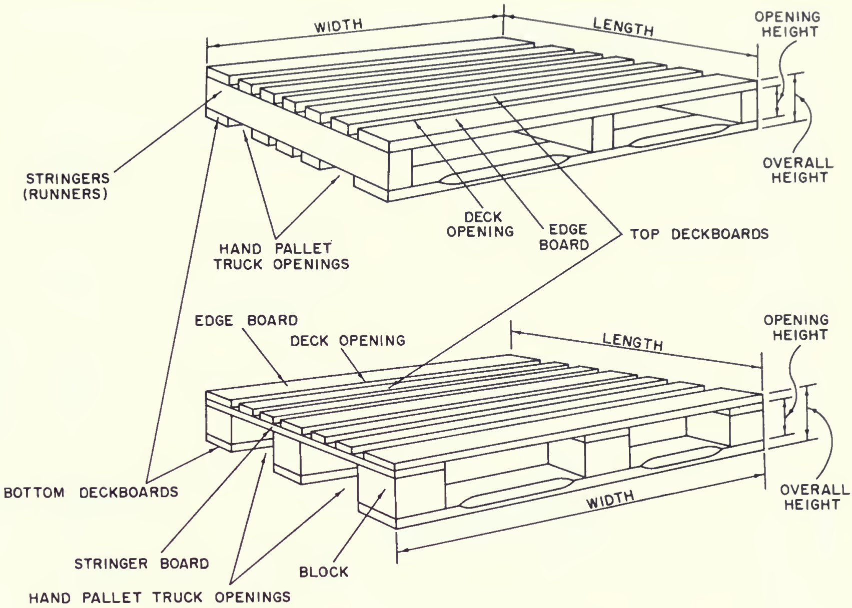

Figure 22-20.—Nomenclature of pallet parts. When designating pallet size, length should be given before width. (Top) Stringer design, partial four-way entry. (Bottom) Block design, full four-way entry.

small-scale producers who make pallets occasionally to fill local needs. The industry is a significant consumer of sawed wood products, using nearly 40 percent of the United States hardwood production and about 5 percent of sawn softwood products; typically, of all wood used, about 70 percent is hardwood and 30 percent softwood (Martens[6]).

E. George Stern, Professor Emeritus, Virginia Polytechnic Institute and State University, estimated United States pallet production in 1979 at 296 million units selling for $2.38 billion, using 18 percent of the lumber produced in this country, and requiring more than 200 million pounds of nails and staples for their assembly.

Pallet production increased from 43.2 million pallets in 1953 at an annual compound rate of about 8 percent to 1979, for a total increase of 685 percent to about 300 million. While about 20 percent of the total movement of domestic products could be handled by pallets, only 5 percent was actually palletized in 1977.[7] Because of competition for raw materials from which to construct increasing numbers of pallets, however, growth of the industry during the 1980's and 1990's is expected to slow to less than 3 percent annually; annual pallet

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[6]Martens, D. G. 1977. Pallets and ties—status, supply, historical and projected demand, alternatives. 8 p. Paper presented at Utilizing the hardwood resource, Oct. 3-4, Madison, Wis.

[7]Wallin, W. G. 1977. Characteristics of the U.S. pallet industry. Unpubl. rep. on file at For. Sci. Lab., Princeton, W. Va. 78 p.

production in the United States is, therefore, not expected to exceed 500 million units by the end of the 20th Century (see figs. 22-21 and 29-18AB).

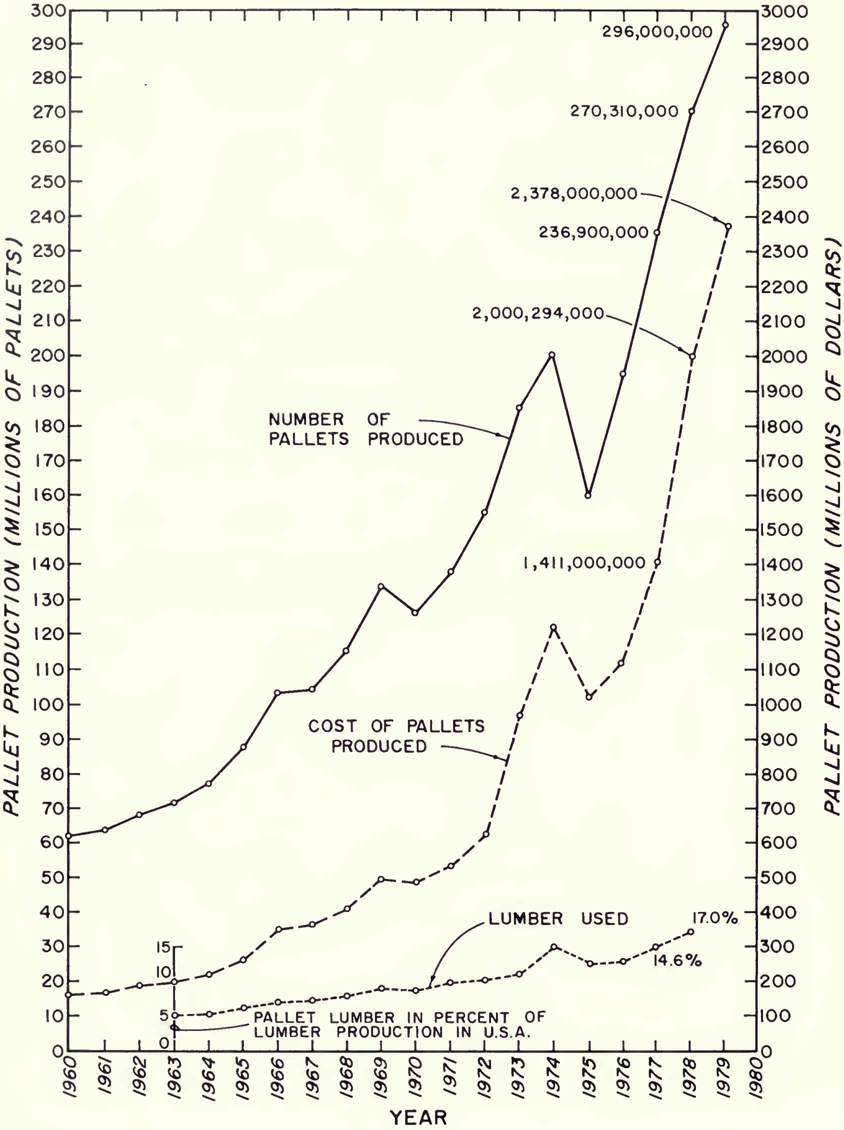


Figure 22-21A.—National annual pallet production in numbers, dollar value, and as a percentage of national lumber production. (Drawing after E. G. Stern 1978, updated from data of the National Wooden Pallet and Container Association.)

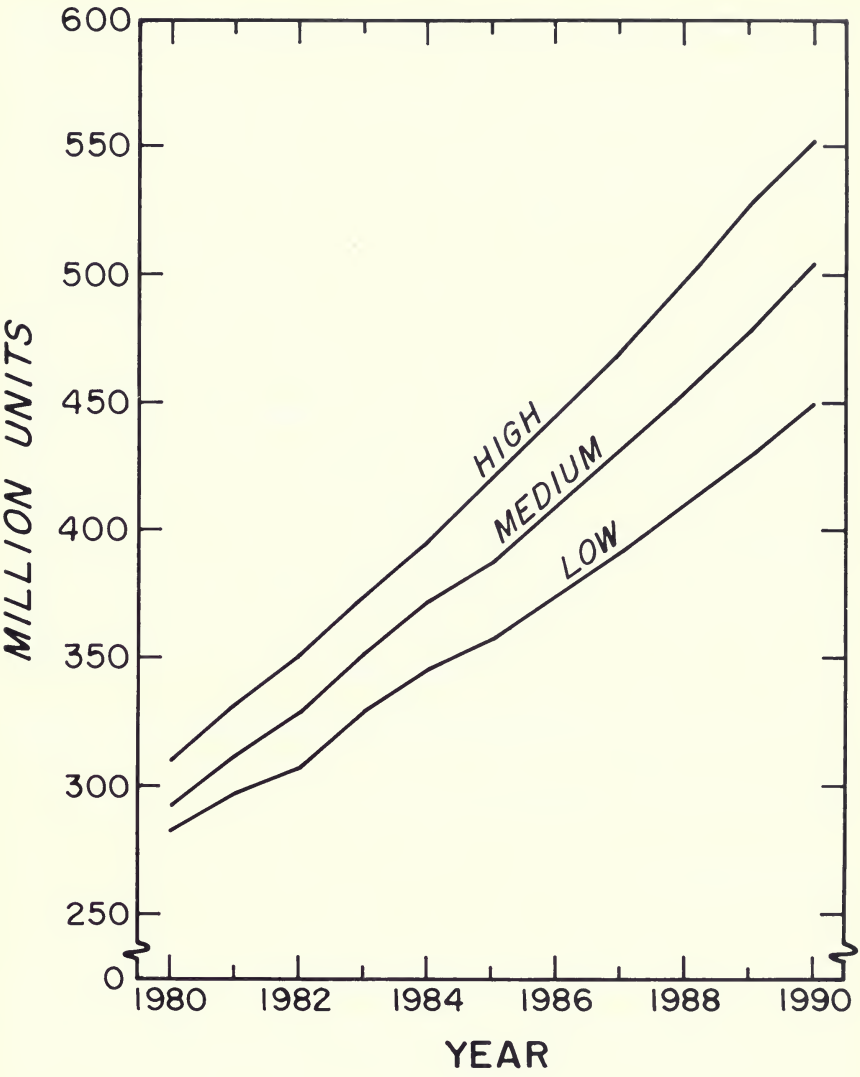


Figure 22-21B.—Low, medium, and high projections of annual pallet consumption in the United States for the years 1980-1990. (Drawing after Schuler and Wallin 1979.)

Competition for wood is expected to further slow growth of the industry beyond 2000. Thus, by year 2030, projected use of lumber in shipping, including pallets, containers, and dunnage, is expected to rise to 15.2 billion board feet—about 2.2 times consumption in 1976, i.e., at an average rate of 1.5 percent annually over this 54-year period. Veneer and plywood use in shipping is projected to increase about 2.4 times to 1.8 billion square feet (3/8-inch basis), and hardboard 2.7 times to 180 million square feet (1/8-inch basis) in the same time period. Nearly all of the increase for these products will come from the growth in pallet demand. By 2030, pallets will account for about 88 percent of the lumber, 85 percent of the veneer and plywood, and 67 percent of the hardboard used in shipping (U.S. Department of Agriculture, Forest Service 1980).

Readers interested in analyses of pallet markets in particular industries will find the following publications useful:

Industry	Reference
Food	Strobel and Wallin (1969)
Steel	Carlson (1966)
Brewing	Lucas (1969)
Defense	Lucas and Wallin (1969)

Of the pallets produced annually in the United States, about 65 percent are classed as reusable (permanent warehouse or exchange type), while 35 percent are expendable, for one-way use. About 98 percent of the reusable pallets are made of wood. Of the expendable shipping pallets, about 80 percent are sawn wood or plywood; the remaining 20 percent are of fiberboard, plastics, or combinations of these materials (Stern 1977c).

From a study in the Maryland-Pennsylvania-West Virginia area, Mount (1971) found that over 53 percent of the pallets sold were shipped further than 200 miles. About 70 percent were sold by the owner-operator or a company salesman; 14 percent were sold through brokers, 9 percent by competitive bidding, and 7 percent through advertising.

Readers interested in mathematical models of economic trends in the industry will find useful Schuler and Wallin's (1980) econometric model, and Wallin's[7] analysis of markets for pallets and likely future trends.

PALLET POOLS

Strobel and Wallin (1969) consider a wooden pallet system most applicable to materials handling in the food industry—from the raw materials, through manufacture and distribution to the retail store. Systems such as plastic or fiber slip sheets (on which loads are handled with special forklift trucks) and clamp trucks (that grip loads from the sides) may be more efficient in a particular situation, but are not applicable system-wide. To make the wooden pallet system work, a pallet exchange (**pallet pool**) is needed. One of the most difficult problems in managing such an exchange system is maintaining and policing quality of the pallets exchanged.

Pallet pools may operate within any industry or among industry groups, but are principally employed by the food, can and bottle manufacturing, brewery, and refractory industries.. National Pallet Leasing Systems, Inc. commercially operates such a pallet pool in the United States (Stern 1977c). Similar pools have operated for many years in Australia and during the late 1970's were launched in Canada and the United Kingdom.

PALLET TYPES CLASSIFIED BY USE

Expendable pallets.—Expendable pallets are used to ship products and are intended for a single trip or a limited number of shipping cycles. They are therefore designed for minimal cost consistent with use and load. Designs incorporate lumber in thicknesses from ¼-inch, plywood from 5/16-inch, and stringers as small as ⅞-inch by 2¾-inches, wood blocks of various sizes, fiberboards, paper tubes, plastics, and metals.

General purpose pallets.—General-purpose pallets are usually heavy duty, double-faced, designed for stacking and racking, and repairable for long life with low maintenance cost. Reusable (permanent) warehouse pallets are in this category. General-purpose pallets may be designed for **two-way** entry to permit entry of forks or pallet hand trucks from two opposite ends. They may also be designed for partial **four-way entry** to permit fork entry from all four sides, but hand-jack entry from the two ends only (fig. 22-20 top). A block design (fig. 22-20 bottom) permits full four-way entry.

Special-purpose pallets.—Special-purpose pallets may be of any design and size appropriate for the job intended. They may be designed for loads of low density and distributed, heavy and concentrated, regular or irregular in shape, small or large size.

PALLET TYPES CLASSIFIED BY CONSTRUCTION

General-purpose wooden pallets may be **single-faced** with one deck on top (fig. 22-19), or **double-faced** with both top and bottom decks (fig. 20-20 top). The double-faced pallet may be **reversible** with identical top and bottom decks so that goods can be loaded on either deck, or **non-reversible** in which top and bottom decks have different openings and goods are loaded only on the top deck.

Wooden pallets may be constructed with **flush stringers** so that outside stringers or blocks are flush with the ends of deckboards (fig. 20-20). In **single-wing** pallets, outside stringers are set inboard of the top deck, but flush with the ends of bottom deckboards. In **double-wing** pallets, outside stringers are set inboard of both top and bottom deckboards. Wing-type pallets (fig. 22-22) permit use of slings (which loop around extended deckboards) as well as fork lifts to handle loaded pallets.

Almost all pallets are assembled with nails or staples. Bolted assemblies lack rigidity and are expensive. Adhesive bonded pallets lack needed impact resistance. Nail styles are discussed in text related to figure 22-36 and nail and staple performance related to wood species is summarized in table 22-15 and related text.

PALLET STANDARDS

Pallet production is increasing rapidly throughout the world, and pallet use is pervasive throughout manufacturing, warehousing, shipping, and merchandis-

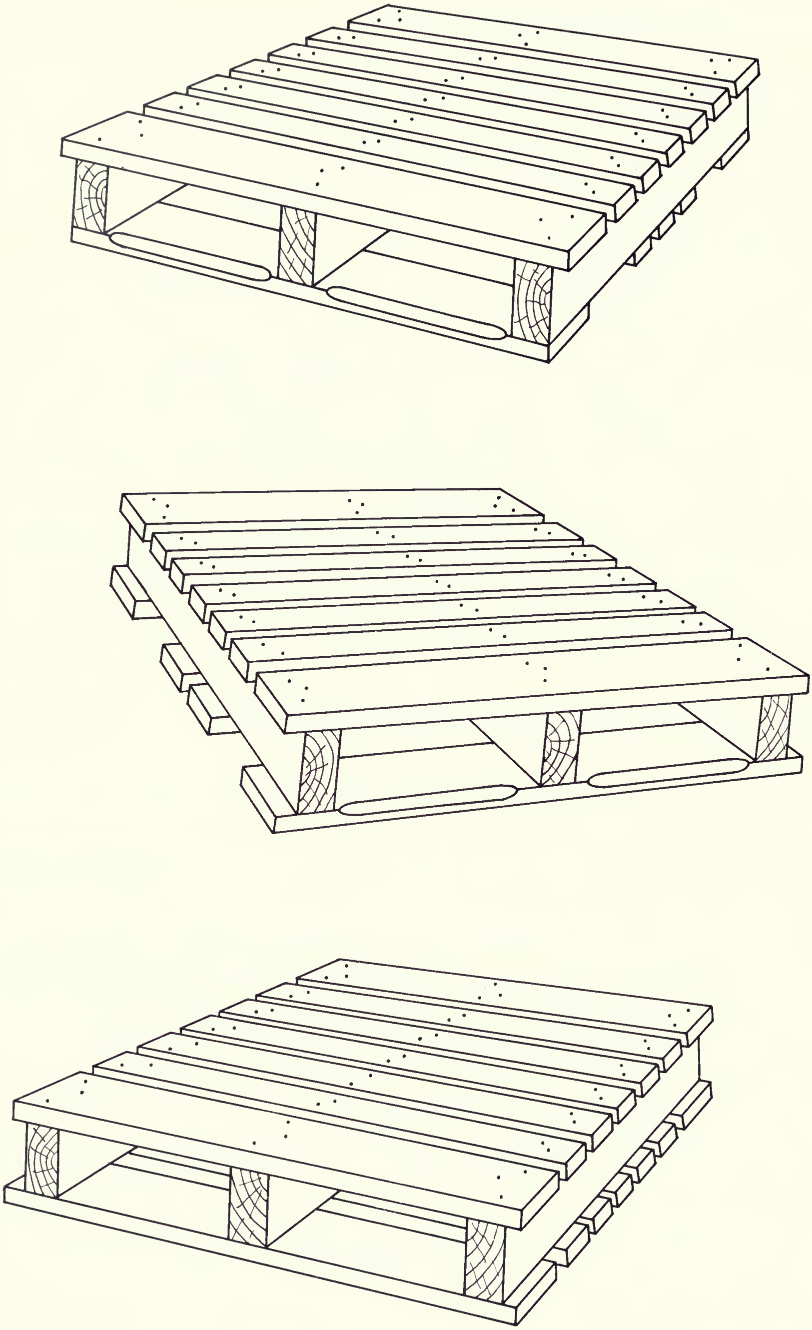


Figure 22-22.—Wing-type pallets. (Top) Single-wing, double-face, non-reversible, four-way, or two-way design. (Center) Double-wing, double-face, non-reversible, usually made in two-way design. (Bottom) Double-wing, double-face, reversible, two-way.

ing activities. Efforts to standardize pallet designs seem appropriate and justified. Such efforts have been promoted by various pallet manufacturers' associations, including the National Wooden Pallet and Container Association (NWPCA) of Washington, D.C., the American National Standards Committee (ANSI) under the auspices of the American Society of Mechanical Engineers (ASME), and the International Organization for Standardization (ISO) Committee TC-51 on *Pallets for unit load method of material handling*. The British Standards Institute (BSI) serves as secretariat for the latter committee.

Pallet standardization in the United States is administered by Committee MH-1 of the American National Standards Institute. ANSI Standard MH-1.4.1 entitled "Procedures for testing pallets" was approved October 18, 1977. ANSI Standard MH-1.2.2-1975 entitled "Pallet sizes" was approved in 1976. ANSI Standard MH-1.1.2—1978 entitled "Pallet definitions and terminology" was approved January 31, 1979. Proposed ANSI Standards MH-1.3.1 entitled "Pallet sizes for use with MH-5 containers" and MH-1.5 entitled "Slip sheets" were in preparation in late 1980. Liaison is established between ANSI Standards Committee MH-1 covering "Pallets" and Committee MH-10 covering package dimensions.

Pallet standards published by the National Wooden Pallet and Container Association (1962) are generally accepted and used by industry. The Department of Defense and the General Services Administration of the Federal Government publish their own standards. Efforts by industry, government, and universities are continuing to provide basic data on which to base national pallet design standards.

Standard sizes for general-purpose pallets.—Stringer and block general-purpose reusable pallets are produced in hundreds of different designs according to customer specifications. E. G. Stern (1979a) diagrammed 17 representative designs of these two types as specified and used by major purchasers and industry groups in the United States, Canada, Europe, Japan, and Brazil. Eight typical designs used in this country are illustrated here (figs. 22-23 through 22-30) and salient features of their designs are summarized in table 22-12. For data on the other nine designs, readers are referred to E. G. Stern (1979a). He noted that a comparison of the pallets raises several questions. For example, why are the 40- by 48-inch pallets not 48- by 40-inch pallets which are more common in industry? Why don't all users standardize on the usual 9 inch notch length? Variation from this length requires use of special knives. Research (Wallin et al. 1975) has indicated that further standardization would benefit all segments of the industry.

Performance standards for general-purpose pallets.—Observers of pallet markets in 1980 noted that pallets are the "tail" and not the "dog" in the materials handling industry, and therefore must be adaptable to a variety of use conditions. Establishment of standard sizes for pallets will occur only when large numbers of users perceive an advantage in such size standardization. Until such perception occurs, it may be more useful to promulgate standards directed to the performance of pallets, rather than their dimensions. Design standards based on engineering principles and knowledge of material properties will help insure required performance.

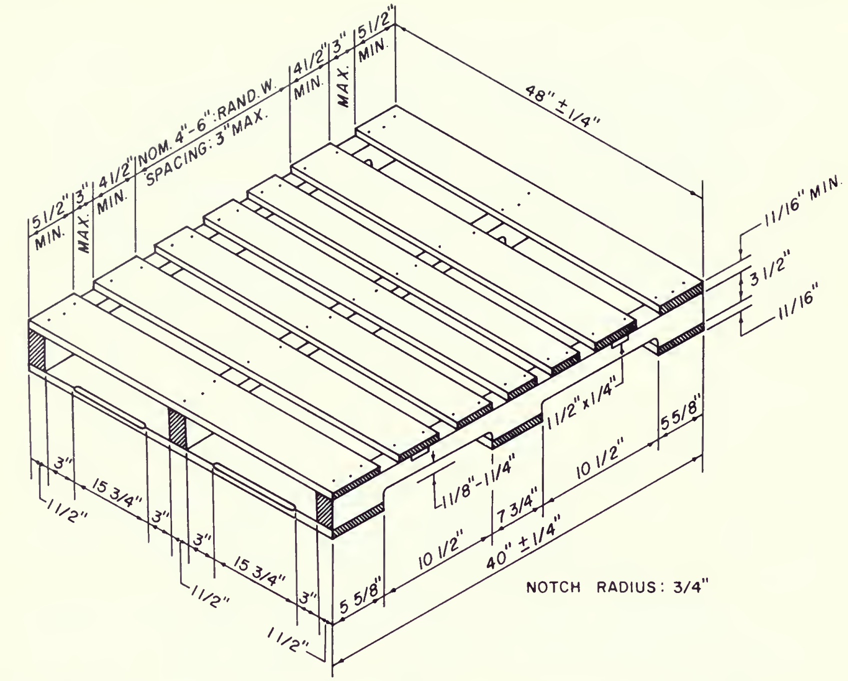
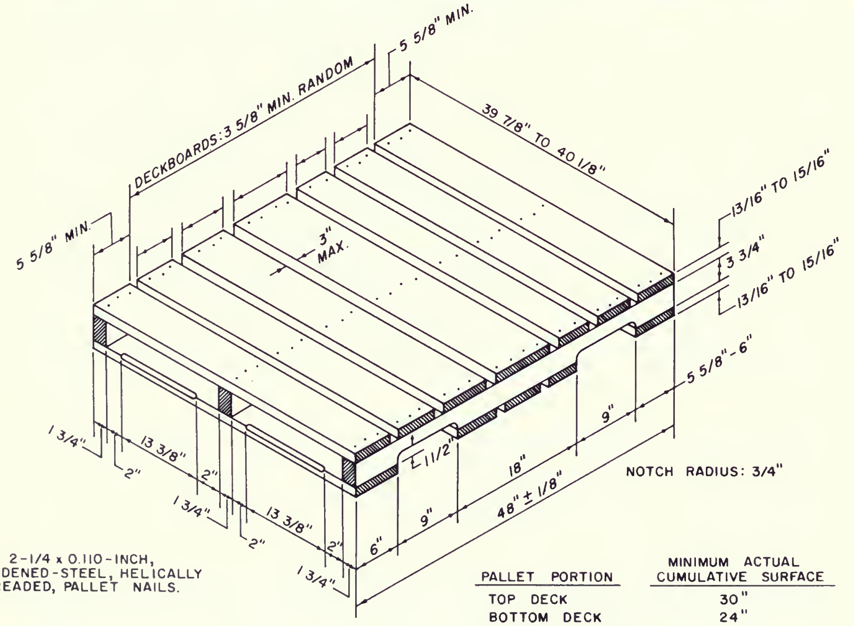


Figure 22-23.—Double-face, non-reversible, flush, four-way entry, 40- by 48-inch, U.S. GSA Federal Supply Service pallet (NN-P-71C, Type III, Size 2, September 1973.) Use of yellow-poplar, aspen, and eastern cottonwood permitted by this specification. All dimensions are in inches. (Drawing after Stern 1979a.)



USE 2-1/4 x 0.110-INCH, HARDENED-STEEL, HELICALLY THREADED, PALLET NAILS.

PALLET PORTION	MINIMUM ACTUAL CUMULATIVE SURFACE
TOP DECK	30"
BOTTOM DECK	24"
CENTER BOTTOM DECK	13"

Figure 22-24.—Double-face, non-reversible, flush, four-way entry, 48- by 40-inch hardwood, Grocery Industry pallet as specified by Grocery Pallet Council (GPC), November 1976. All dimensions are in inches. (Drawing after Stern 1979a.)

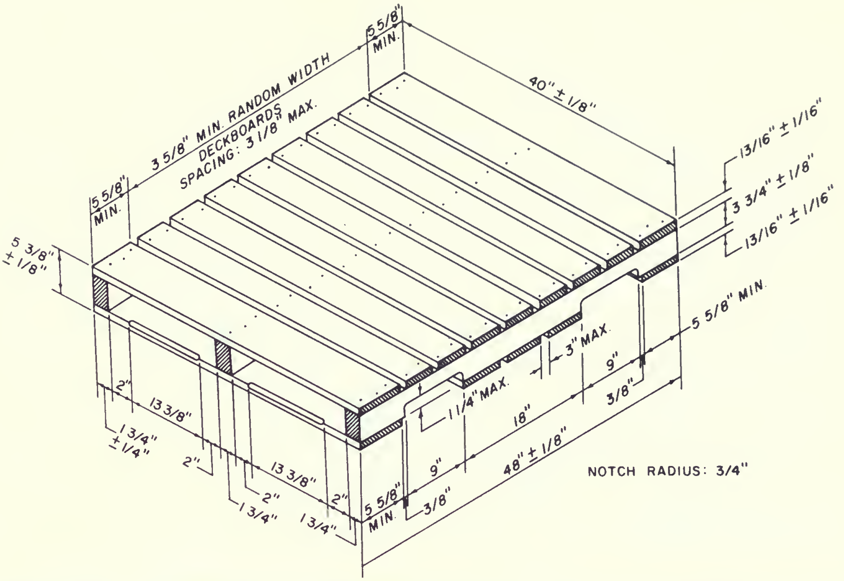


Figure 22-25.—Double-face, non-reversible, flush, four-way entry, 48- by 40-inch, hardwood, Glass Packaging Institute Standard Pallet (PD-100), August 21, 1978. All dimensions are in inches. (Drawing after Stern 1979a.)

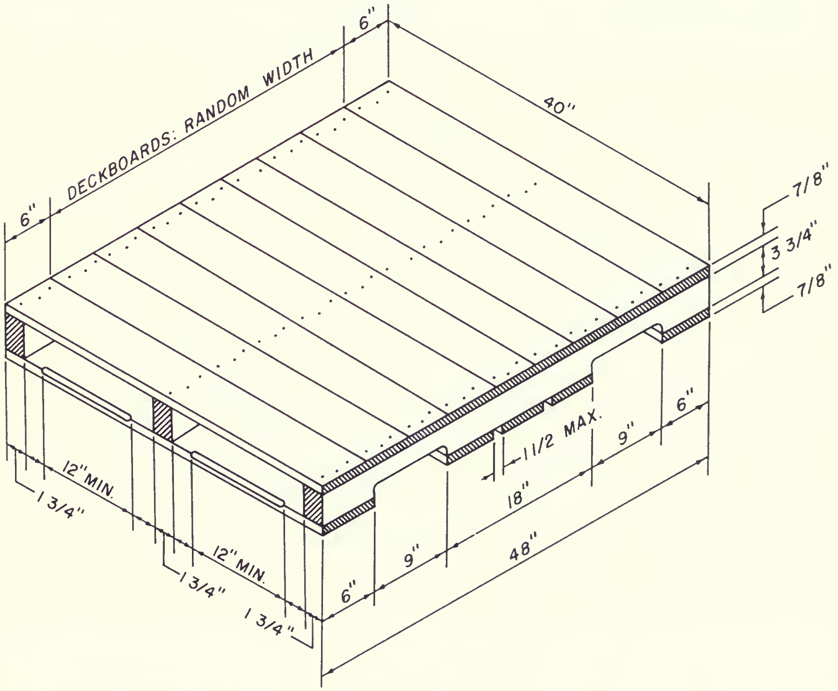


Figure 22-26.—Double-face, non-reversible, flush, four-way entry, 48- by 40-inch, hardwood, Eastman Kodak Standard Solid-Deck pallet, March 1969. All dimensions are in inches. (Drawing after Stern 1979a.)

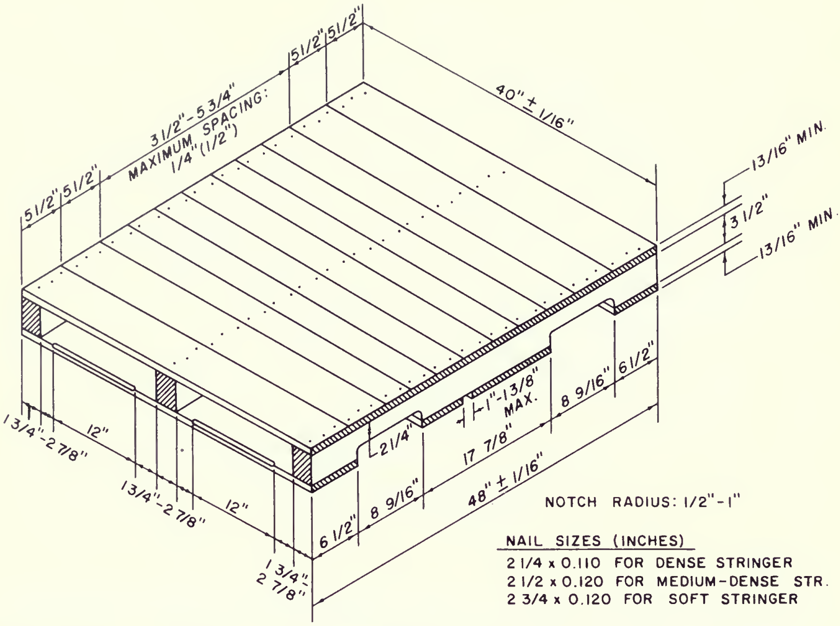


Figure 22-27.—Double-face, non-reversible, flush, four-way entry, 48- by 40-inch, soft or medium-dense or dense species, solid-deck, United States Postal Service pallet (USPS-P-756B (R&DD), October 1975). All dimensions are in inches. Stringer sizes are dependent on wood species and moisture content. (Drawing after Stern 1979a.)

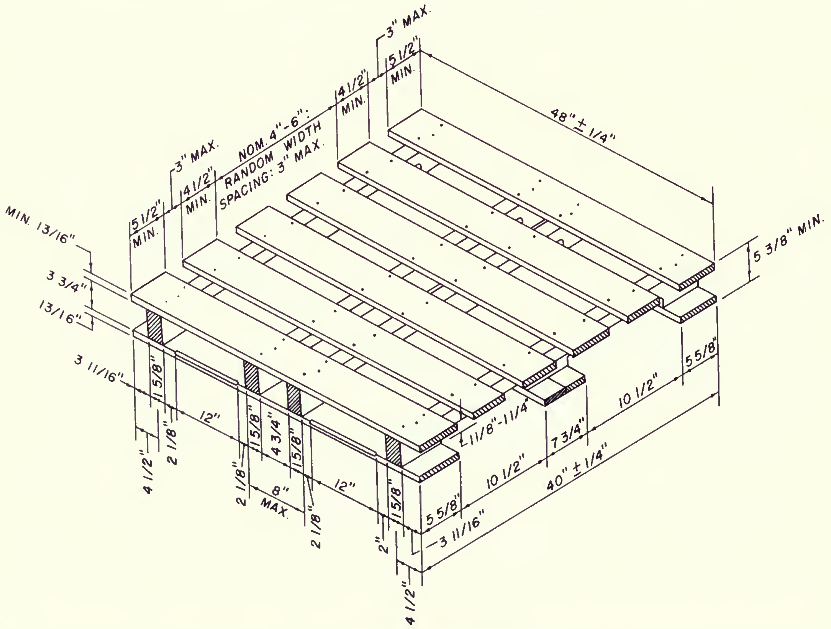


Figure 22-28.—Double-face, non-reversible, double-wing, four-way entry, four-stringer, 40- by 48-inch, hardwood, stevedore, U.S. GSA Federal Supply Service pallet (NN-P-71C, Type V, Size 2, September 1973). Use of yellow-poplar, aspen, and eastern cottonwood permitted by this specification. All dimensions are in inches. (Drawing after Stern 1979a.)

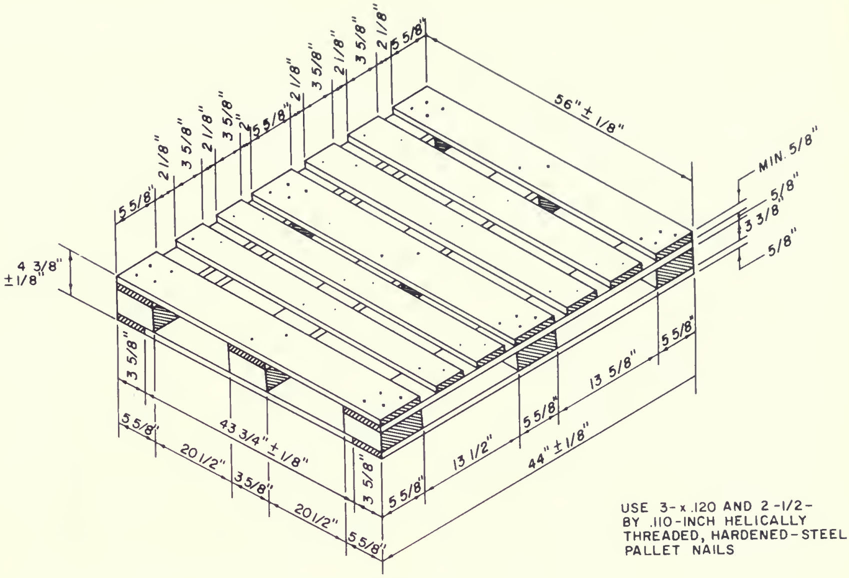


Figure 22-29.—Single-face, non-reversible, flush, four-way entry, nine-block, 44- by 56-inch, hardwood empty-can storage and shipping pallet. Can Manufacturers Institute, May 1974. All dimensions are in inches. (Drawing after Stern 1979a.)

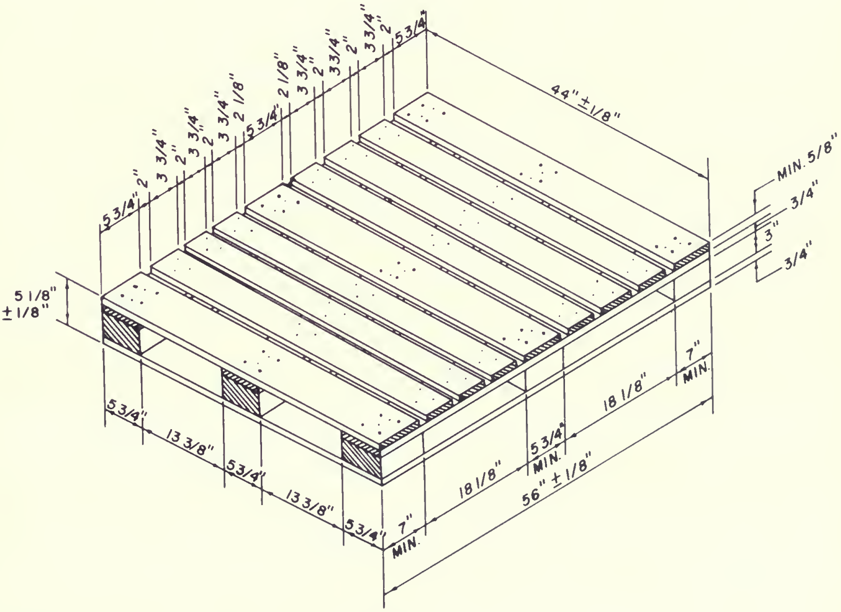


Figure 22-30.—Single-face, non-reversible, flush, four-way entry, nine-block 56- by 44-inch, hardwood, bulk glass-container pallet with mitered corners on bottom deck frame. Glass Container Manufacturers Institute (PD-110), June 1972. All dimensions are in inches The 22 small dots indicate 1-½-inch-long, non-hardened, clinched, plain-shank nails for top mat assembly. The large dots represent 3-¼- by 0.135-inch nails for fastening the top mat to the blocks. The bottom deckboards are attached to the blocks with 2-¼- by 0.120-inch nails. (Drawing after Stern 1979a.)

TABLE 22-12—*Eight standard hardwood four-way-entry pallets* (E. G. Stern 1979a)[1,2]

Statistic	Figure number							
	22-23	22-24	22-25	22-26	22-27	22-28	22-29	22-30
Organization	GSA	GPC	GPI	EK	USPS	GSA	CMI	GCMI
Type[3]	S	S	S	S	S	S	B	B
Size	48x48	48x40	48x40	48x40	48x40	40x48	44x56	56x44
Length or width tolerance	±¼	±⅛	±⅛	—	±1/16	±¼	±⅛	±⅛
Minimum height	4⅞	5-⅜	5-¼	5-½	5-⅛	5-⅜	4-¼	5
Deckboards								
Leading-edge width	5-½	5-⅝	5-⅝	(6)	5-½	5-½	5-⅝	5-¾
Minimum thickness	11/16	13/16	¾	⅞	13/16	13/16	⅝	⅝
Minimum width (6)	5-½	5-⅝	5-⅝	Random	5-½	5-½	5-⅝	5-¾
Minimum width (4)	3-½	3-⅝	3-⅝	Random	3-½	3-½	3-⅝	3-¾
Maximum top spacing	3	3	3-⅛	0	0	3	2-⅛	2
Maximum bottom spacing	0	3	3-½	1-½	1-⅜	0	13-⅝	13-⅜
Chamfer length	15¾	13-⅜	13-⅜	12	12	12	None	None
Stringers (or stringerboards)[2]								
Minimum width	1½	1-¾	1-½	1-¾	1-¾	1-⅝	3-⅝; 5-⅝	3-¾
Minimum height	3½	3-¾	3-⅝	3-¾	3-½	3-¾	⅝	¾
Notch width	10½	9	9	9	8-½	10-½	—	—
Notch height	1⅛	1-½	1-¼	—	¾-1-¼	1-⅛-1-¼	—	—
Notch end distance	5-½	6	6	6	6-½	5-⅝	—	—
Notch radius	¾	¾	¾	—	½-1	—	—	—
Blocks								
Number	None	None	None	None	None	None	9	9
Corner	—	—	—	—	—	—	5-⅝x 5-⅝	7x 5-¾
Intermediate	—	—	—	—	—	—	3-⅝x 5-⅝	5-¼x 5-¾
Height	—	—	—	—	—	—	4-¼	3
Minimum deck coverage								
Top	Var.	30	Var.	48	48	Var.	31-⅜	39-¾
Bottom	18¾	24	Var.	Var.	Var.	19	10-⅞	17-¼
Center bottom	7¾	13	Var.	Var.	Var.	7-¾	3-⅝	5-¾
Back-up deckboard	None	None	None	Random	5-½	None	None	None

[1]All dimensions are in inches; values in parentheses are nominal.

[2]All designs have three stringers (or stringerboards) except the GSA pallet shown in figure 22-28, which has four.

[3]S means stringer pallet; B means block pallet.

SPECIES GROUPINGS

Specialists in pallet design are not unanimous in grouping species according to their serviceability in wooden pallets. Generally the classifications are based on specific gravity of the woods, but designers are more immediately concerned with modulus of rupture, modulus of elasticity, impact strength, and nail-holding capability. In 1980 the hardwood species groupings recognized by the National Wooden Pallet and Container Association were based on wood specific gravity, as follows—by common name:

Class A (lease dense)	Class B (medium)	Class C (most dense)
Aspen	Ash (except white)	Beech
Basswood	Butternut	Birch
Buckeye	Chestnut	Hackberry
Cottonwood	Magnolia	Hard maple
Willow	Soft elm	Hickory
	Soft maple	Oak
	Sweetgum	Pecan
	Sycamore	Rock elm
	Tupelo	White ash
	Walnut	
	Yellow-poplar	

Pallet purchasers usually specify species according to these classes, and specify dimensions and size independently.

The U.S. Department of Defense (1959) established four species groups as follows, listed by common name:

Group I	Group II	Group III	Group IV
Aspen (popple)	Douglas-fir	Ash (except white)	Beech
Basswood	Hemlock	Soft elm	Birch
Buckeye	Southern pine	Soft maple	Hackberry
Cedar	Tamarack	Sweetgum	Hard maple
Chestnut	Western larch	Sycamore	Hickory
Cottonwood		Tupelo	Oak
Cypress			Pecan
Fir (true firs)			Rock elm
			White ash

STIFFNESS AND RIGIDITY OF 48- BY 40-INCH NAILED PALLETS OF 22 PINE-SITE HARDWOODS[8]

Stern (1978) evaluated five laboratory-constructed pallets (fig. 22-31) of each of 22 pine-site hardwood species for stiffness and rigidity. The pallets were non-reversible, double-face, flush, four-way, 48- by 40-inch, with three notched stringers. The lumber was sawn from logs 7 to 17 feet in length measuring 6 to 18 inches in top diameter. Logs for seven of the species were obtained from central Louisiana (small logs from southern pine sites), and the balance from Virginia (somewhat larger logs). The lumber was planed while green to the

[8]Condensed from Stern (1978).

dimensions shown in figure 22-31. In making the green pallet parts, an effort was made to use only high-quality lumber insofar as possible. Each pallet contained 28.6 nominal board feet of lumber.

Sixty-nine tough hardened-steel pallet nails were used in assembling the top deck and 42 in the bottom deck. They were pointless, 3 inches long, 0.120 inches in diameter, and had four helical flutes. Pallets were assembled from green lumber and nails were hammer driven as shown in figure 22-31.

Pallet weight.—Pallet green weights when assembled ranged from 93 pounds for yellow-poplar to 128 pounds for cherrybark oak and averaged 113 pounds. At test, the pallets (deckboards and stringers) had dried to approximately 12 percent moisture content and ranged from 53 pounds for yellow-poplar to 88 pounds for mockernut hickory, with an average of 72 pounds (table 22-13).

Specific gravity.—Data from each deckboard and each stringer of each of the 110 pallets tested, indicated that specific gravity of the deckboards averaged 0.66, and ranged from 0.36 for yellow-poplar to 0.95 for mockernut hickory (based on weight and volume when ovendry). Stringer specific gravity ranged from 0.40 for yellow-poplar to 0.94 for mockernut hickory, and averaged 0.68 (table 22-13).

Pallet stiffness under static load.—The pallets, when equilibrated to an average moisture content of approximately 12 percent, were static tested for stiffness, i.e, for their deflection when loaded in 200-pound increments, for a period of 2 minutes, up to a total of 2,000 pounds. Pallets undergoing test were supported at each corner on 2-inch by 2-inch supports and top-loaded at pallet center point with a hydraulic jack through a spherical seat to a 9/16-inch-thick, 12- by 14-inch steel plate with width and length parallel with pallet width and length, respectively. Pallet deflection was measured at the pallet's center directly under the load, and at the center of the pallet's ends and sides.

Average pallet deflections, after application of the 2,000-pound concentrated load for 2 minutes, were as follows (table 22-13):

- At pallet center—Average of 0.69 inch with range from 0.50 for scarlet oak to 0.95 inch for post oak.
- At midpoint of pallet ends at the 13/16-inch end deckboard—Average of 0.39 inch with range from 0.28 for scarlet oak to 0.56 for post oak.
- At midpoint of pallet sides at the outer 1-7/8- by 3-7/8-inch stringer—Average of 0.30 inch with range from 0.21 inch for northern red oak to 0.41 inch for post oak.

To arrive at an index of stiffness, average deflections observed at these five locations in the five pallets of each species were summed; an average index for all 22 species was determined and species expressed as a percentage of this average (fig. 22-32). Among all 22 species, Shumard oak and northern red oak performed best and post oak poorest; the poor showing of post oak was attributable to cupping of bottom leading-edge deckboards, causing significant deflection with application of the first 200-pound load increment. Among the six non-oaks of Species Class C, mockernut hickory and white ash performed best and hackberry poorest. Among the five hardwoods of Species Class B, yellow-

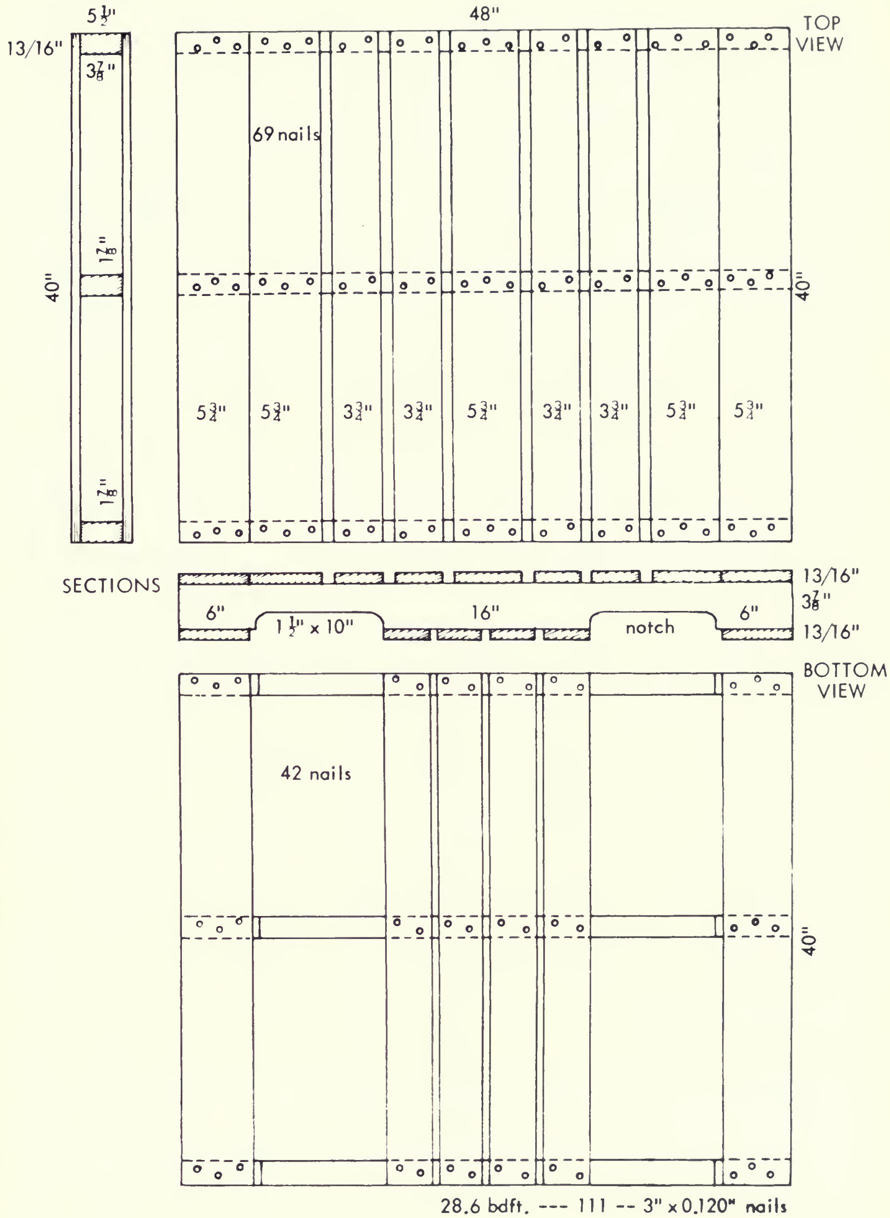


Figure 22-31.—Non-reversible, double-face, flush, four-way, three-stringer, nailed pallet measuring 48 by 40 inches. Paired 5-¾-inch top leading-edge deckboards are snugged against each other for added impact strength. (Drawing after Stern 1978.)

poplar and black tupelo performed best, and sweetgum poorest. Yellow-poplar and black tupelo, both species Class B woods, had less deflection than white oak—which had deflection average for all 22 species.

Impact rigidity of pallets.—After static test, and while held at approximately 12 percent moisture content, the pallets were suspended by one corner, and released by a solenoid-operated mechanism to drop from a height of 40 inches (between lowest pallet corner and the impact surface) onto the smooth surface of a massive concrete block. This procedure was repeated 12 times, always dropping the pallet onto the same pallet corner. The changes in length of each of the four pallet diagonals—between marks near the four corners of both pallet top and bottom—were recorded after each drop. No major failures occurred except on one sweetgum pallet where the impacted end of a bottom deckboard fractured.

TABLE 22-13—*Weight of 48- by 40-inch nailed hardwood pallets of 22 species, specific gravity of deckboards and stringers, and pallet deflections at five locations resulting from a 2,000-pound concentrated load applied for 2 minutes to the center of the top deck while the pallet is supported at the four corners* (Data from Stern 1978)[1]

Species	Pallet weight[2]	Specific gravity[3]		Deflection		
		Deckboards	Stringers	Sides[4]	Ends[5]	Center
	Pounds			*Inch*		
Ash, green	69	0.63	0.61	0.28	0.37	0.65
Ash, white	71	.63	.65	.25	.35	.57
Elm, American	64	.58	.61	.34	.40	.79
Elm, winged	80	.74	.75	.30	.37	.64
Hackberry	65	.56	.61	.34	.49	.83
Hickory, mockernut	88	.86	.88	.22	.35	.55
Maple, red	72	.61	.63	.34	.46	.78
Oak, black	81	.73	.73	.32	.39	.72
Oak, blackjack	81	.72	.77	.29	.49	.82
Oak, cherrybark	78	.73	.75	.31	.35	.65
Oak, laurel	72	.75	.72	.32	.34	.69
Oak, northern red	76	.66	.72	.21	.34	.51
Oak, post	80	.72	.78	.41	.56	.95
Oak, scarlet	77	.70	.68	.26	.38	.62
Oak, Shumard	77	.74	.72	.22	.29	.51
Oak, southern red	71	.64	.69	.23	.37	.61
Oak, water	76	.70	.72	.28	.33	.59
Oak, white	84	.77	.80	.33	.39	.69
Sweetbay	57	.51	.54	.37	.36	.83
Sweetgum	61	.54	.58	.33	.44	.82
Tupelo, black	62	.54	.57	.29	.42	.69
Yellow-poplar	53	.45	.43	.29	.40	.65
Average	72	.66	.68	.30	.39	.69

[1]See figure 22-31 for pallet design; each value is the average for five pallets.

[2]At approximately 12-percent moisture content.

[3]Based on weight and volume when ovendry; each value is the average for five pallets based on data from each stringer and each deckboard of each pallet.

[4]Midpoint of the sides at the outer edge of the outer stringer.

[5]Midpoint of the ends at outer edge of the 13/16-inch end deckboard.

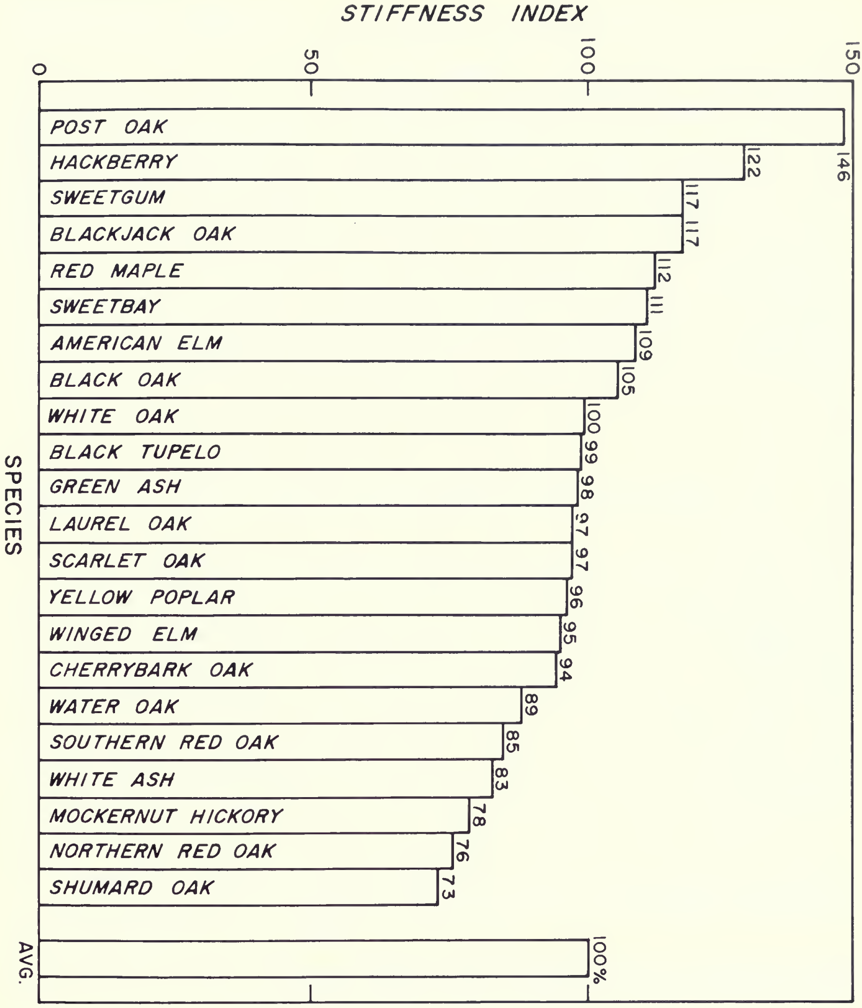


Figure 22-32.—Stiffness index of 48- by 40-inch nailed hardwood pallets suspended at the corners and subjected to a 2,000-pound concentrated center load for 2 minutes. The index is derived from the cumulative average deflection measured at five locations on each of five pallets of each species. White oak pallets had an index of 100, average for the 22 pine-site hardwood species evaluated. See table 22-14 for deflection values. (Drawing after Stern 1978.)

After six drops, average distortion of the pallet diagonals was 1.8 percent with a range from 1.3 percent for green ash to 2.7 percent for laurel oak. Even after 12 drops, none had more than 4 percent distortion of pallet diagonal length; the average was 2.2 percent with range from 1.6 percent for green ash to 4.0 percent for laurel oak (table 22-14).

The change in lengths of pallet diagonals had a straight line relationship (R^2 = 0.77) to the specific gravity—hence weight—of deckboards and stringers; the greater the specific gravity, the greater the distortion.

TABLE 22-14—*Percentage distortion of diagonal lengths of 48- by 40-inch pallets of 22 hardwood species after 6 and 12 feet fall drops onto one corner from a height of 40 inches* (Stern 1978)[1,2]

Species	Distortion of diagonal length after	
	6th drop	12th drop
	Percent	
Ash, green	1.3	1.6
Yellow-poplar	1.3	1.7
Hackberry	1.4	1.7
Sweetgum	1.5	1.8
Maple, red	1.5	1.9
Elm, American	1.5	1.9
Sweetbay	1.6	2.0
Oak, water	1.6	2.0
Ash, white	1.6	2.0
Oak, scarlet	1.7	2.1
Elm, winged	1.7	2.1
Oak, cherrybark	1.7	2.1
Oak, Shumard	1.7	2.1
Oak, northern red	1.7	2.1
Tupelo, black	1.8	2.2
Oak, blackjack	1.8	2.3
Oak, black	1.8	2.3
Oak, post	1.9	2.5
Oak, southern red	2.2	2.8
Oak, white	2.3	2.9
Hickory, mockernut	2.5	3.1
Oak, laurel	2.7	4.0
Average	1.8	2.2

[1]See figure 22-31 for design of pallets; each value is an average based on five pallets.
[2]Pallets had approximately 12 percent moisture content at test.

STAPLED PALLETS OF PINE-SITE HARDWOODS

Stern (In press a) staple-assembled pallets having the same dimensions as the nail-assembled pallets depicted in figure 22-31, using wood of 17 pine-site hardwoods available from his 1978 experiment, and performed simultaneously with it. The stapled pallets were assembled green using tool-driven 2-½-inch-long, 15-gauge, 7/16-inch-crown, plastic-coated staples—144 per pallet.

Static bending stiffness of the stapled pallets was about the same as that of nailed pallets. Impact rigidity of the stapled pallets, however, was only about one-fifth that of the nailed pallets. Readers needing more details should consult Stern (In press a).

OTHER TEST DATA

Hundreds of tests have been conducted to evaluate pallets, but conclusions often differ and comparisons among tests are difficult. For example, Kurtenacker (1969) concluded that in rough handling tests, pallets made of yellow-poplar (a low-density species) tend to outperform pallets of hickory (a high-density species). Stern and Dunmire (1972) found that while yellow-poplar pallets, being lighter in weight than similar pallets made from hickory and oak, initially resist a substantially greater number of impacts in revolving test drum tests, the strength loss rate for yellow-poplar pallets is much greater than for oak and hickory pallets. They concluded, therefore, that pallets made from oak and hickory were usable substantially longer than similar pallets made of yellow-poplar.

LUMBER GRADES FOR DECKBOARDS AND STRINGERS

The service performance of double-face stringer-type pallets is strongly dependent on the impact strength of the end deckboards (on both upper and lower decks) and on the strength of the stringers. To aid pallet users in specifying pallets, the National Wooden Pallet and Container Association has published, and periodically revises, descriptions of four grades of pallet parts termed Precision, Premium, AA, and A in descending order of quality. Grades and grading criteria are employed by industry to specify minimum quality acceptable. Quality control is exercised by excluding parts containing unacceptable defects. Readers interested in grading criteria should consult the Association for current information.

Below-grade pallet shook.—Permanent warehouse pallets generally require use of parts which meet criteria for A-grade parts, as do heavy-duty expendable pallets, designed to be used five or six times.

To evaluate performance of one-trip expendable pallets, Wallin[9]—at the request of pallet manufacturers—proposed a fifth grade which permits defects not permissable in Grade A, and which are estimated to reduce the strength of parts by 75 percent, as follows:

Characteristic	Grade 5
Knots	Average diameter to three-fourths width of piece
Cracks	Unlimited
Splits/shake	Unlimited
Wane	Not limited except nails not driven into or through wane
Decay	Up to one-half width in stringers. Not more than one nail per joint driven through the decay; no nails driven into decay in stringer
Slope of grain	Unlimited
Moisture content	Unlimited
Other defects	Limited to the equivalent of those listed above

[9]Wallin, W. B. 1979. Grading rules for below-grade pallet shook for expendable pallets and quality standards and performance criteria for below-grade pallet shook for use in expendable pallets. U.S. Dep. Agric. For. Serv., Northeast. For. Exp. Stn., Unpublished version of April 10, 1979.

Quality distribution of pallet parts from low-grade lumber.—Large and Frost (1974) conducted a study of northeastern and southern hardwood lumber to determine if the mix of lumber presently used to manufacture pallet parts is good enough to provide the quality parts needed in exposed and vulnerable areas of warehouse pallets identified as follows:

- The two top deck endboards—15 percent of total deck volume.
- The two bottom deck endboards—15 percent of the total deck volume.
- The two outside stringers—67 percent of total stringer volume.

At seven mills a total of 20,942 board feet were graded and cut into pallet parts. Species collected in the northeast included maple, beech, and birch; oak was sampled from central Appalachia and oak, sweetgum, and black tupelo from southeastern states.

Large and Frost (1974) concluded that amounts of high quality deckboards (Grade 2 and better) in existing pallet lumber mixtures are sufficient to permit the placement of quality parts in the vulnerable peripheral parts of pallets. To place Grade 2 and better stringers in outside positions (67 percent of stringer volume) requires selective cutting, the use of higher lumber grades, lumber sorting, or some other method of improving the quality mix.

They found that there are significant differences in quality distribution of pallet parts cut from different grades of lumber, and that selective cutting yields a significantly larger proportion of high-quality parts than gang cutting (fig. 22-33). There is, however, no appreciable difference in the quality of parts cut from different species of lumber of comparable quality.

See also: Craft, E. Paul; Whitenack, Kenneth R., Jr. A classification system for predicting pallet part quality from hardwood cants. Broomall, PA: Northeast. For. Exp. Stn.; 1982; USDA For. Serv. Res. Pap. NE-515. 7 p.

PARALLEL-LAMINATED-VENEER

As further discussed in section 22-10, it is possible to rotary-peel thick oak veneer and then bond the veneer into two- or three-ply sheets with grain of all plys parallel. Such sheets can then be crosscut and ripped into pallet deckboards of desired dimensions. Kurtenacker (1975a) successfully used such two-ply, ¾-inch-thick, northern red oak deckboards, nailed or stapled to green solid oak stringers, in field tests of reusable pallets for handling brick and concrete blocks.

In use, the laminated-deckboard pallets equalled the performance of those with solid deckboards. During free-fall-on-corner drop tests, the 11-inch-wide edge deckboards provided more resistance to racking (had more rigidity) in the plane of the pallet deck than did similar-size pallets that had a greater number of narrower solid wood deckboards.

No significant difference was found between laminated-deckboard pallets assembled with pallet staples and those assembled with standard helically-threaded pallet nails; thus, satisfactory performance may be expected from staple-assembled pallets if about five staples are used for every three nails, based on total fasteners in the pallet. In Kurtenacker's test, the staples were formed from 15-gage galvanized steel wire, had 2-½-inch-long chisel-pointed legs with a 7/16-inch crown, and the lower 1-⅛-inch of the staple legs were coated with a plastic material. Staples were driven so that the crowns made an angle of about 45° with the grain of the deckboards. The helically threaded pallet nails were 2-½ inches long with wire diameter of 0.120 inch.

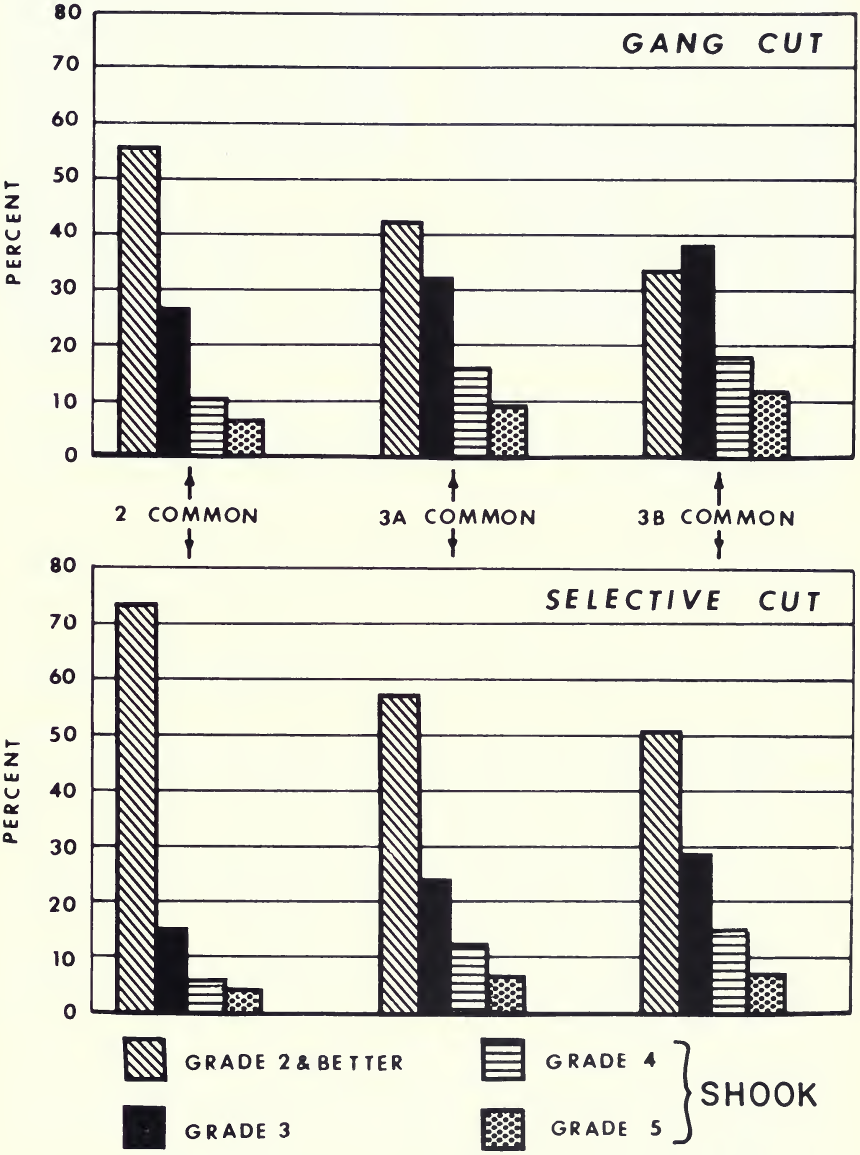


Figure 22-33.—Quality distribution of hardwood pallet shook cut from three lumber grades by two cutting methods. Gang-cut shook is cut by running long lumber through multiple crosscut saws; selective cutting employs a single saw so that defects can be removed. (Drawing after Large and Frost 1974.)

M 124 882, M 124 883

Figure 22-34.—Plywood pallets. (Left) Two-way pallets each carrying 1,800-pound load of rolled roofing, stacked four high in a warehouse. (Right) Four-stringer plywood pallets, each loaded with 1,200 pounds of flour stacked three high in storage. (Photos from Heebink 1965.)

PLYWOOD

Heebink (1965) found pallets with softwood plywood decks (fig. 22-34) durable and serviceable. In some instances damage from rough handling occurred; the most prevalent kinds of damage were as follows:

- Fraying and splintering of plywood deck edges. Few users considered it objectionable; repairs, if necessary, were made by replacing the edges with 4- to 6-inch-wide strips of new plywood.
- Breaking of bottom deckboards of plywood. This occurred especially when pallet loads of bagged goods such as flour were piled on each other. Reversible pallets, with plywood decks on both top and bottom are recommended for this situation (fig. 22-34 right).
- Some four-way pallets had crushed corners and some had split blocks, when the blocks were solid wood; laminated plywood blocks proved resistant to splitting.
- Bolthead pullthrough. This was serious when it occurred and was caused by routing out too much material for countersinking boltheads, or using bolts with too small heads. Flathead bolts requiring no countersinking and head diameters of at least 1 inch were recommended.

Pallets must not only be strong, they must absorb large impact loads. Extreme rigidity is afforded by a one-piece plywood deck, sometimes at the expense of shock absorbency. Stern (1969a) concluded that stiff-stock (non-hardened) nails should be used, instead of hardened (medium-carbon) steel nails for the assembly of plywood pallets, thus providing joints better able to absorb shocks; some experts disagree with this conclusion, however. Use of two-piece decks, instead of one-piece, also improves shock absorbency of plywood pallets slightly.

Major advantages of plywood for pallet decks include resistance to splitting, high impact and puncture resistance, continuity and smoothness, rigidity, and light weight. Of increasing importance in automated pallet handling systems is the surface smoothness of the decks and the accurate sizing possible when plywood decks are used.

Softwood plywood top decks ⅝-inch thick perform comparably to 13/16-inch hardwood butted-end-board construction. For bottom deckboards softwood plywood ¾-inch thick may be needed to perform comparably with 13/16-inch hardwood boards.

E. G. Stern (1979b) found that stringer-type, double-face, four-way, flush, non-reversible pallets with solid decks can be made very impact resistant if ¾- by 6-inch oak end boards are combined with ¾-inch-thick plywood central panels; performance was best when face grain of the plywood portion of the deck was oriented perpendicular to the stringers.

Hardwood plywood, in 1980, was little used for pallets, but new technology for rounding up, and peeling short, small hardwood logs (fig. 18-252) should improve the competitiveness of hardwood plywood for structural uses. Hardwood plywood pallet decks could be a large and important market for pine-site hardwoods.

Readers interested in design of plywood pallets are referred to the manual on the subject published by the American Plywood Association (1975).

COMPOSITE BOARD

A hardwood flakeboard core overlaid on top and bottom with dense hardwood veneer (fig. 24-53) has much promise for pallet decks. Mechanical properties of such a composite are given in section 24-19, and an economic feasibility study of an operation to manufacture the board is summarized in section 28-26.

The hardwood composite has most of the advantages previously cited for softwood plywood, and should be considerably cheaper to manufacture. Moreover, the hardwood raw material is closely adjacent to manufacturing regions and population centers where pallet markets are concentrated. Because most pallet deckboards are less than 4 feet long, short hardwood veneer logs—available in plentiful supply—can be used for their manufacture.

Perceiving that pallet decks need the impact resistance provided by solid hardwood end boards, and the rigidity provided by a panel deck, Netercote et al. (1974) combined hardwood lumber end boards with a central panel of hardwood randomly oriented flakeboard, all overlayed on both surfaces with rotary-peeled hardwood veneer to make a composite full-deck panel ⅝-inch thick. The veneer was oriented with grain perpendicular to the end boards and parallel to the stringers of the 48- by 40-inch warehouse-type pallets. The stiffness and resistance to end impact of these pallets was considerably greater than lumber or plywood decked pallets of comparable design, but with ¾-inch-thick decks.

FLAKEBOARD

Flakeboard pallet decks constructed of southern hardwoods have not been extensively evaluated, but it seems likely that they will be used in some applications, yet to be determined. Flakeboards have less impact strength and puncture resistance than plywood, but could serve well in appropriate thicknesses.

Kurtenacker (1975b) found that flakeboards with densities of 37 and 42 pounds per cubic foot showed no appreciable distortion in the plane of the decks when tested for diagonal rigidity, but they failed after three to six 40-inch free-fall drops on one corner because of nailhead pullthrough. Both flakeboard and plywood deckboard were crushed and gouged by repeated forklift impacts, but both were intact after accelerated aging. Nailing characteristics of the flakeboards appeared comparable to those of plywood.

Should oak and hickory flakeboards find use as pallet decks, they likely will be manufactured in a density range from 45 to 55 pounds per cubic foot. (See sections 24-9 through 24-16 for properties of such flakeboard, and sections 28-25, 28-27, 28-31, and 28-32 for economics of manufacture.)

Molded flakeboard pallets.—Section 28-19 summarizes an economic feasibility analysis of an operation for molding pallets from a hardwood flake and resin mixture (see figs. 28-22 and 28-23; also figs. 24-60 through 24-62).

In some sophisticated designs, reinforcing ribs are moulded in place; the ribs may be externally formed with shaped platens or internally formed between flat platens by adding additional flakes in the rib area to cause localized densification.

FIBERBOARD

R. K. Stern (1979ab) compared the performance of medium-density fiberboard with that of northern red oak lumber in construction of nine-block, four-way pallets and reusable warehouse four-way pallets of notched-stringer design.

Block pallets.—R. K. Stern's (1979a) work indicated that for nine-block, four-way pallets, a 1-inch top-deck thickness of medium-density hardwood fiberboard is needed to achieve performance comparable with northern red oak pallets having ¾-inch deckboards. Pallets of this style having 1-inch-thick fiberboard decks (medium-density) appear to be equal to, or better than, all-lumber pallets for use in mechanical handling and automatic palletizing systems—i.e., where pallet dimensional stability is necessary for smooth operation of the system.

Stringer-type pallets.—From his study of 48- by 40-inch, flush-type, non-reversible warehouse pallets, R. K. Stern (1979b) concluded that one-piece medium-density hardwood fiberboard pallet decks should be thicker than ¾-

inch to equal or exceed performance of ¾-inch-thick northern red oak spaced deckboards. This conclusion was based on evaluation of damage from handling impacts, bending stiffness, and diagonal rigidity. Pallets with fiberboard decks on wood stringers do not rack nearly so much, but crush at the corners more easily, than all-lumber counterparts. Stern also concluded that fiberboards for decking on stringer-type pallets should have a density of at least 39 pounds per cubic foot.

To evaluate pallets with 1-inch-thick fiberboard top decks, R. K. Stern (1980) glue-laminated (with phenol-formaldehyde adhesive) two ½-inch hardboards comprised of about 85 percent oak fibers and 15 percent sweetgum and elm, and nail-fastened them in place of lumber top decks. These pallets, and red oak lumber, notched-stringer, partial 4-way-entry pallets of warehouse design were tested in the laboratory and in service. The hardboard-lumber pallets withstood impact better, racked much less during cornerwise drop testing (but failed sooner), and performed similarly to the all lumber pallets during indoor and outdoor handling and storage conditions. The study indicated that standard helically threaded pallet nails can be used satisfactorily for both exterior and interior exposure.

PALLET DESIGN

Block versus stringer design.—The literature contains conflicting opinions of the relative merits of block versus stringer designs. Stern and Dunmire (1972), after testing of yellow-poplar, hickory, and oak pallets before and after 4 years of service, concluded that the descending order of rough-handling resistance of reusable pallets was picture frame (a block design with mitered lower deckboard corners; see fig. 22-30), three-stringer design without notches in stringers, and notched-stringer pallets. Kurtenacker et al. (1967) reached a similar conclusion.

Reeves (1975) found that stringer pallets required less lumber to construct, and were stiffer, stronger, and more durable in use than block pallets without "picture frame" design (fig. 22-35).

E. G. Stern (1973a) found that both block and stringer designs can be serviceable. In a 1980 review of this chapter he noted that block pallets, given preference to stringer pallets in Europe, have to be well built if they are to be used as permanent warehouse and exchange pallets; he concluded that in this country, if there is no compelling reason to use block pallets, they should be confined to one-way expendable use.

Deckboards of stringer type pallets.—There is general agreement, based on laboratory tests, that impact resistance and rigidity of stringer-type pallets is increased by leaving no space between the end deckboard and the deckboard adjacent to it (fig. 22-31). This improvement has been noted in top deckboards by E. G. Stern (1973b), R. K. Stern (1975), and Franco (1978). E. G. Stern (1973b, 1977d) concluded that bottom as well as top end deckboards should be snug against adjacent deckboards for improved performance. Six-inch-wide end

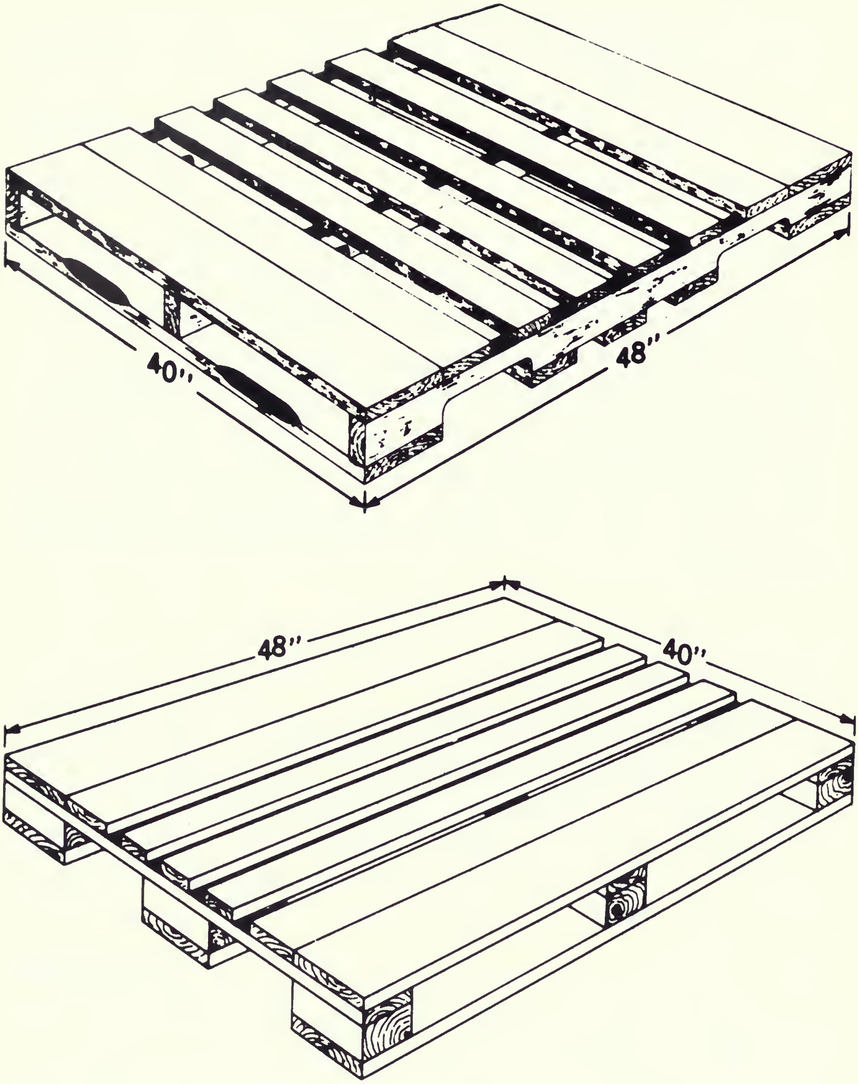


Figure 22-35.—Reeves (1975) found the stringer pallet design (top) superior to the block design (bottom), which lacks lateral lower deck ties.

deckboards give better service than those 4 inches wide; and 6-inch-wide backup boards perform better than those 4 inches wide. Stiffness and rigidity are further improved if pallets have two 1 by 6's instead of two 1 by 4's as bottom center deckboards (E. G. Stern 1974a).

Stringer design.—Stringer thickness for most standard pallet designs is in the range from 1-¼ to 1-⅞ inches, and usually not more than 1-¾ inches. There is some inclination to increase this dimension to 2-¼ inches for the class B woods of medium density listed earlier in this section and to 2-¾ inches for class A woods of low density.

E. G. Stern (1979c) compared yellow-poplar, sweetgum, and sweetbay pallets with 2-¼-inch-thick stringers assembled with 129 nails to pallets assembled onto 1-⅞-inch-thick stringers with 111 nails as shown in figure 22-31. On average, pallets with the 20 percent thicker stringers and 16 percent more nails had 7 percent less deflection of pallet sides, 4 percent less deflection at pallet ends from a centered concentrated load, and 6 percent less distortion in cornerwise free-fall tests than did pallets with 1-⅞-inch-thick stringers. In pallets made with both sizes of stringers, yellow-poplar performed better than sweetgum or sweetbay.

Stringer strength contributes to pallet longevity, so the design of stringers is of interest. Kurtenacker (1969) found that hickory and yellow-poplar stringer-type reusable 48- by 40-inch warehouse pallets (non-reversible, double-face-flush) performed best when designed for two-way entry only, i.e., stringers not notched; simulated wane on the top edge of stringers weakened them less than notches made for four-way entry. Pallets having notches achieved by nailing on blocks performed better than those with one-piece stringers notched with 1-½-inch radius at corners. Stringers with notches cut curved at the ends were stronger than those with straight sloped cuts at the ends. Stern (1969b) also found that built-up blocks below continuous upper stringers provided optimum performance, especially if the blocks were made of plywood.

Strength and durability computations.—The load that can be safely placed on a pallet, and the service life obtained from it, depend on:

- Pallet use: the load distribution, the manner in which the pallet is supported on the floor, in stacks, or in racks, and the roughness with which it is handled during empty and loaded transport.
- Pallet design: pallet size, pallet construction, and fasteners
- Raw materials: mechanical properties of the pallet parts and fasteners

For **permanent pallets** that are used in racks, ultimate bending strength of the notched stringers and deck deflection are critical factors. For **expendable pallets** deck deflection usually governs design. Durability depends to a large degree on the quality and number of fasteners used.

Readers interested in computations yielding pallet designs based on engineering principles should find useful the procedures outlined by Wallin et al. (1976) and Wallin (1977).

Computer programs for pallet design are available from Virginia Polytechnic Institute, Blacksburg.

Test methods.—Engineers needing descriptions of pallet test methods are referred to E. G. Stern (1974b), Wallin et al. (1976), American Society for Testing and Materials Standard D 1185, and to ANSI MHI-1977.

PALLET FASTENERS

Some plywood-decked pallets are assembled with bolts, and—on an experimental basis—some have been assembled with adhesives (Kurtenacker 1969, 1973ab, 1975a; R. K. Stern 1975). Bolted assembly is expensive, and because bolts are inserted in oversize holes, pallets so assembled lack rigidity. Adhesive-bonded pallets have generally not withstood the impact loads to which pallets are subjected; also, joints bonded in green wood weaken as boards dry and shrink. The preponderance of pallets are therefore assembled with nails and staples. These nails and staples account for 3 to 6 percent of the total cost of pallets (Bond and Sendak 1970).

Nail styles.—In stringer-type warehouse pallets, 6-inch deckboards are generally secured with three nails and 4-inch with two (fig. 22-31). In block-type pallets, four nails usually fasten 6-inch deckboards to the corner blocks (fig. 22-29). For normal pallet assembly with pine-site hardwoods in green condition, predrilling prior to nailing is not necessary. With very dense woods such as hickory, however, it is often advantageous to predrill the deckboards prior to assembly; predrilling with jigs results in optimum nail location, straight nailing, and fewer split deckboards and stringers (Stern and Franco 1979).

Both stiff-stock and hardened-steel pallet nails have been used since 1960 for assembly of warehouse pallets; experts are not unanimous in defining these terms, but industry generally accepts the following:

- **Stiff-stock nails** are bright, nonhardened, low to medium-high carbon-steel nails.
- **Hardened-steel nails** are made of medium- or medium-high-carbon steel, heat-treated and subsequently tempered. Heat treatment and tempering makes the nails tough as well as stiff.

To segregate types of nails, test criteria have been established based on data obtained from a Morgan impact bend angle tester (MIBANT tester). Bend angles on stiff-stock nails may vary from 25 to 60° or more. Hardened steel nails usually have bend angles of 20° or less. Pallet manufacturers normally specify the MIBANT bend angle of nails they purchase. From a 25-nail sample so tested, none should show partial or complete head failure and not more than two should show partial or complete shank failure (E. G. Stern 1974b).

From field observations during the years 1966 through 1971 of commercial shipping operations at 17 locations in the United States, W. B. Wallin and W. H. Sardo, Jr. concluded that pallet life could be signficantly increased and cost reduced by using hardened-steel nails. E. G. Stern (1974c) confirmed these findings in the laboratory; hardened-steel nails increased rigidity of stringer-type red oak warehouse pallets 64 percent compared with stiff-stock nails of the same size.

E. G. Stern (1974d) found that for optimum results these hardened pallet nails should be 3 inches long (rather than 2-¼ or 2-½ inches), made from 0.120-inch wire, have four helical flutes with about 60° thread angle and 0.136-inch thread-crest diameter, be pointless, and have a flattened, thin-rimmed, umbrella head about 5/16-inch in diameter (fig. 22-36).

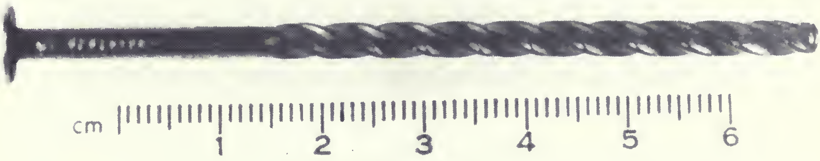


Figure 22-36.—Three- by 0.120-inch pointless, helically-threaded, hardened-steel pallet nail with thin-rimmed umbrella head; the four flutes have a thread angle of 63 degrees.

Performance of pallet nails in 22 pine-site hardwoods.—The effectiveness of these nails (fig. 22-36) was evaluated in deckboard-stringer joints by E. G. Stern (1976). Twelve deck-board stringer joints for each of the 22 species were assembled with a single nail from green lumber and tested after several weeks equilibration at 70°F and 50 percent relative humidity. Forces required to pull the nailhead through the deckboard and to withdraw the nail shank from the stringer were measured. Moisture content at test was 10 to 12 percent. Specimens for the test came from the same lumber associated with data in table 22-13, in which specific gravities are tabulated.

Pull-through resistance of the nailhead, which averaged 1,129 pounds (table 22-15), was minimum in yellow-poplar (704 pounds), sweetgum (820 pounds), and sweetbay (845 pounds); it was maximum in winged elm (1,407 pounds) and mockernut hickory (1,311 pounds).

Shank withdrawal resistance, which averaged 1,198 pounds (table 22-15), was minimum in yellow-poplar (628 pounds), black tupelo (923 pounds), and sweetbay (998 pounds); it was maximum in northern red oak (1,522 pounds) and mockernut hickory (1,437 pounds).

For these nails, forces (in pounds) were loosely correlated to wood specific gravity based on ovendry volume and weight (G), as follows:

$$\text{Nail-head pull-through resistance} = 1{,}857G \qquad (22\text{-}1)$$
$$\text{Nail-shank withdrawal resistance} = 3{,}801G^{5/8} \qquad (22\text{-}2)$$

Readers needing to relate withdrawal forces per inch of nail penetration to nail type, and nail-head pull-through resistance to nail-head area are referred to figures 24-7, 24-8, and 24-19 of Koch (1972).

Nailing standards.—When wood species of different densities are used for the construction of wooden pallets, different sizes and numbers of nails are needed to assemble pallets of comparable strength. Wallin and Stern (1974), in a tentative nailing standard for warehouse and exchange pallets, suggested that for optimum performance, only hardened-steel nails, 3- by 0.120-inch be used for mixtures of soft, medium, and dense species, and that all nails be helically threaded with a thread angle of about 60 degrees. For dense species only, they recommend 2-¼- by 0.110-inch nails; for mixtures of dense and medium dense species (e.g., pine-site hardwoods), they suggested 2-½- by 0.120-inch nails.

TABLE 22-15—*Forces to pull nailheads and staples through deckboards and to withdraw nail shanks and staple legs from stringers of 22 pine-site hardwoods* (Data from E. G. Stern 1976)[1]

Species	Nails[2]		Staples[3]	
	Head pull-through resistance	Shank withdrawal resistance[4]	Crown pull-through resistance	Leg withdrawal resistance[5]
	Pounds			
Ash, green	1,298	1,124	739	191
Ash, white	1,215	1,099	708	173
Elm, American	986	1,082	585	204
Elm, winged	1,407	1,369	811	191
Hackberry	1,053	1,087	545	120
Hickory, mockernut	1,311	1,437	690	190
Maple, red	1,092	1,340	773	105
Oak, black	1,407	1,420	715	296
Oak, blackjack	1,098	1,123	570	227
Oak, cherrybark	1,207	1,096	627	374
Oak, laurel	1,091	1,103	582	497
Oak, northern red	1,085	1,522	609	538
Oak, post	1,261	1,317	543	226
Oak, scarlet	1,198	1,477	521	311
Oak, Shumard	1,248	1,311	683	494
Oak, southern red	1,083	1,222	553	280
Oak, water	1,274	1,316	625	271
Oak, white	1,235	1,482	624	286
Sweetbay	845	998	463	160
Sweetgum	820	877	513	188
Tupelo, black	922	923	575	175
Yellow-poplar	704	628	456	152
Average	1,129	1,198	614	257

[1]Joints were assembled from green lumber and equilibrated to 10 or 12 percent moisture content before static test; each value is the average of about 12 joints. In 57 percent of the nail tests, and 24 percent of the staple tests, the fasteners failed before pull-through or withdrawal.

[2]The hardened-steel pallet nails were 3 inches long by 0.120 inch, pointless, helically-threaded, with thin-rimmed umbrella head about 5/16-inch in diameter. The four flutes had a thread angle of 63 degrees.

[3]The staples were plastic-polymer-coated 2-½-inch-long, 15-gage, galvanized staples with 7/16-inch-wide crown and short symmetrical chisel points driven so that crowns made a 45-degree angle with deckboard grain.

[4]Nail penetration into the stringer was 2-3/16 inches.

[5]Staple penetration into the stringer was 1-11/16 inches; withdrawal force given is for both legs.

Staples.—Staples as well as nails are used as pallet fasteners in warehouse and exchange pallets. Steel wire for these staples should be 15 gauge or larger and have a tensile strength of at least 120,000 pounds. The staples should be driven so the crowns make a 45-degree angle with deckboard grain and be countersunk 1/16-inch. Number of staples per joint are specified by pallet purchasers.

Stern (In press b) further compared the 2-½-inch-long, 15-gauge plastic coated staples described in footnote 3 of table 15 with the 3-inch nails described in footnote 2; he concluded that approximately three times as many 2-½-inch staples as 3-inch nails may be required to provide equivalent deckboard-stringer separation resistance in hardwoods in the axial direction of the fasteners. To replace 2-½-inch-long nails similar to the 3-inch nails, at least twice as many staples as nails may be required for equivalency. These comparisons assume that fasteners do not split deckboards or stringers during assembly. Field performance data for southern hardwood pallets assembled with such large numbers of staples are not available, however.

Kurtenacker (1973b) found that northern red oak joints of sawn lumber assembled with such staples did not perform as well in static loading of pallet corners as did an equal number of 2-¼- or 2-½-inch pallet nails; in impact tests, however, corners with the plastic-coated staples performed as well as, or better than, nailed corners. Kurtenacker (1975a) concluded that for fastening northern red oak deckboards of knife-cut, parallel-laminated veneer, such staples performed satisfactorily if about five staples were substituted for every three pallet nails.

Performance of staples in 22 southern hardwoods.—The effectiveness of the 2-½-inch staples was evaluated in southern hardwood deckboard-stringer joints by E. G. Stern (1976). Test conditions were the same as those described for table 22-15. Staples in Stern's test had semi-flat legs (0.067 by 0.073 inch), short symmetrical chisel points, and were driven by an air-gun, one per joint.

Crown pull-through resistance, which averaged 614 pounds (table 22-15) was minimum in yellow-poplar (456 pounds), sweetbay (463 pounds), and sweetgum (513 pounds); it was maximum in winged elm (811 pounds) and red maple (773 pounds).

Leg withdrawal resistance, which averaged 257 pounds (table 22-15), was minimum in red maple (105 pounds), hackberry (120 pounds), and yellow-poplar (152 pounds); it was maximum in northern red oak (538 pounds), laurel oak (497 pounds), and Shumard oak (494 pounds). Leg withdrawal resistance from mockernut hickory was only 190 pounds, about the same as from sweetgum (188 pounds).

For these staples, forces (in pounds) were loosely correlated to wood specific gravity based on ovendry volume and weight (G), as follows:

$$\text{Staple-crown pull-through resistance} = 1{,}024G \qquad (22\text{-}3)$$

$$\text{Staple-leg withdrawal resistance} = 794G^{5/2} \qquad (22\text{-}4)$$

DECKBOARD AND STRINGER MANUFACTURE

Mount (1971) found that about 55 percent of the pallet manufacturers in West Virginia, Pennsylvania, and Maryland purchased random-length long lumber, about 35 percent random-length cants, and about 10 percent cut-to-size pallet shook. Since that time cutting of pallet shook from random-length cants has increased. Also since 1970, equipment has become available to economically cut lumber from short, low-grade hardwood logs (6 to 12 feet in length). Most recently, mills have been designed to rapidly make pallet shook from bolts cut to deckboard or stringer length (36 to 50 inches). Brief descriptions of these options follow.

From random-length long logs.—Sawmills appropriate for long hardwood logs are described in section 18-10, and chipping headrigs suited to hardwoods are discussed in section 18-9. Usually upper grades of lumber from such logs are sold to the furniture trade, and the lower grades are utilized for pallets, containers, flooring, and crossties. Lumber grade yields are tabulated in chapter 12. Readers interested in an economic feasibility study, with flow plan and illustrations of machines, will find Koch's (1957) analysis useful; although some of the machine designs have been improved during the years since this study was made, the flow diagrams are still appropriate for random-length hardwood logs of low grade.

From short logs.—Lumber manufacture from short logs is illustrated in figures 18-104ABCD, 18-105, 18-106, 18-109, and 18-113 through 18-123. Economic feasibility studies of the short log system in pallet manufacture are summarized in sections 28-3, 28-11, and 28-17.

From random-length cants.—Development of reliable, thin-kerf, circular gangsaws for hardwood cants (see figs. 18-76 and 18-77 and related discussion) greatly simplified pallet shook manufacture. By combining a cant infeed deck with a cut-off saw, a gang ripsaw, and a stacker, a two-man crew can saw and stack up to 4,000 board feet of pallet shook per hour. Numerous designs of these simple production lines are available; that illustrated in figure 22-37 is typical.

From deckboard- and stringer-length bolts.—Application of the shaping-lathe headrig should facilitate highly efficient use of low-grade small hardwoods. Crook and major defects are eliminated from stems by cross-cutting them to deckboard or stringer length (36 to 52 inches) before conversion. Operating principles of shaping lathe headrigs are illustrated in figure 18-104ABCD; economic feasibility studies of pallet manufacturing operations built around them are summarized in sections 28-17, 28-26, and 28-32. In one configuration, presorting of bolts for length and diameter ahead of the headrig is not necessary. The scanner and automatic setworks incorporated in the 54-inch machine permit it to process bolts of random diameters from 5 to 26 inches and lengths from 36 to 52 inches while automatically converting them to square, rectangular, octagonal, or cylindrical patterns to optimize yield at ripsaw or veneer lathe (fig. 18-104D top). Production rate is six or seven bolts per minute. Residue can be in the form of flakes (fig. 28-19) or pulp chips (fig. 28-20 bottom).

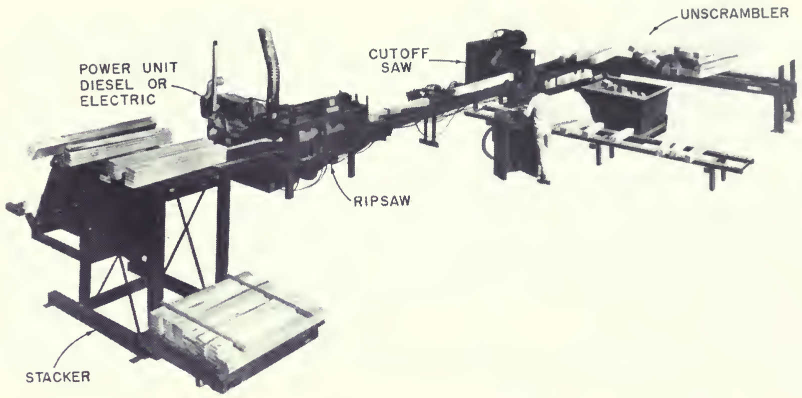


Figure 22-37.—Production line for feeding cants, crosscutting them to deckboard or stringer length, gang-ripping them into boards, and stacking the boards. (Photo from EZ Manufacturing Company.)

From thick veneer.—A bolt cut to deckboard length and rounded up as shown in figures 18-104C and 18-252, can be peeled into thick veneer (figs. 18-250 and 251) for parallel lamination into two-ply or three-ply deckboards. Hann et al. (1971) examined the economics of such an operation and concluded that pallet deckboards can be fabricated from red oak bolts by a process that combines rotary-knife cutting, press-drying, and gluing immediately after drying in a total processing time (log to dried pallet deckboard) of approximately 15 minutes. Yield of deckboards in their study was about 80 percent of log volume. They suggested that such a plant should be sized to produce daily enough deckboards for about 2,000 warehouse and exchange pallets.

Notching of stringers.—Stringer notches (see figure 22-24) are cut at high production rate by continuously feeding stringers transversely (and on edge) past peripheral-milling shaper-type cutterheads that cut the two notches in one pass. For plants requiring lower rates of production, machines are available that clamp the stringers singly and route or shape the two notches.

Chamfering of deckboards.—Many pallet designs call for chamfered lower deckboards (fig. 22-24) to ease entry of lift-truck forks. These chamfers are cut with shaper heads on hopper-fed machines.

PALLET ASSEMBLY

Hand assembly.—Stringers and deckboards can be manually assembled into pallets with no more equipment than hammers, nails, and an assembly table. To replace hand hammers, air-operated tools are available for rapidly driving nails and/or staples up to 3-½ inches in length; although easy to maintain and use, they require more expensive fasteners than bulk-purchased hammer-driven fasteners. If equipped with air-operated nail guns, two people should be able to assemble at least 160 GPC warehouse pallets (fig. 22-24) per 8-hour shift for a production rate of 10 pallets per man-hour (Nelson 1975).

Partially mechanized assembly.—Multi-head automatic nailing machines using bulk nails and multi-head automatic stapling machines using collated staples increase productivity per man, can be set to variable nailing and stapling patterns, countersink the fasteners, and can be economically justified at production rates of 400 to 500 GPC pallets (fig. 22-24) per day. Two machine operators should be able to produce about 400 such pallets in an 8-hour shift, i.e., about 25 pallets per man-hour.

Mechanized assembly.—Several more-or-less mechanized assembly systems are available that incorporate assembly jigs, multi-head nailers and staplers, pallet turners, and pallet stackers. Most are sufficiently flexible to accommodate either block or stringer designs in sizes from 30 by 30 inches up to about 60 by 72 inches.

In the system illustrated by figure 22-38 functions are as follows (refer to position numbers on the figure):

1. The jig is loaded with pallet shook, sent through the machine, and nailed. The jig returns to the loading position where the first pallet is lifted out, turned over, and placed in front of the jig, which is then reloaded for the second pallet.
2. The bottom boards are then placed on the first pallet and the jig is indexed through the machine automatically. When the jig reaches the rear of the machine, the finished pallet is released into a turnover device which turns it right side up for stacking.
3. The nail hoppers feeding the automatic nailer are divided so that short nails can be driven and clinched and long nails may be driven into blocks and stringers.
4. Automatic device to turn pallet over.
5. Automatic stacker; 2 to 30 pallets per stack.
6. Accumulator conveyor.
7. Index wheel with cams that automatically position the pallet for nailing, and control movement of the jig.

With this system, two men can produce approximately 600 pallets per 8-hour day, i.e., nearly 40 pallets per man-hour.

A fully automatic assembly line was introduced in the early 1970's, in which nailing machines operate on a continuous basis. The FMC Corporation's Fastline System includes two nailing machines, a pallet turner, an automatic stringer loading device, and deckboard positioning hoppers for each nailing machine. Stringers are automatically fed into the positioning systems. As the stringers pass below the bottom deckboard hoppers, deckboards are positioned on the stringers. Once positioned, the parts are nailed. The partial pallet is then turned over and conveyed beneath the top deckboard hoppers. Top deckboards are then nailed and the completed pallet stacked for removal. Three operators plus two inspectors man the production line which produces at rates from 2,000 to 3,000 pallets per 8-hour day, i.e., more than 50 pallets per man-hour.

Nelson (1975) described a simple mechanized pallet assembly line in which hand staple guns are machine mounted for automatic driving. The system,

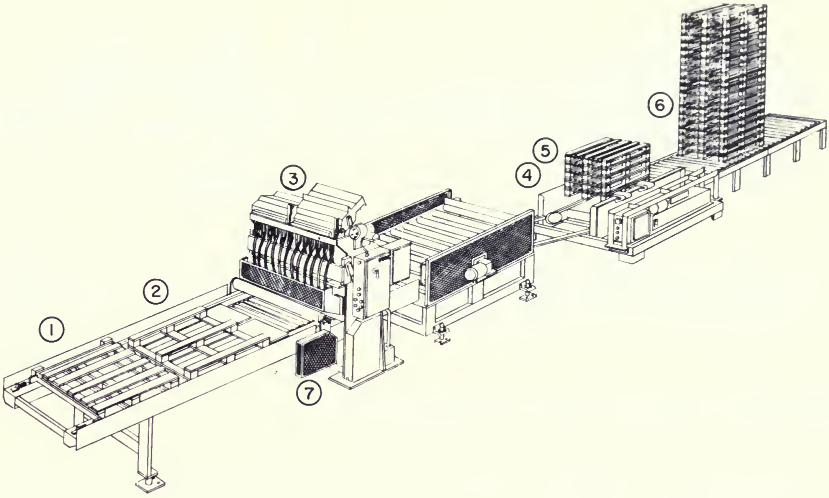


Figure 22-38.—FMC UNI-PAL system for mechanized assembly of nailed pallets. See text for functions associated with numbered locations. (Drawing from FMC Corp.)

manufactured by Nelson Enterprise, Inc., West Monroe, La., requires five operators: a stringer loader, two machine operators, and two inspectors. Production rate is reported to be 200 pallets per hour or 40 pallets per man-hour.

Still another mechanized production line is illustrated in figure 22-39; it produces about 150 pallets per hour with two operators plus one or two inspectors. Pallet manufacturers knowledgeable in the use of such mechanized lines estimate pallet reject rates at 2 or 3 percent, all of them repairable.

For further information on pallet manufacturing procedures, readers are referred to Eichler (1976) and USDA Forest Service, Forest Products Laboratory (1971). Also, the U.S. Forest Products Laboratory, Madison, Wisconsin periodically prepares lists of their publications related to pallet design, performance, and manufacture.

PALLET MANUFACTURING—COST DISTRIBUTION

Sendak (1973) found that 56 pallet manufacturers in Pennsylvania made a gross profit of about 5 percent on sales; lumber accounted for 50 percent of pallet sales price, nails 4 percent, and labor 19 percent. The remaining 22 percent went for other variable costs (10 percent), rent and depreciation (3 percent), and administration, taxes, and other fixed costs (9 percent). These proportions varied significantly according to degree of plant mechanization.

Chapter 28 includes economic feasibility analyses of six pallet manufacturing operations, variously mechanized, including one that molds pallets from a flake-resin mixture (sections 28-2, 28-11, 28-17, 28-19, 28-26, and 28-32).

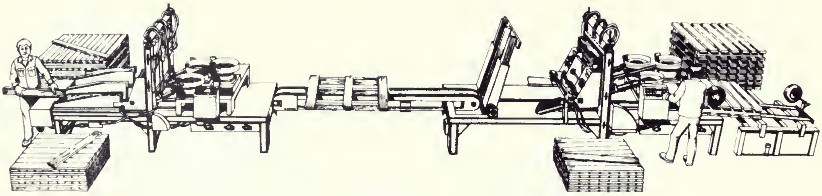


Figure 22-39.—Mechanized pallet assembly line incorporating two nailers, for manufacture of pallets 24 to 60 inches in length and 26 to 50 inches in width. (Drawing from Viking Engineering and Development Incorporated.)

RESIDUES FROM PALLET MANUFACTURE

As lumber cost represents close to 50 percent of the selling price of a wood pallet, knowledge of degree of utilization is essential to successful operation. (See also table 27-122A and paragraph *Yield of pallet cants and lumber* in subsection PALLETS, section 27-2.)

A small amount of the hardwood lumber purchased by pallet producers is sawn for the furniture and flooring markets. Such lumber is usually in thicknesses of 1 or 2 inches. National Hardwood Lumber Association standards allow rough boards to be sawn from ⅜- to ¾-inch-thick in ⅛-inch increments and ¾-inch to 2 inches thick in ¼-inch increments. The pallet manufacturer usually purchases cants and lumber in the thickness needed so that remanufacture is efficient. Cants are surfaced on two sides and resawn to final dimension. Hardwood pallet lumber is usually purchased to specified dimensions nominally 4 and 6 inches wide, and stringers to nominal 2- by 4-inch dimension. With good purchasing and manufacturing procedures, residues from surfacer and ripsaw can be minimal. Notching machines, trimmers, and cull boards create substantial residues, however. In a closely controlled operation, residues may total 12 to 15 percent of incoming wood. Not all operations are so efficient, however.

Perry (1976) analyzed residues from nine pallet plants in Ohio, Kentucky, Tennessee, and Alabama. He found that 30 to 40 percent of the weight of lumber admitted to production lines was converted to residues during manufacture of pallets. Six to 18 percent is lost as surfacing residue, 6 percent at the cutoff saws, and another 7 to 19 percent at the ripsaws. Five percent of the weight of end deckboards is converted to residues during chamfering, and 7 percent of stringer weight during notching (fig. 22-40).

Perry found that a thousand board feet of input lumber had ovendry weight and moisture content varying with species, as follows:

Species	Ovendry weight	Moisture content, ovendry-weight basis
	Pounds per thousand board feet	*Percent*
Oak	3,079	62
Sweetgum and black tupelo	2,950	77
Elm	2,918	48
Hickory	2,915	73
Ash	2,499	66
Yellow-poplar	2,468	65
Maple	2,412	70

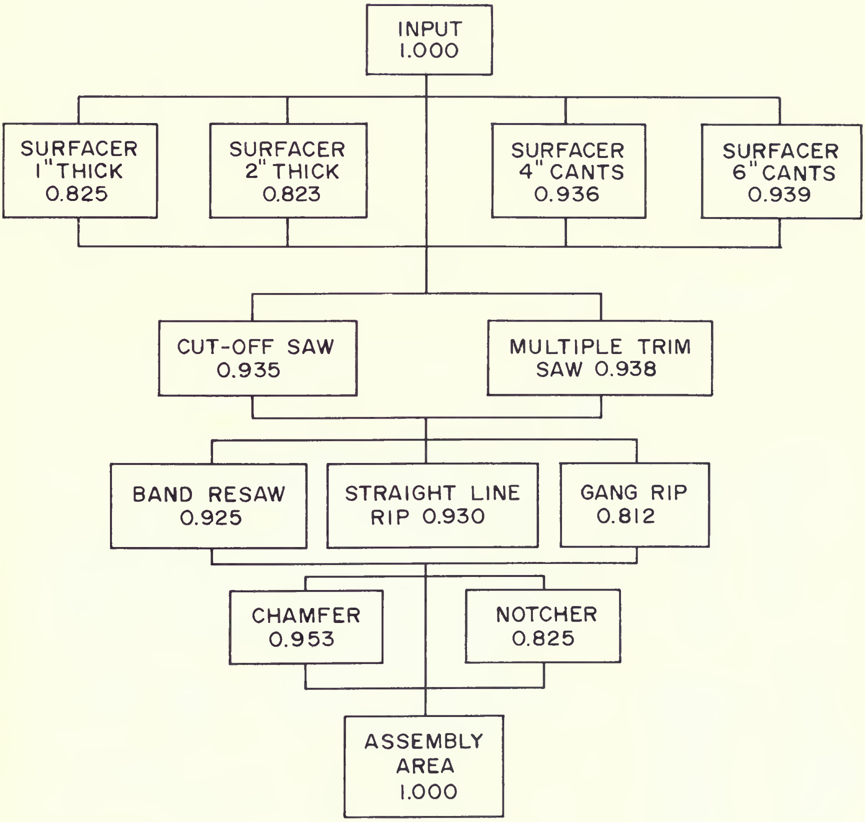


Figure 22-40.—Weight yield factors at various machines during conversion of hardwood lumber to assembled pallets. The yield factors are percentages in decimal form, i.e., 0.825 to 82.5 percent yield. (Drawing after Perry 1976.)

He found that the yields of deckboards from 1-inch lumber through surfacer, cut-off saw, straight-line ripsaw, and chamfering machine was 68.4 percent. Residue was 31.6 percent, which for each thousand board feet of oak lumber amounted to 972 pounds on an ovendry basis and 1,576 pounds green.

Yield of stringers manufactured from cants moving through the 4-inch surfacer to multiple trim saw, to gang ripsaw, to notcher was 58.8 percent. Residue was 41.2 percent, which for each thousand board feet of oak cants input amounted to 1,269 pounds for an ovendry basis and 2,055 pounds green.

Perry (1976) analyzed these residues by type and found that the largest percentage was shavings, and less than half of 1 percent was in culls, as follows:

Residue type	Proportion of total residue, by weight
	Percent
Shavings	66
Trim ends	15
Sawdust	10
Edgings	9
Cull	0
	100

PALLET REPAIR

Efficient unit-load handling with warehouse and exchange pallets requires a well-organized pallet repair program. Frost and Large (1975) found, from inspection of 1,700 damaged pallets at four repair centers, that missing deckboards at pallet ends account for more than 50 percent of total deck damage; longitudinal breaks and splits outside the stringer notches account for more than 80 percent of total stringer damage.

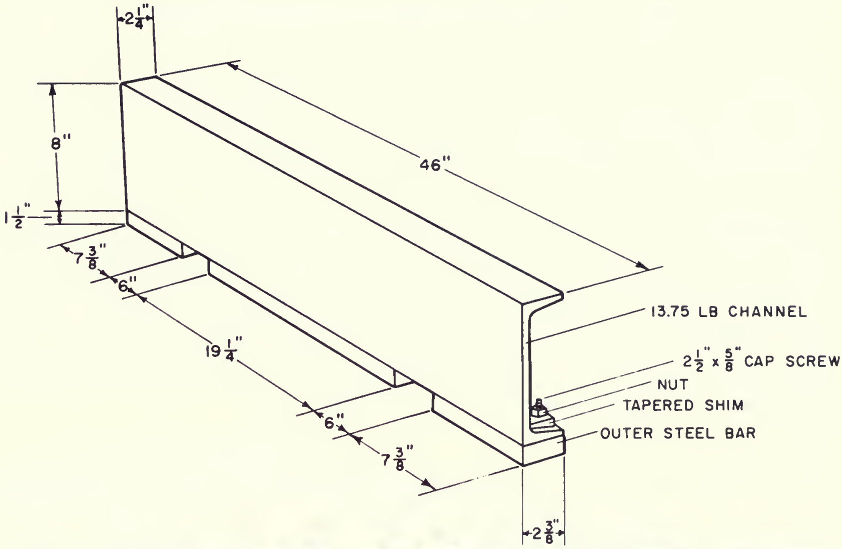
Frost and Large found that two-man crews, each with its own work table, pneumatic nail guns, hand tools, and repair parts, operating at a work station served by forklift trucks, could repair 30 to 40 pallets per hour—15 to 20 per man-hour.

One of the commercial repair and salvage companies dismantles pallets with a hydraulic machine which holds one deck of the pallet stationary while forcing the stringers away from that deck. Protruding nails are cut off with a grinder. The company salvages enough lumber to repair some damaged pallets and also to manufacture new ones. About 1,500 pallets are repaired per day; the company serves an area about 200 miles in diameter.

In 1974 a commercial pallet dismantling machine (an un-nailer) was introduced and assembly line equipment has since been developed. By 1980, pallet repair and recycling businesses were operational in most market areas.

FORKLIFT-TRUCK MODIFICATION TO REDUCE DAMAGE

Most damage to deckboards is caused by loads applied by forklift trucks during pallet handling, rather than by the product load. R. K. Stern (1973, 1975) found that use of an impact panel (fig. 22-41) to better distribute forklift-truck impact loads against stringer ends, rather than concentrate them on the deckboards, significantly reduced pallet damage.



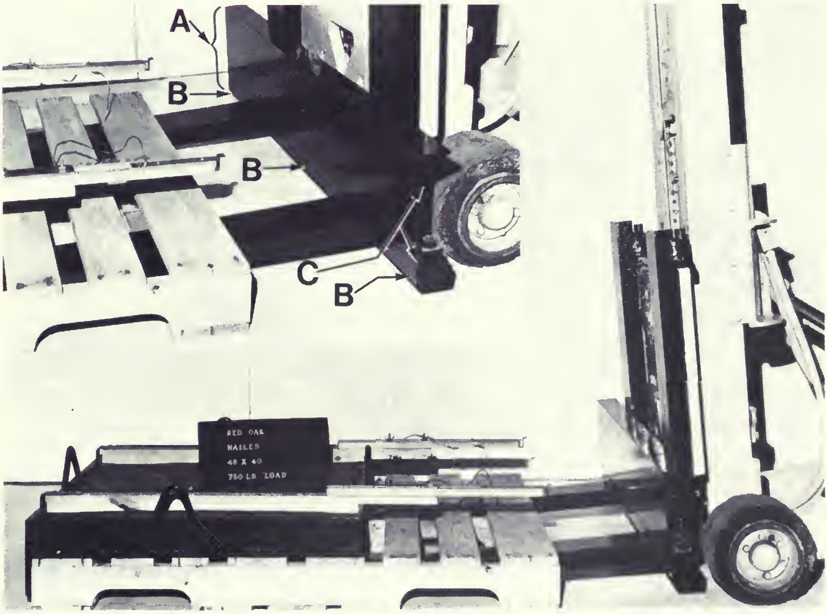


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Figure 22-41.—Modified fork tine assembly developed by the U.S. Forest Products Laboratory to lower unit stresses caused by handling. Inset: Detail of impact panel used in this research. (Photo and drawing from R. K. Stern 1975.)

OTHER REFERENCES

Readers needing additional information on pallet design, performance, and specifications are referred to the bibliographic listings[10] periodically published by the U.S. Forest Products Laboratory, Madison, Wis. and to the series of bulletins issued by Virginia Polytechnic Institute and State University's Wood Research and Wood Construction Laboratory, Blacksburg, Va.

22-8 CRATES AND CONTAINERS

Virtually all of the growth in production of pallets and containers is attributable to increased use of pallets; wooden crate production, while industrially very important, is not expected to increase substantially (fig. 29-18AB). Production of nailed wooden boxes and both tight and slack cooperage has declined significantly since the advent of kraft linerboard to make strong corrugated-paper boxes, and plastic, glass, and metal containers for liquids. Wire-bound and nailed veneer crates continue to be made in considerable volume, but face stiff competition from paper products. Veneer overlayed on both sides with kraft paper, however, can strongly compete with corrugated-paper boxes for some applications. This section is limited to supplying a few key references for readers interested in the manufacture of crates and containers.

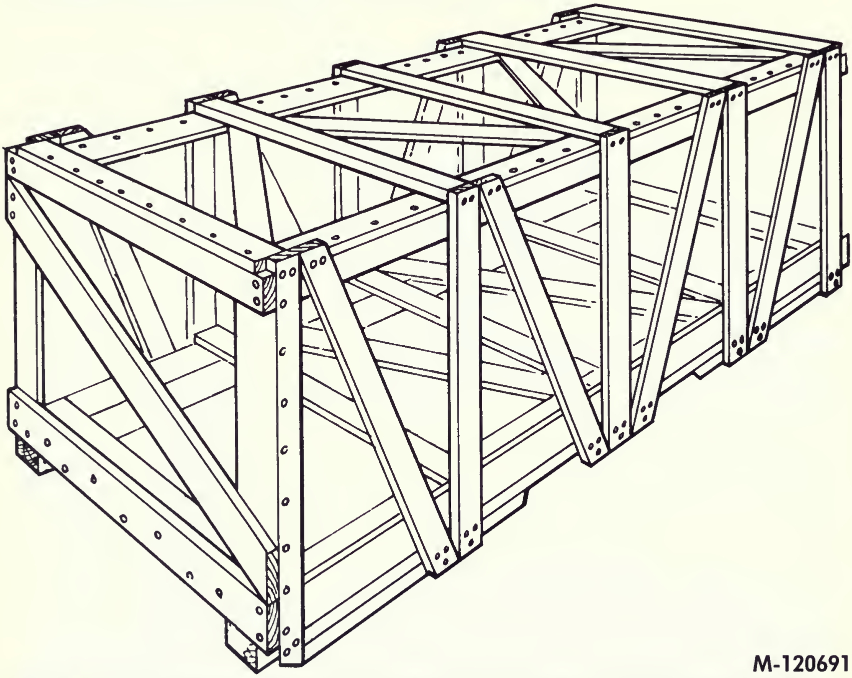

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Figure 22-42.—Typical open crate. (Drawing after Anderson and Heebink 1964.)

[10]U.S. Department of Agriculture, Forest Service. 1975. Forest Products Laboratory list of publications on wood containers and pallets. 10 p. U.S. Dep. Agric. For. Serv., For. Prod., Madison, Wis.

CRATES

A wood crate is a structural framework of members sometimes sheathed together to form a rigid enclosure, which will protect the contents during shipping and storage. A crate differs from a nailed wooden box, in that the framework of members in sides and ends provides the basic strength (fig. 22-42), whereas a box relies for its strength solely on the boards of the sides, top, and bottom.

Most crates manufactured in the United States are made of softwoods. It might seem, since crate components are typically short, that most of the pine-site hardwoods could be used more intensively. To make such usage viable, however, a system is needed for producing crate parts cheaply and promptly on order. Custom crate manufacturers typically prefer the long lengths obtainable in spruce, Douglas-fir, southern pine, and other commercial softwoods because these long lengths give them flexibility to instantly produce crate parts in a great variety of sizes.

Readers interested in crate design are referred to Anderson and Heebink's (1964) 131-page manual which describes and illustrates design of wood crates by engineering principles. The authors pay particular attention to construction of crate bases, tops, sides, and ends. Materials and other factors that affect crate design are discussed, as well as test methods, and loading and shipping procedures.

BOXES

Factories for manufacture of wood boxes (fig. 22-43) were, before World War II, a familiar feature in most communities, whether agricultural-rural or industrialized-urban. The success of corrugated containers caused the demise of many—perhaps most—of these enterprises. For some products, however, the wood box remains a viable competitor.

Readers interested in the design and construction of wood boxes are referred to the following publications:

Subject	Citation
Nailed and lock-corner wood boxes	USDA Forest Service, Forest Products Laboratory (1958)
Nailing better wood boxes and crates	Anderson (1959)
Wood containers and pallets, references	[10]
Preservative moisture-repellent treatment	Verrall (1959)
Preservative treatments for protecting wood boxes	Verrall and Scheffer (1969)
Wood beverage cases that cause little damage to bottle caps	Anderson and Miller (1973)
Assessment of common carrier shipping environment	Ostrem and Godshall (1979)

Odor and taste imparted to food by wood boxes.—In earlier days, it was common to pack butter in wood boxes, principally of yellow-poplar. Butter may

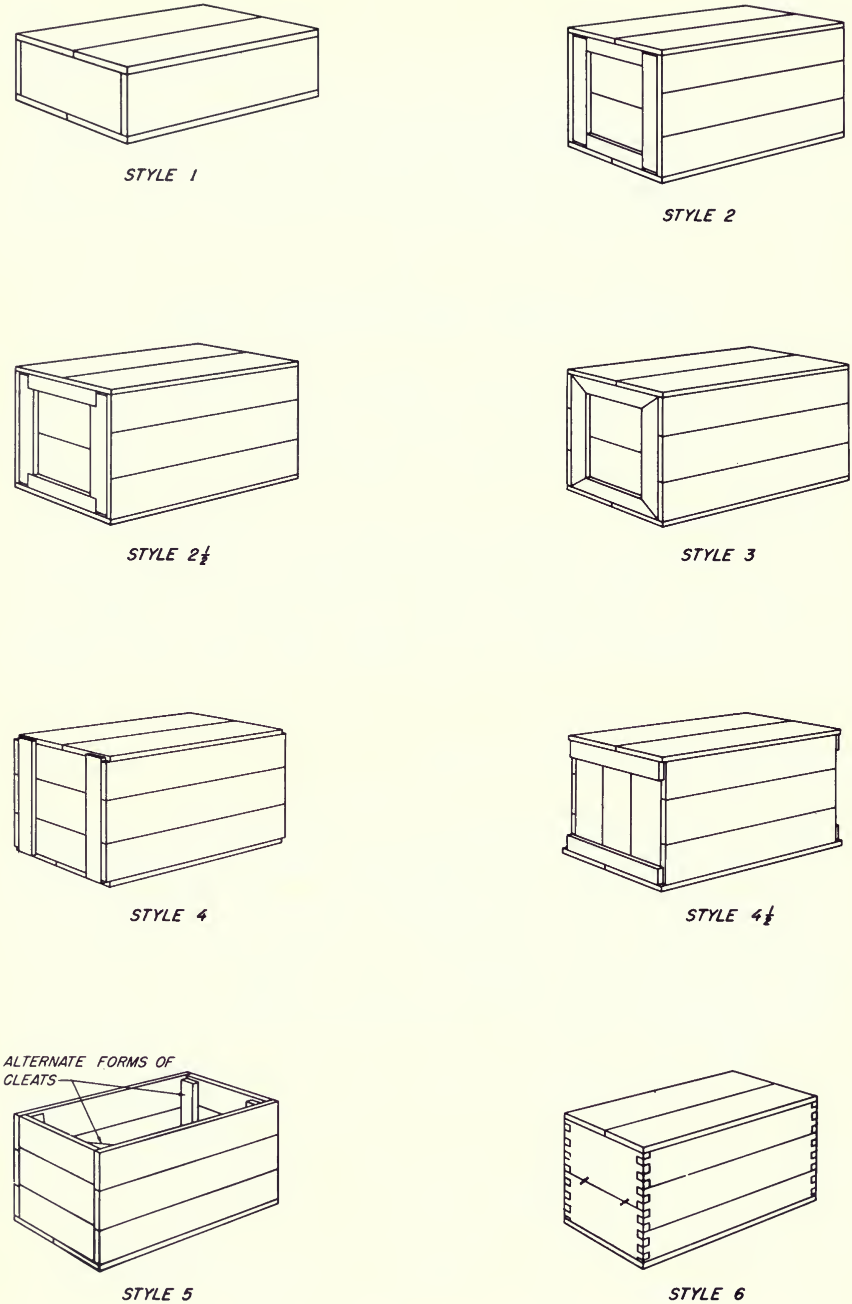


Figure 22-43.—Eight styles of wood boxes. Style 1 box has uncleated ends; style 2 box has full-cleated ends and butt joints; style 2-½ box has full-cleated ends and notched cleats; style 3 box has full-cleated ends and mitered joints; style 4 box has two exterior end cleats; style 4-½ box has two exterior end cleats; style 5 box has two interior end cleats; style 6 or lock-corner box. (Drawing after U.S. Department of Agriculture, Forest Service 1958.)

be contaminated in odor and taste by the wood of such boxes. Davis (1934) ranked 11 southern hardwoods according to the odor and taste they imparted to butter as follows (the best at top left and the poorest at bottom right):

Ash	Sycamore	Elm	Sweetgum (heartwood)
Soft maple	Beech	Black tupelo	Magnolia
Hackberry	Yellow-poplar	Cottonwood	

TIGHT COOPERAGE

In the early 1900's, roundwood used in the manufacture of barrels, kegs, pails, and tubs made of wood staves totalled about 1.8 billion board feet annually—about 40 percent in tight cooperage and 60 percent in slack cooperage (fig. 29-20). Since then, new technology, changes in consumer buying habits, and new packaging techniques have sharply reduced demands for cooperage. By 1976, consumption had dropped to 94 million board feet, mostly for tight cooperage. Over half the tight cooperage was used for bourbon barrels, with the remainder used for chemical and other containers. The slack cooperage was mainly used for barrels to contain food and hardware. Future demands for cooperage logs and bolts are expected to remain close to the level of the early 1970's at about 100 million board feet.

White oak is the premium species for bourbon barrels. Comparison of the tyloses plugged vessels of white oak (fig. 5-22) with the open vessels of southern red oak (fig. 5-39) make it clear why white oak is favored for tight cooperage. Because white oak staves for bourbon barrels typically come from high-quality trees of large size (fig. 27-20), their manufacture from pine-site hardwoods is not a major activity.

Readers interested in the technology of manufacturing tight cooperage are referred to the following publications:

Subject	Reference
Woods used in tight cooperage	Wagner (1949)
Production of barrels	Grant (1950)
Performance of laminated and solid staves in white oak tight cooperage	Kurtenacker and Patrick (1948)
Manufacture of tight plywood cooperage	E. G. Stern (1947a)

VENEER CONTAINERS

Veneer baskets.—A few small operations convert sweetgum, black tupelo, and cottonwood into veneer baskets ranging in size from 2-quart capacity to the traditional bushel basket. They are used to ship vegetables and fruit. To make the baskets, bolts are first conditioned by steaming, then debarked, rotary-peeled into veneer, and the veneer clipped to width. While still warm and flexible, the veneer strips are assembled into flat radially-oriented wagon-wheel-shape patterns; these flat assemblies are then bent into the typical basket shape and veneer hoops installed. After assembly the baskets are heated and dried so they will harden and retain their bent shape. Flat covers are also fabricated from veneer strips.

Veneer crates.—Sweetgum, black tupelo, and magnolia are commercially peeled to provide ⅛- and 1/6-inch veneer for stapled crates (fig. 22-44) to hold citrus fruit. Kurtenacker and Skidmore (1947) found that water oak veneer in these thicknesses is also suitable for such crates.

For a period following World War II, wire-bound veneer boxes and crates were manufactured in large quantities at many locations. They also, however, have lost ground to the corrugated box. Readers needing information on specifications and design of wirebound crates are referred to the bibliographic listings[10] periodically published by the U.S. Forest Products Laboratory, Madison, Wis.

Paper-overlayed veneer.—For produce containers requiring more strength than corrugated paper construction provides, veneer overlayed on both sides with kraft paper can be used (Anonymous 1976b). Boxes made of this composite material are resistant to moisture and strong enough to stack even when exposed to moisture. Readers interested in the manufacture and properties of paper-overlayed veneer are referred to Mohaupt (1959) and Clark (1954, 1955). Federal Specification PPP-V-205, obtainable from General Services Administration, applies to *veneer, paper-overlaid, container grade*. It would seem that short bolts of small pine-site hardwoods, converted to veneer by the procedure illustrated in figure 18-252, could provide an economical substrate for paper overlay.

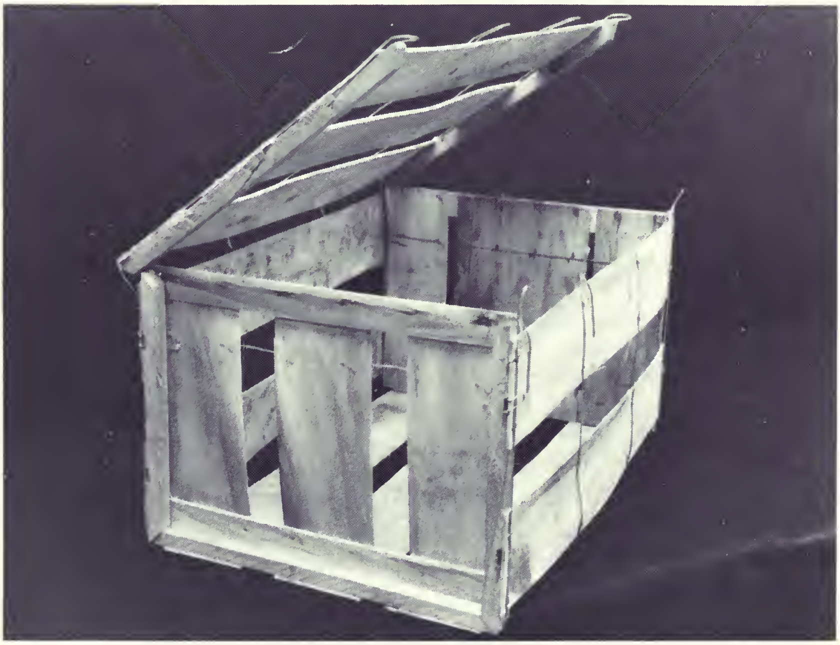


Figure 22-44.—A wire-bound lettuce crate made of ⅛-inch black tupelo veneer.

22-9 DECORATIVE VENEER AND PLYWOOD

Hardaway (1978) of the Hardwood Plywood Manufacturers Association, described the American hardwood plywood industry as relatively stable in the 1960's and 1970's (fig. 22-45). He found that domestic production peaked in 1972 at about 2 billion square feet (surface measure), but dropped to about 1.3 billion in 1975; by 1978 it was up to 1.5 billion. Slow growth in domestic production is forecast to the year 2030. For use volume by category see figures 29-36ABC.

Imports of hardwood plywood considerably exceed domestic production. From 1.6 billion square feet (⅜-inch basis) in 1963, imports grew to a high of 6.4 billion sq ft in 1972; by 1979 imports were 3.8 billion sq ft. During the peak import year of 1972, 97 percent came from Asia, more than three-fourths from Korea and Taiwan; over four-fifths of all imported hardwood plywood was lauan (Quinney and Micklewright 1974[11]). In 1978, about 84 percent of the imports came from Korea and Taiwan (USDA Forest Service 1980).

Quinney and Micklewright[11] found that in 1972 about 86 percent (surface measure) of the hardwood plywood produced domestically had a veneer core. It seems likely, however, that fiberboard, and flakeboard cores will be increasingly used for inner plys of hardwood plywood. (See sec. 28-23 and 28-24 for economic feasibility analyses of reconstituted cores in decorative plywood pan-

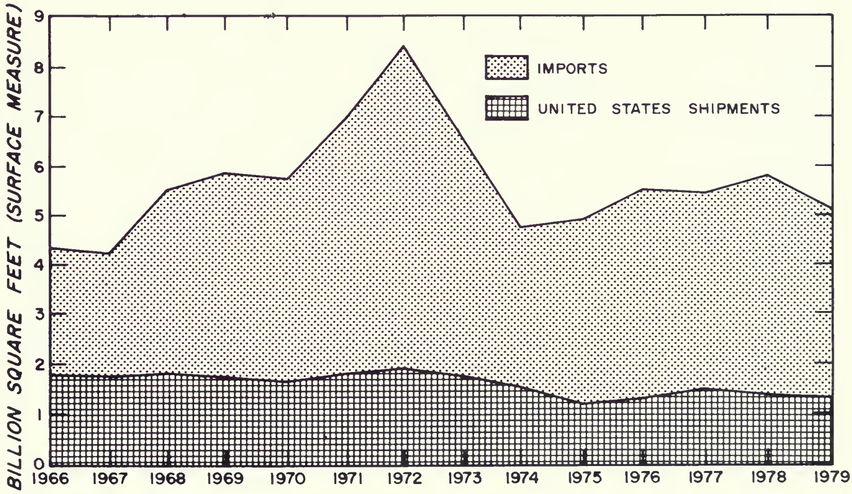


Figure 22-45.—United States consumption of domestically produced and imported hardwood plywood from 1966 through 1977. (Data from U.S. Department of Commerce, Bureau of the Census, Current Industrial Reports, Hardwood Plywood.)

[11]Quinney, D. N., and J. T. Micklewright. 1974. Markets and marketing of wood-based panel products in North America. Doc. No. 7, 19 p. Paper presented at the world consultation on wood based panels. Food and Agric. Org. of the United Nations.

els, and sec. 28-26 for analysis of an operation to make hardwood-veneer-faced structural panels with a flakeboard core.)

The Hardwood Plywood Manufacturers Association recognizes five product manufacturing groups within the industry:

- **Cut-to-size** flat and curved plywood parts are made for the furniture industry.
- The **prefinished-product** segment includes both the manufacturers of plywood blanks for refinishing and the companies that apply the finish.
- **Stock panels** are made in standard sizes, not prefinished, and are marketed for remanufacture, seldom for wall panelling. They are commonly ¾-inch thick. (See Lindell 1972 for an analysis of this market.)
- **Block flooring** is a 3-, 4-, or 5-ply laminated hardwood veneer product—usually measuring 9 by 9 inches.
- **Veneer,** manufactured for use in containers and remanufactured products, is warehoused, and distributed to a variety of industries.

Hardaway (1978) reported that there are approximately 167 plants manufacturing hardwood plywood in North America, and about 53 that prefinish it; some of these plants perform both operations. Lambert (1978) gave the following data on location of hardwood plywood plants in North America:

Location	Number of plants
Thirteen Southern States of United States	
Alabama	6
Arkansas	2
Florida	4
Georgia	5
Kentucky	4
Louisiana	2
Mississippi	5
Missouri	1
North Carolina	22
South Carolina	13
Tennessee	8
Texas	2
Virginia	13
Subtotal Southern States	87
Remaining states in Continental United States (18 in Wisconsin)	64
Canada	16
Total	167

For more precise data, readers are referred to the directory of producers of hardwood plywood periodically published by the Hardwood Plywood Manufacturers Association, Reston, Virginia.

Bertelson (1974) found that in the seven Mid-South States (Texas, Louisiana, Mississippi, Alabama, Oklahoma, Arkansas, and Tennessee), about half the hardwood veneer plants produced veneer for boxes, baskets, and hampers; and half produced veneer for other plywood products. Plants manufacturing container-grade veneer can use logs of smaller diameter and poorer grade than those cutting veneer for more exacting products.

Readers interested in an econometric model of domestic hardwood plywood and veneer markets are referred to a publication in preparation in 1982 by W. B. Wallin of the U.S. Department of Agriculture, Forest Service, Northeastern Forest Experiment Station, Princeton, W. Va.

PREFINISHED HARDWOOD PLYWOOD

Prefinished panelling is the major component of the hardwood plywood market. In 1972, 4.5 billion sq ft of prefinished hardwood plywood were shipped from domestic plants; almost 60 percent of this prefinished material was imported, however, and only about one-fourth of all prefinished hardwood plywood was produced in the same establishment that did the prefinishing (Quinney and Micklewright[11]). Prefinished hardwood plywood includes panels that are face finished on one or both surfaces by sanding (including scoring or grooving) and the addition of fillers, sealers, waxes, oils, stains, varnishes, paints, or enamels; this category also includes panels that have been overlaid with non-wood materials.

Mobile homes are a major market for prefinished hardwood plywood. In 1972, when 615,800 units were manufactured, each contained an average of 2,000 sq ft of hardwood wall panelling for a total consumption of 1.2 billion sq ft (Forest Industries 1974). Interior walls of recreational vehicles are another major market for prefinished plywood.

C. E. McDonald (1979) of the Hardwood Plywood Manufacturers Association concluded that the prefinished panelling market may have passed its peak and could enter a decline. Lauan and other tropical hardwoods are no longer inexpensive or readily available. Other pressures come from potential regulations limiting permissable combustibility of interior wall finish of mobile homes, and from concern over formaldehyde emissions from urea-formaldehyde glue bonds.

VENEER SPECIES CUT IN THE SOUTH

Bertelson (1974) found that in the seven Mid-South States, sweetgum, oak sp., yellow-poplar, and tupelo sp. accounted for most of the veneer log production (fig. 22-46), and that Alabama led the Mid-South in production of hardwood veneer logs with 60.7 million board feet—37 percent of the 162 million board feet total. Mississippi was next with 31.2 million, followed by Texas, Arkansas, Louisiana, Tennessee, and Oklahoma.

In the Southeast, Knight and Nichols (1964) found that North Carolina was the leading producer of hardwood veneer logs, with 140 million board feet—29 percent of the more than 484 million board feet total. Georgia ranked second, with 129 million board feet, followed by Florida, South Carolina, and Virginia. Southern bottomland hardwoods provided the bulk of veneer logs. Sweetgum and tupelo sp. supplied 60 percent of total production; another 20 percent was

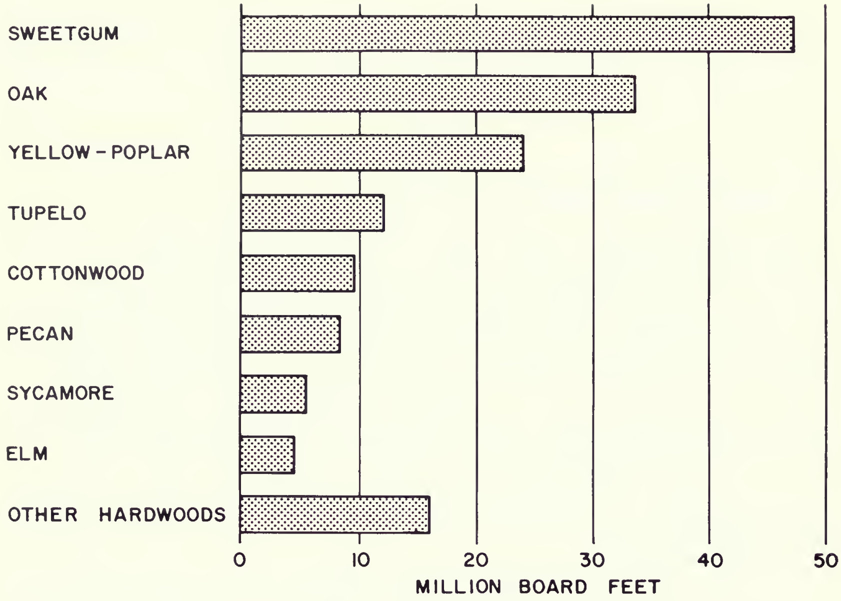


Figure 22-46.—Hardwood veneer log output in the seven Mid-South States by species, 1972. (Drawing after Bertelson 1974.)

yellow-poplar. Other leading species in order of volume produced were red oak sp., magnolia sp., white oak, and red maple. While data are not published, it is likely that by the early 1980's the percentage of oak veneer logs produced in the Southeast increased.

In the Tennessee Valley area, southwest Virginia, and southwest North Carolina, Harold (1976) found that annual growth of high-quality hardwood timber appropriate for veneer production exceeded annual cutting by nearly 40 million board feet (International ¼-inch log rule). Of this resource, oaks comprised about half and red maple, yellow-poplar, and hickory were important components.

SPECIAL PROBLEMS IN USING PINE-SITE HARDWOODS

Lutz (1975), in his study of the potential of pine-site hardwoods for veneer products, listed veneer-log requirements for four classes of decorative veneer products, as follows:

- Architectural face veneer

  Logs should be at least 15 inches in diameter, 12 to 16 feet long, with clear surfaces. Ash sp. and select oak sp. are among the pine-site hardwoods used.
- Prefinished panels

  Logs should be at least 15 inches in diameter, 8 feet long, and can admit occasional pin knots, burls, gum spots, and slight mineral streaks. Sweetgum, tupelo sp., and yellow-poplar are used as well as ash sp. and oak sp.

- Furniture veneer
  Logs should be at least 15 inches in diameter, 6 feet long, with at least three-fourths of the surface clear. Species used are the same as for prefinished panels.
- Finn-ply (thick plywood with one clear face, made from many thin plys)
  Logs should be about 11 inches in diameter, 4 feet long, and can admit knots to 1-½ inches in diameter, burls, stain, and bird peck, but should be 20 percent clear. Species could include hickory in addition to the species used for prefinished panelling.

Few pine-site hardwood logs have the diameter, length, and quality required for architectural face veneers. Some can meet requirements for prefinished panels—particularly those given a rustic finish. Because log lengths for furniture veneer are less—6 feet, or even 4 feet—a significant supply of furniture veneer bolts can be cut from pine-site hardwoods; moreover, as technology is developed (see figs. 18-251 and 252 and sec. 28-31) to peel logs 9 to 11 inches in diameter, it is likely that the pine-site oaks can furnish significant amounts of rotary-peeled furniture veneer for 4-foot panels. (See section 28-23 for an economic feasibility study of manufacturing southern hardwood, platen-pressed flakeboard cores for decorative hardwood plywood.)

Technology developed by plywood manufacturers in Finland may also be suitable for some pine-site hardwoods. Finn-ply is made in thicknesses up to and exceeding 1 inch from thin veneer cut from logs about 4 feet log and as small as 9 inches in diameter. Through use of retractable chucks, core diameters are only 2-½ inches. In a 1-inch-thick panel, only one sheet (the face) in 16 needs to be clear if veneer thickness is 1/16-inch. The round-up and rotary-peeling layout illustrated in figure 18-252 and sec. 18-31 is appropriate for such an operation. In the Finnish system, 4-foot-long veneers are scarf-jointed to yield veneers of desired length.

In addition to very high speed round-up machines equipped with scanners and accurate centering devices, and lathes equipped with retractable chucks and back-up rolls, manufacturing plants equipped to make Finn-ply or small furniture panels will likely be equipped for continuous feeding of veneer to veneer dryers, electronic sensing and clipping of defects, crossfeed veneer splicing, and automated glue spreading, panel assembling, pressing, unloading, trimming, and sanding.

Another veneer product that might have promise for pine-site hardwoods is thin (1/10-inch), narrow (3-7/16-inch), short (2, 3, and 4-foot) clear strips of rotary-peeled veneer dried and packaged in quantities adequate to cover a 32-square-foot area—the same as a 4- by 8-foot panel. This veneer, which is thin enough to cut with shears, is sold to consumers for home craft decorative purposes such as wall panelling glued in place to form mosaic or herringbone patterns. Species that appear suitable are white oak, ash, and perhaps sweetgum which can yield interesting color variations between heart and sapwood. A West

Coast company has had considerable success in marketing such a product made from western red cedar (*Thuja plicata* Donn ex. D. Don).

SPECIFICATIONS AND STANDARDS

Defects and grades of trees and logs, and the veneer cut from them are described in sections 12-5, 12-6, and 12-7. This subsection is concerned with product standards for hardwood decorative plywood, block flooring, and stock panels.

Decorative plywood.—Voluntary Product Standard PS 51-71 (U.S. Department of Commerce 1972) establishes marketing classifications, quality criteria, test methods, definitions, and grade-marking and certification practices for plywood produced mainly from hardwoods. Hardwood plywood panels are constructed with an odd number of plys to produce a balanced panel; all inner plys, except the core or center ply occur in pairs having the same thickness and grain direction (fig. 22-47). Face veneers may be randomly matched or specified in a variety of patterns (fig. 22-48). Veneers are graded as Premium, Good, Sound, Utility, Backing, or Specialty.

Premium grade veneer is smooth, tight-cut, and full length. When used as a face, and when it consists of more than one piece it is edge-matched with tight joints, in patterns variable among species and with veneer cutting technique as specified in the grading rules. Characteristics permitted are defined in the grading rules but in general include small burls, occasional pin knots, color streaks or spots, and inconspicuous small patches; however, knots (other than pin knots), worm holes, rough-cut veneer, splits, shake, and decay are not permitted. Sapwood is not permitted in some classifications, e.g., sweetgum selected for red color, or plain- and rift-sliced oak.

Good grade veneer is smooth, tight-cut, and full-length. When used as a face and when consisting of more than one piece, the edge joints are tight but need not be matched for color or grain; sharp contrasts, however, in grain, figure, or natural characteristics are not permitted between adjacent pieces of veneer. Characteristics allowed are defined in the grading rules, but in general include small burls, pin knots, color streaks or spots, inconspicuous patches and usual characteristics inherent in the species; however, knots (other than pin knots), wormholes, rough-cut veneer, splits, shake, and decay are not permitted.

Sound grade veneer is free of open defects, but need not be matched for grain or color (table 22-16). **Utility grade** and **Backing grade** veneer permit some open defects as specified in table 22-16. **Specialty grade** veneer can have characteristics as agreed upon between buyer and seller; wormy, birdseye, or pecky characteristics appropriate for wall panelling generally fall in this category.

Glue bonds in hardwood veneer are classified by their water resistance. Technical Type and Type I plywoods are most resistant (levels of joint shear strength and integrity after a severe cyclic-boil test are specified). Type II

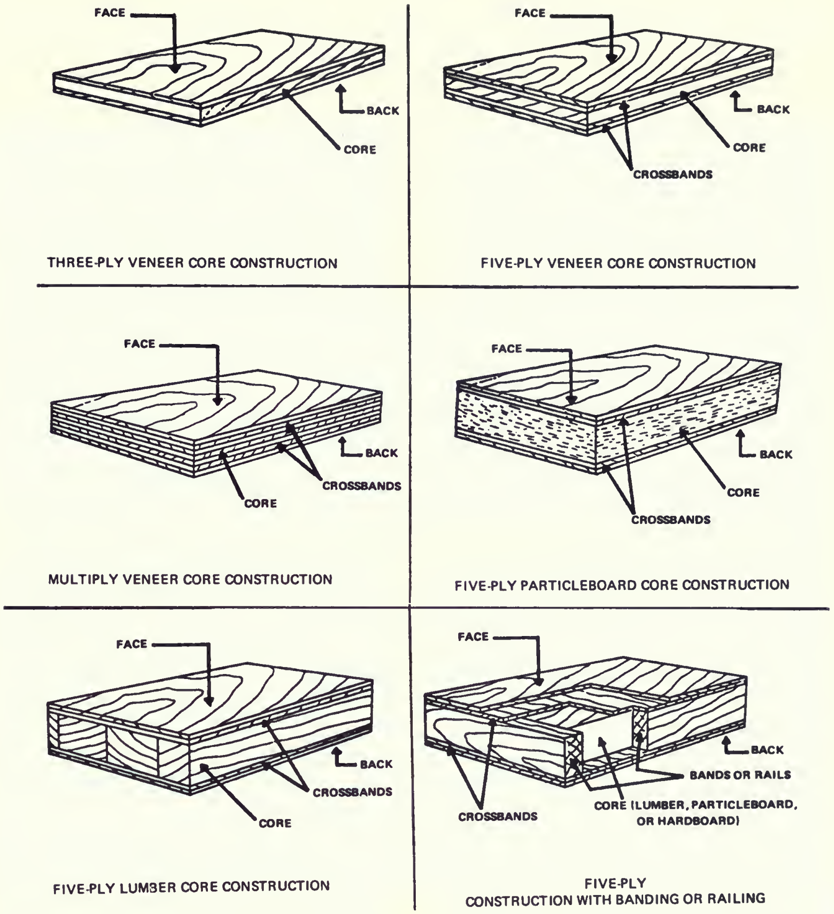


Figure 22-47.—Typical hardwood plywood constructions. (Drawing after U.S. Department of Commerce 1972.)

plywood glue bonds are intermediate and must withstand a three-cycle soak test. Type III plywood specimens need only withstand a two-cycle soak test.

Block flooring.—Laminated hardwood block flooring standard ANSI 010.2 dated 1975 (American National Standards Institute, Inc. 1975) establishes the specifications for this product which is commonly available in oak sp. (fig. 22-49) and ash—as well as other eastern hardwood species such as pecan, hard maple, birch, beech, walnut, and cherry. Conventional dimensions of flooring blocks are 9 by 9 inches square and 15/32-inch thick. Blocks are glue-laminated from three, four, or five plies of veneer; the grain of each ply is at right angles to the grain of adjacent plies, except in four-ply blocks in which the grain of the two center plies run in the same direction. In three-ply and four-ply construction, the face ply is at least 0.100-inch-thick after sanding; in five-ply construction, the face ply after sanding must measure at least 0.080 inch thick. Unfinished flooring blocks are usually square edged; prefinished blocks may be square-edged but are commonly tongued or grooved on all four edges.

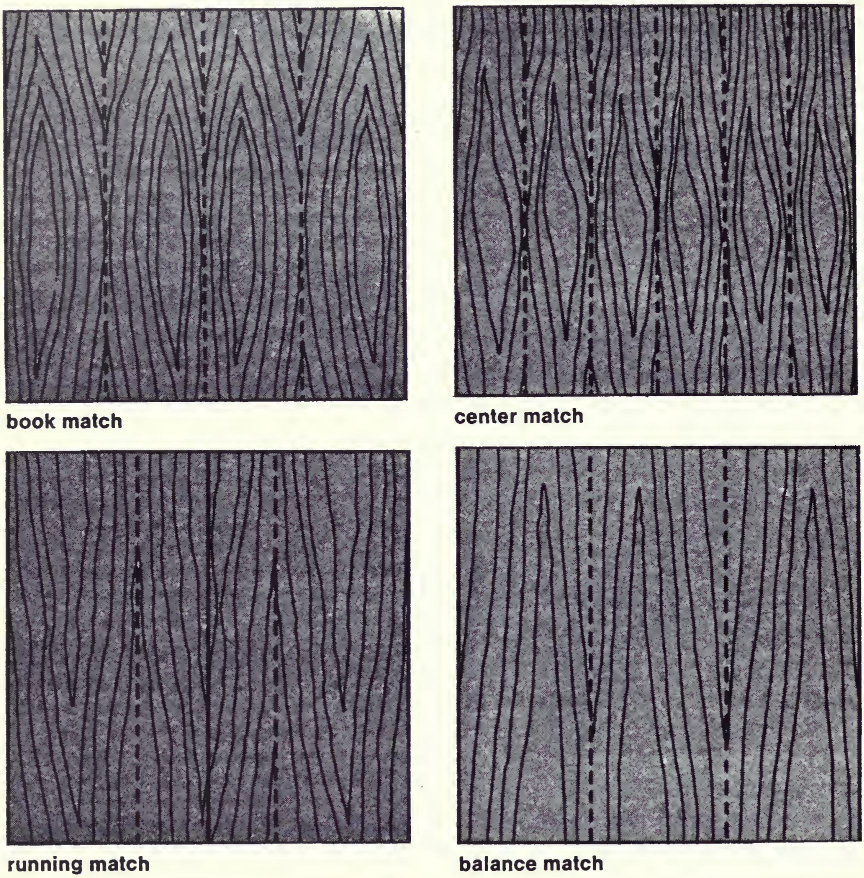


Figure 22-48.—Four patterns obtainable by matching veneers. (Drawing after Hardwood Plywood Manufacturers' Association.)

Stock panels.—Stock panels are manufactured in many combinations of length, width, and thickness. The common panel sizes, however, are 48 by 48 inches, 48 by 96 inches, and 48 by 120 inches; thicknesses range from ⅛-inch to 1-3/16 inches. For architectural woodwork, ¾-inch-thick panels predominate because edges may be splined, shiplapped, or otherwise readily fastened. Stock panels are made with four different core constructions, as follows:

Core construction	Usual panel thickness
	Inches
Lumber	½ to 1-¼
Veneer	⅛ to ¾
Particleboard	¼ to 1-3/16
Medium-density fiberboard	¼ to ¾

Stock panels made with lumber or veneer cores weigh less than those with particleboard or medium-density fiberboard cores, and have somewhat better screw-holding capability. Edges are most easily machined on panels with lumber or medium density fiberboard cores.

Wood flush doors.—Wood flush doors in a range of sizes are made, depending on intended use, in a wide variety of solid and hollow core constructions with wood veneer, plywood, high-pressure decorative laminate, hardboard, and composition faces. Standards for such doors are given in National Woodwork Manufacturers Association Industry Standard I.S. 1-78 *Wood Flush Doors*.

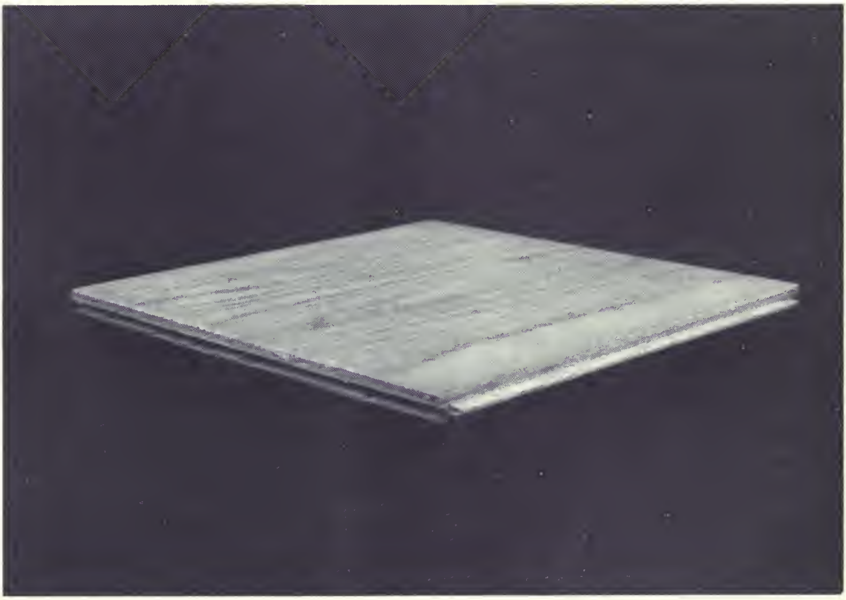


Figure 22-49.—Laminated oak block flooring; these 3-ply prefinished blocks measure 9 inches square and 15/32-inch thick. All four sides are provided with tongues or grooves to match adjacent blocks.

TABLE 22-16—*Veneer characteristics and allowable defects of Sound, Utility, and Backing grades of hardwood veneers* (U.S. Department of Commerce 1972)

Defects	Sound grade	Utility grade	Backing grade
Sapwood	Yes	Yes	Yes
Discoloration and stain	Yes	Yes	Yes
Mineral streaks	Yes	Yes	Yes
Sound tight burls	Maximim diameter 1 inch	Yes	Yes
Sound tight knots	Maximum diameter ¾-inch	Yes	Yes
Knotholes	No	Maximum diameter 1 inch	Maximum diameter 3 inches
Wormholes	Filled or patched	Yes	Yes
Open splits or joints	No	Yes; 3/16-inch for one-half length of panel	1 inch for one-fourth length of panel; ½-inch for one-half length of panel; ¼-inch for full length of panel
Doze and decay	Firm areas of doze	Firm areas of doze in face. Areas of doze and decay in inner plys and backs provided serviceability of panel is not impaired	Areas of doze and decay provided serviceability of panel is not impaired.
Rough cut	Small area	Small area	Yes
Patches	Yes	Yes	Yes
Crossbreaks and shake	No	Maximum 1 inch in length	Yes
Bark pockets	No	Yes	Yes
Brashness	No	No	Yes
Gum spots	Yes	Yes	Yes
Laps	No	Yes	Yes

LINEAR EXPANSION OF VENEERED FURNITURE PANELS

Excessive linear expansion and contraction across the grain of veneered furniture panels and decorative wall panelling causes joints to become visible and face veneer to crack as wood moisture content changes. This movement is controlled by the linear expansion coefficients of face veneers and cores perpendicular to the grain of the face veneers, and by the ratio of their thicknesses. Suchsland (1971), using an optical comparator, found that panels constructed with platen-pressed particleboard cores had lowest expansion coefficient; the addition of veneer crossbands (five-ply construction) did not further reduce expansion coefficients of such panels. Veneered lumber-core panels crossbanded with veneer (five-ply construction) were inferior to veneered particleboard core panels. Linear expansion of lumber core panels could be reduced, however, by increasing the thickness of the crossband veneers. Commercial fiber sheet crossbands showed less restraining effect than crossband veneer. (See chapter 23 for linear expansion data for fiberboards and section 24-10 for a discussion of linear expansion of flakeboards). In solid wood, linear expansion parallel to the grain is near zero. From green to ovendry, pine-site hardwoods average about 5.1 percent shrinkage radially across the grain and about 9.7 percent tangentially across the grain; low-density woods tend to shrink and swell less than those of high density (tables 8-9 and 8-12).

Lutz et al. (1976) evaluated five fibrous sheet materials for potential value as crossbands. None of the synthetic crossbands was as stable or strong in maximum tensile load as 1/20-inch yellow-poplar veneer in the grain direction.

SURFACE CHECKING IN VENEERED FURNITURE PANELS

Development of cracks or checks on the veneered surface of furniture, cabinets, and wall panelling is a major problem for producers of these items. Checks perpendicular to the grain or in an irregular or net pattern are usually defects of the finish coating and are not further discussed here.

Surface checks parallel to the grain are usually attributable to shrinkage of the face veneer in response to changes in its moisture content. Species with uniform anatomical structure, such as birch (*Betula* sp.) offer the most resistance to checking. Oak, with its large pores and wide rays has least resistance to finish checking; the wood rays and the boundaries between rays and vertical tissue are common avenues for extension of lathe checks to the surface. Large pores, with their maximum diameter in the direction of the thickness of flat-grain veneers, are frequently included in the path of developing checks (Keith 1964).

Keith (1964) and Jayne (1953) found that veneer should be cut with minimum penetration of lathe checks, since surface checks are traceable to their presence. Keith (1964) concluded that face veneers should be no thicker than about 1/20-inch, and that all panel components should be conditioned to a low moisture content before assembly; face veneers should be below 6 percent moisture content, core moisture can be somewhat greater. Veneer surfaces containing the lathe checks (the loose side) should be placed against the core, excess moisture should not be introduced with the glue, and excessive sanding of the assembled panel should be avoided. After assembly, during machining and finishing, panels should not be allowed to increase in moisture content above about 8 percent. During storage, shipment, and use, exposure to atmosphere of high relative humidity should be avoided.

22-10 STRUCTURAL WOOD

Softwoods dominate the market for structural wood. There are, however, some applications where hardwoods prevail—most notably for crossties, mine timbers, and highway posts. There are also economic trends developing that encourage consideration of some hardwoods (e.g., yellow-poplar) for structural lumber and a range of hardwoods for structural plywood and reconstituted panels.

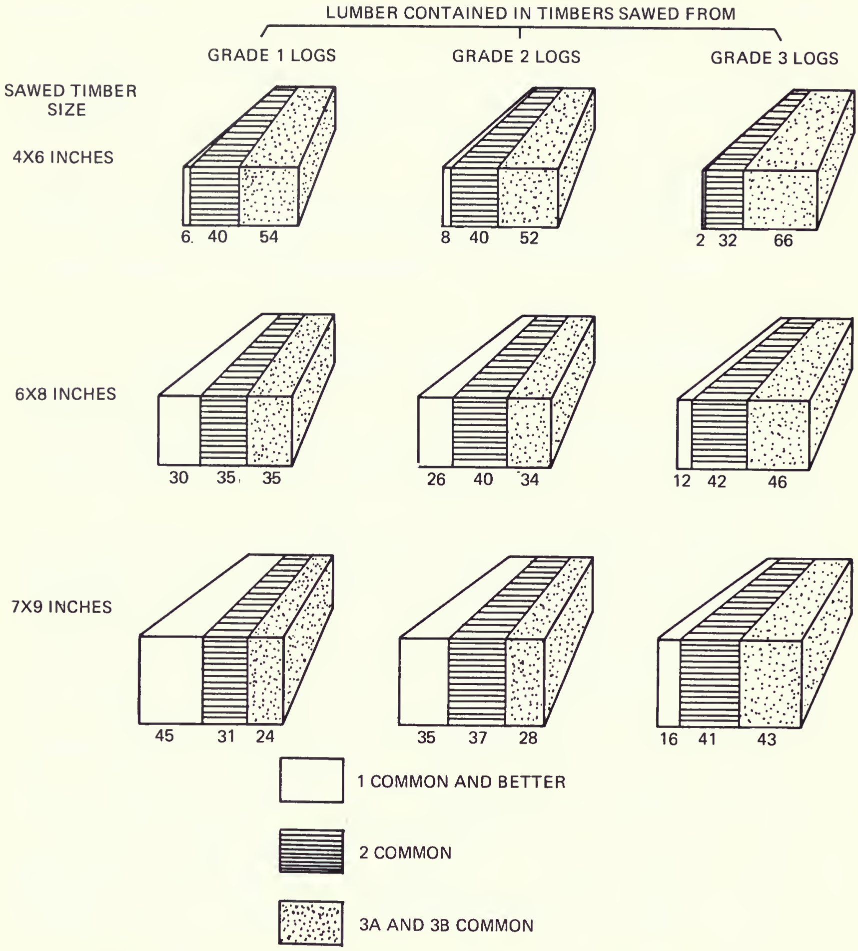


Figure 22-50.—Proportionate distribution of lumber grades in different-size timbers sawn from Appalachian hardwood logs of three grades—all species combined. (Drawing after Garrett 1969.)

TIMBER VS. LUMBER FROM LOW-GRADE LOGS

Some sawmill operators believe that central portions of low-grade hardwood logs should be manufactured into timbers or crossties; the argument for so doing is summarized in table 22-17 and figure 22-50. Typically, low-grade logs from pine-site hardwood trees contain high percentages of low-value 3A and 3B Common lumber which fails to return the cost of its manufacture. Most of this low-grade wood is in the center of the log and can be cut into heart-center cants for crossties or timbers, rather than into lumber of grades depicted in figure 22-50. Moreover, cant volume will exceed board volume by one-quarter to one-third (table 22-17). It takes less time to saw cants than boards, and the timbers are usually worth more per board foot than the mix of lumber obtainable from the central portion of a low-grade log.

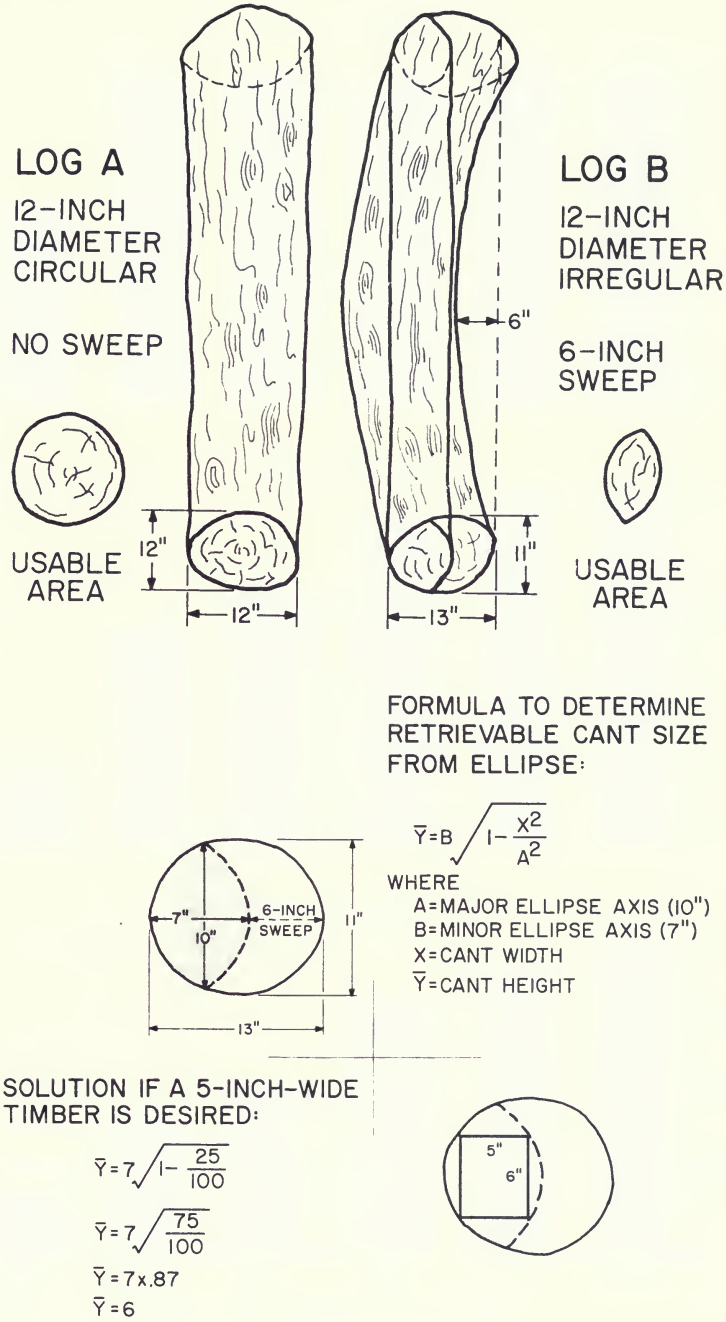


Figure 22-51.—(Top) Effect of sweep and shape on the portion of the log usable for manufacture of timbers. (Bottom) Method for computing maximum retrievable timber size. (Drawing after Garrett 1970.)

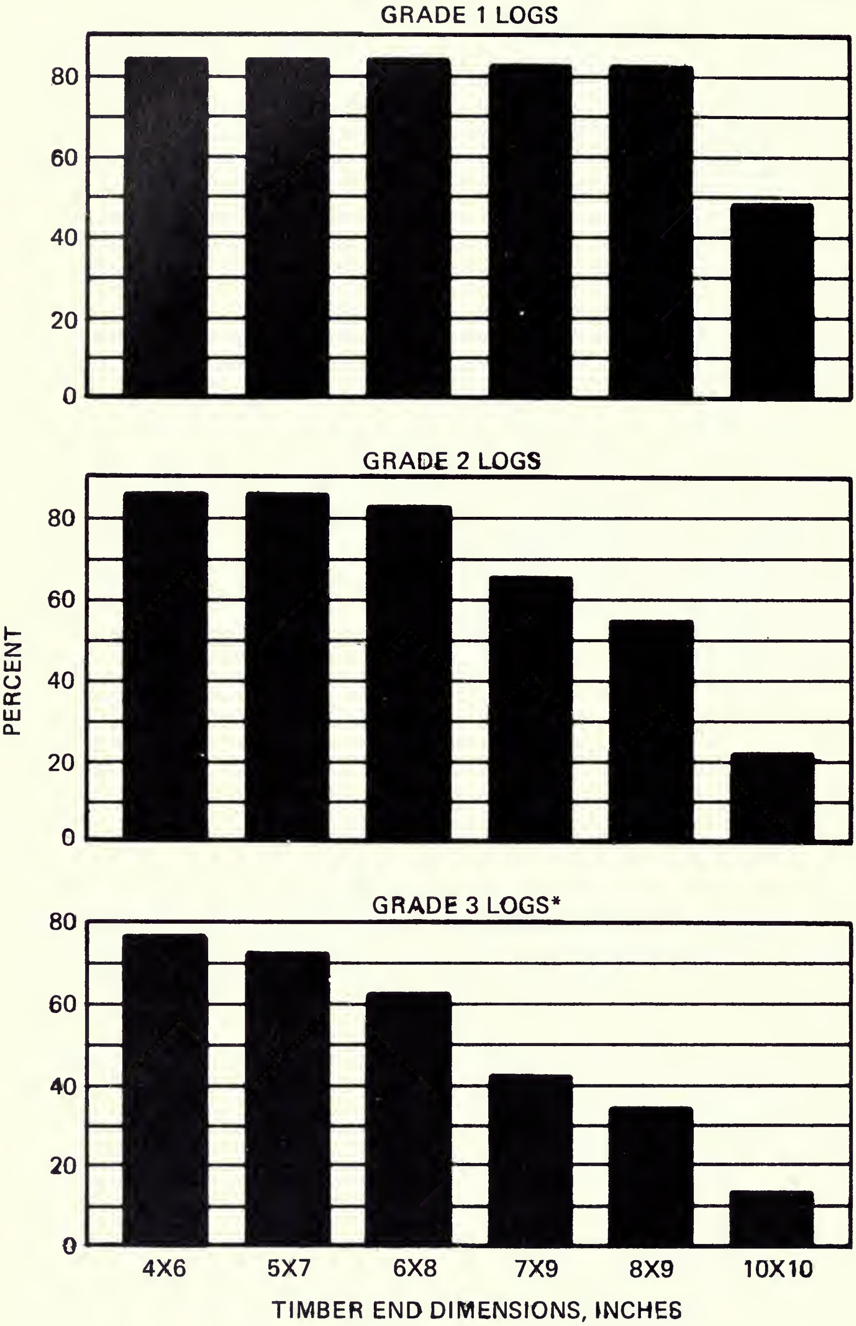


Figure 22-52.—Portion of Appalachian red oak, white oak, and hickory logs of three grades suitable for manufacture of various-size timbers. Grade 3 logs include construction and local-use logs. (Drawing after Garrett 1969.)

TABLE 22-17—*Comparison of cant volume and 4/4 lumber yield that can be sawn from 12-foot-long cants of various end dimensions* (Niskala and Church 1966)[1]

Cant end dimensions (inches)	Cant volume	4/4 lumber yield	Volume difference	Proportionate volume increase from cants
	Board feet			*Percent*
4 x 4	16.0	12.0	4.0	25.0
4 x 5	20.0	15.0	5.0	25.0
4 x 6	24.0	18.0	6.0	25.0
5 x 5	25.0	15.0	10.0	40.0
5 x 6	30.0	20.0	10.0	33.3
5 x 7	35.0	25.0	10.0	28.6
6 x 6	36.0	24.0	12.0	33.3
6 x 7	42.0	30.0	12.0	28.6
6 x 8	48.0	36.0	12.0	25.0
7 x 8	56.0	42.0	14.0	25.0
7 x 9	63.0	45.0	18.0	28.6
8 x 8	64.0	48.0	16.0	25.0

[1]Based on 1-⅛-inch-thick 4/4 hardwood lumber sawn with ¼-inch kerf.

The size timber obtainable from a log is related to both log diameter and sweep (fig. 22-51), and is therefore related to log grade. Considering mill-run diameters of Grade 3 logs cut from Appalachian red oak, white oak, and hickory, Garrett (1969) found that only 12 percent would yield 10- by 10-inch timbers, but 76 percent would yield 4 by 6's (fig. 22-52). When sawing 6- by 8-inch and 7- by 9-inch timbers from mill-run logs, Church and Garrett (1970) found that the percentage of logs yielding such timbers varied not only with log diameter but also among species (table 22-18).

Garrett (1969) concluded from his study that when markets for sawn timbers are available, the combined production of lumber and timbers from physically suitable logs will give greater dollar return than production of lumber alone. He further concluded that mill operators who engage in the dual production of lumber and timbers must carefully direct log-bucking and sawing practices to provide maximum income. If logs are bucked to conform to sawn-timber lengths, then potential dollar yields from high-value side lumber are sacrificed because of the preponderance of short boards. Conversely, if logs are bucked to produce long high-grade lumber, then overlength waste blocks from timbers reduce volume yield and dollar income. There is no perfectly satisfactory solution. However, when a sawmill operator has a choice, he should saw timbers from those species and log grades that normally would give him the lowest hourly return if sawed exclusively into lumber.

Putnam's (1959) analysis of dollar returns from southern oaks and gums cut for lumber alone or for lumber plus railroad timbers supports Garrett's conclusions.

TABLE 22-18—*Percent of mill-run hardwood logs of three species suitable for the production of full-length 6- by 8-inch and 7- by 9-inch timbers, by scaling diameter* (Data from Church and Garrett 1970)[1]

Sawlog diameter (inches)	Red oak		White oak		Hickory	
	6 x 8	7 x 9	6 x 8	7 x 9	6 x 8	7 x 9
	Percent of logs					
8	0	0	—	—	0	0
10	8	0	31	0	37	3
12	70	38	78	32	81	33
14	77	75	80	77	82	77
16	84	84	77	77	72	72
18	84	84	70	70	73	73
20	81	81	75	75	71	71
22	80	80	—	—	0	0
24	75	75	25	25	—	—
All diameters	71	62	72	56	75	52

[1]Based on measurements of more than 1,100 Appalachian hardwood logs (including sugar maple, data for which are not shown), collected at three sawmills.

CROSSTIES

The manufacture of railroad crossties is an important segment of the eastern hardwood industry. Crossties account for 11 to 14 percent of the 7.5 billion board feet of hardwoods cut annually (table 22-19), using low-grade wood that is difficult to sell in other markets. Untreated 7- by 9-inch crossties usually sell at about two-thirds to three-fourths the price per board foot of No. 2 Common oak sp. in the South (Reynolds 1977). Only once between 1960 and 1980 did the price for crossties exceed that of No. 2 Common, and that only briefly during 1975 (fig. 29-45).

TABLE 22-19—*Proportions of all sawn hardwood in the United States*[1] *according to end use* (Data from Reynolds 1977)

End use	Year		
	1971	1972	1973
	Percent		
Furniture	34	33	29
Pallets	28	22	34
Containers and boxes	11	14	[2]
Crossties	11	14	13
Flooring	8	9	9
Laminated decking	3	4	8
Other	5	5	7
	100	100	100

[1]Hardwood volume sawn in the United States totaled about 7 billion board feet, lumber scale, in 1973 (fig. 29-15B).
[2]Included with pallets.

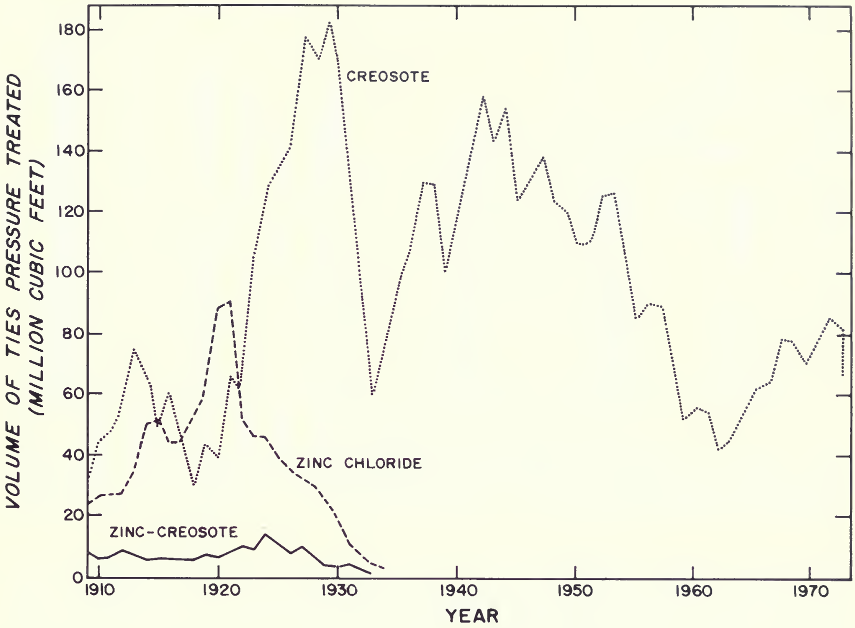


Figure 22-53.—Volume of crossties pressure-treated by three processes. (Drawing after Bescher 1977.)

Annual production.—Annual production of pressure-treated crossties peaked in 1930 at about 180 million cubic feet (fig. 22-53), reached a second lower peak of about 150 million cubic feet during World War II, and was at a low of about 40 million cubic feet in the early 1960's; by 1979 volume rose to about 122 million cubic feet. Figure 29-21 shows that the number of ties put in place in the United States dropped sharply from over 40 million in the latter years of World War II to about 12 million in 1961, and then rose slowly to about 24 million by 1979. Industry sources (Reynolds 1977) estimate that the market for crossties through the late 1980's will range from a low of 20 million to a high of 35 million pieces; at 40 board feet each, sawn tie volume might therefore range from 0.8 billion board feet to 1.4 billion board feet—in any event probably not exceeding 20 percent of total annual sawn hardwood volume.

Species.—Oaks predominate in use for crossties (fig. 22-54); sweetgum and tupelo sp. are also much used. Other pine-site species used for crossties include ash, elm, and red maple. For an indication of relative durability of creosoted crossties of these species, see figure 22-55 top. Although not charted in figure 22-55, hickory is also acceptable (Kemp 1951). Each railroad buys the species it finds acceptable and affordable; they commonly buy all of the acceptable species offered in the proportions they occur on the woodlands being cut.

Sizes and specifications.—Each railroad has specifications for the crosstie and switchties that they purchase, but they are not uniform among companies. Some standardization, however, is provided by the National Hardwood Lumber

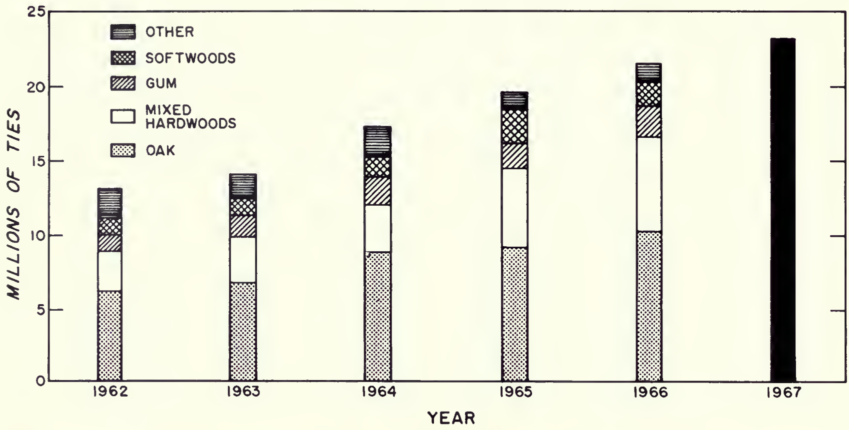


Figure 22-54.—Number of crossties treated annually in the United States, 1962-1967. Species categories indicated for 1962 through 1966. (Drawing after Smith 1968.)

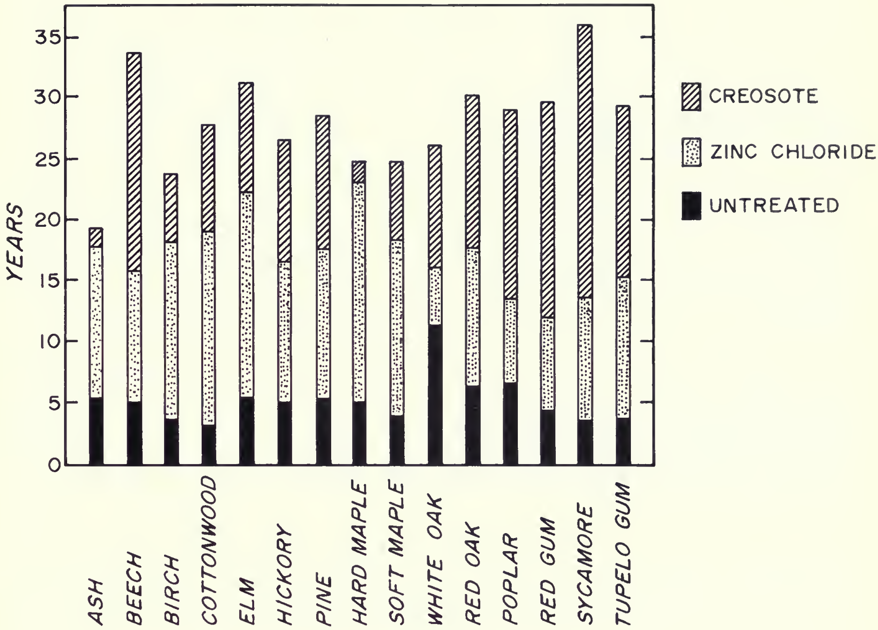
Association (1965) specifications governing crossties and switch ties, as adopted by the Railway Engineering Association (functioning also as the Engineering Division of the Association of American Railroads), which have been made an "American Standard" by the American Standards Association. Cross-sectional sizes of ties manufactured under this Standard are shown in table 22-20. The Standard also contains details of straightness (a straight line along a side from the middle of one end to the middle of the other end must everywhere be more than 2 inches from the top and bottom surfaces), depth of axe or saw-tooth marks (not more than ½-inch), taper between top and bottom surfaces (not to exceed ½-inch), decay (blue stain permissable), shake (allowed if its length does not exceed one-third the tie's width), and split (one which is not over 5 inches long allowed, provided anti-splitting devices are applied).

On switch ties, a large knot whose diameter exceeds one-fourth the width of the surface on which it appears may be allowed if it occurs outside the section between 12 inches from each end of the tie, i.e., if it occurs on an end of the tie. On crossties, such large knots cannot occur within sections 20 to 40 inches from the middle of standard-gauge ties or 15 to 25 inches from the middle of narrow-gauge ties.

Readers interested in specifications of crossties should also consult AREA specifications (Association of American Railroads 1980-81) published by the Association of American Railroads.

Ballast for crossties.—Crossties serve best if they are installed on **ballast** of crushed hard rock usually measuring ¾-inch to 2 inches in diameter, and of sufficient depth (12 to 18 inches) to firmly support the tie and give it adequate drainage. Stability of the ballast determines the loading mode of crossties (fig. 22-56).

Tie spacing.—Crossties are normally centered 19-½ inches apart on mainline tracks—3,250 per mile; many segments of mainline track, however, have spacing of 21-¼ inches.



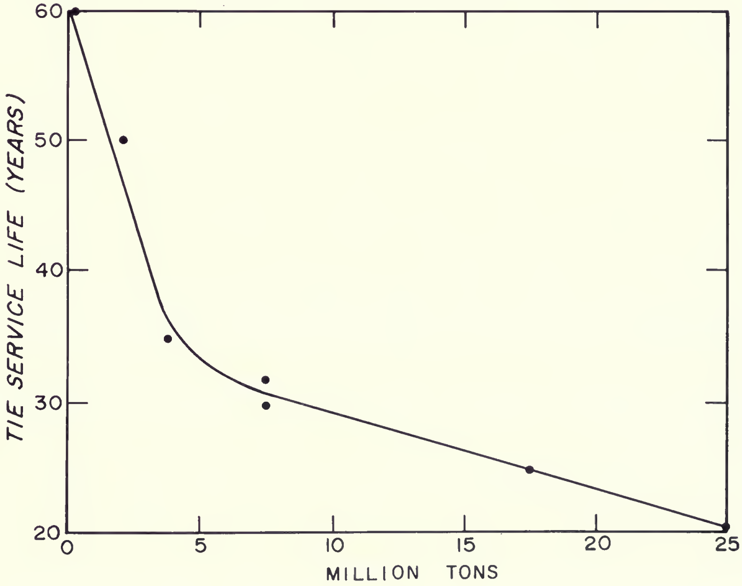


Figure 22-55.—(Top) Service life of crossties of 15 species, untreated, zinc chloride-treated, and creosoted. (Bottom) Relation of traffic to service life of creosoted crossties. (Drawing after Bescher 1977.)

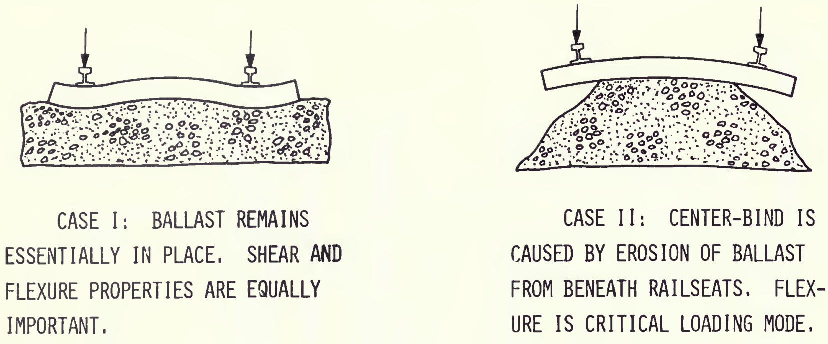


Figure 22-56.—Stability of ballast determines loading mode of crossties. (Left) With ballast in place, shear and flexure properties are equally important. (Right) Center-bind is caused by erosion of ballast from beneath railseats; flexure is the critical loading mode. (Drawing after Tschernitz et al. 1979.)

TABLE 22-20—*Size categories, thicknesses, and widths of sawn or hewn crossties and switchties* (National Hardwood Lumber Association 1965)[1,2,3]

Size category	*Sawn* or *hewn* on top, bottom, and sides		*Sawn* or *hewn* on top and bottom only	
	Thickness	Width on top	Thickness	Width on top
	Inches			
0[4]	5	5	5	5
1[4]	6	6	6	6
2	6	7	6	7
3	6	8	6	8
			7[5]	7[5]
4	7	8	7	8
5	7	9	7	9
6	7	10	7	10

[1]Each railroad will specify species desired.

[2]All thicknesses and widths apply to sections of the tie between 20 and 40 inches from the center of the tie for standard gauge, 15 and 25 inches for narrow-gauge. All determinations of width will be made on the top of the tie, which is the narrower of the horizontal surfaces, or the one with narrower or no heartwood if both surfaces are the same width.

[3]Each railroad will specify the size category desired in the lengths desired. The thicknesses, widths, and lengths specified are minimums. Ties more than 1 inch thicker, wider, or longer than specified will be rejected.

[4]None accepted for standard-gauge railway ties.

[5]Seven- by 7-inch ties are designated size 3A.

Methods to secure rail to crosstie.—Before pressure treating with creosote, top surfaces of crossties are machined flat (if necessary) at two locations to receive steel plates (fig. 22-57) which distribute vertical traffic loads over a larger area than the rail flange. The tie plates are also formed to restrain lateral movement of the rails and are generally perforated with four holes on each side of the rail location (eight in all) to receive spikes which secure the rail and plate to the crosstie (usually only two spikes are installed on each side of the rail). Tie plates vary in size depending on rail weight (9 to 138 pounds per lineal foot). For the lighter rails tie plates commonly measure 5 by 11 inches; for the heaviest rail, 7 by 12 inches—occasionally 7 by 16 inches.

Before pressure treating, ½-inch-diameter guide holes for spikes are drilled. The spikes, which typically are made of high carbon steel, measure 6 inches long, ⅝- by ⅝-inch in cross section, and have chisel points. Spike heads commonly measure 1-5/16 inches wide and 1-9/16 inches long. Force to withdraw such spikes immediately after driving in creosoted oak crossties is usually in excess of 4,500 pounds. Withdrawal resistance lessens after repeated loadings from passing trains. Readers interested in lateral resistance of steel rails secured to red oak crossties will find Murphy's (1979) analysis useful.

Crosstie life.—Bescher (1977) summarized available data on the life of the creosoted crossties installed in mainline tracks. Tests beginning in 1909 and 1910 by the Chicago, Burlington, and Quincy Railroad showed that untreated ties had a life of about 5 years; those treated with zinc chloride had lives of 15 to 16 years, and those with creosote 27 to 30 years. Tie life varied not only with treatment, but by species (fig. 22-55 top).

Crosstie life also varies significantly with the quality of track and ballast maintenance, and with severity of traffic; accordingly, crossties in tracks of a midwestern railroad that traditionally made a profit and maintained its tracks had service lives varying from 25 to 60 years depending on the amount of traffic (fig. 22-55 bottom).

Tie life is longest in side and yard tracks (60-year average), intermediate in branch lines (about 30 to 35 years), and shortest on heavily-used mainline tracks (about 25 years—possibly 35 years); on curved portions of mainline tracks, crosstie life is shortest. With increasing weight of rolling stock, this life is expected to drop to 20 to 25 years.

Howe (1979) noted that the life of a softwood tie was about 20 years in curves of 4 degrees and over on western sections of Canadian National Railroad tracks in the days of steam locomotives. The crosstie would continue to hold gauge (maintain correct distance between rails) after the respiking necessitated by one rail replacement and two transpositions (turning rails end for end to equalize rail wear). With the advent of multiple diesel engines pulling 50 to 150 cars each weighing 220,000 to 263,000 pounds, Canadian National's experience indicates a life of only 6 years for softwood crossties on mainline curved track sections carrying heavy commodity loads.

For further discussion of the service life of treated crossties, see sec. 21-4.

Reasons for crosstie failure.—Tie life depends in part on quality of track maintenance. Clean, large, well-tamped ballast tends to have less water in its lower levels, and therefore the crossties resting in the ballast change moisture content to a lesser degree between wet and dry weather than if the ballast contains fines and is not well-maintained. Changes in moisture content contribute to formation of splits and checks which are the major defects leading

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Figure 22-57.—(Top) Typical tie plate measuring 7 by 9 inches under 120-pound rail secured by spikes. The assembly is undergoing tests in a wear machine in which grit and water are dripped onto the rail section. It is usual to drive only two spikes on each side of the rail, even though each side of the tie plate has four perforations. (Bottom) Tie plate being spiked to an experimental 7- by 9-inch crosstie laminated from thick-sliced hardwood veneer. (Photo from files related to work of Tschernitz et al. 1979, courtesy of Koppers Company.)

to removal of treated ties from mainline tracks—particularly in oak (fig. 22-58). Some veteran observers of crossties in service conclude that the only way to reduce weathering of the top surface of a tie is to keep it wet continuously, with no opportunity to dry. This would suggest that poorly drained wet ballast might slow weathering of upper tie surfaces.

The causes for removal vary with species (table 22-21). After splits, the major causes for removal of treated hardwood mainline crossties are plate cut (fig. 22-59) and decay. Hardwood ties are far more resistant to crushing and shattering than those made of pine, although tie life appears not greatly different (table 22-21).

Perem (1971) found that in sugar maple (*Acer saccharum* Marsh.), the major seasoning checks usually form on the broad tie face nearest the pith and extend toward the pith in the planes of the rays. Perem found the most severe checking in ties with the pith about halfway between the broad faces; in such ties, an initial narrow seasoning check, present when installed, creates a plane of weakness along which repeated loading in service develops subsequent splitting. He concluded that the risk of splitting in service is least in boxed-heart ties with the pith less than 1 inch from a broad face, whether placed in the track with pith side up or down. No similar data for crossties of southern hardwoods are published.

Figure 22-58.—Badly split creosoted oak mainline crosstie.

Figure 22-59.—Plate cut in oak mainline crossties.

In addition to splits, plate cut, and decay in the crossties, the spikes may lose their ability to resist withdrawal when the rails flex under load; such failure is termed **spike kill** and is manifested by spike heads raised above the tie plate, and by loss of control of track gauge.

Readers interested in track maintenance will find useful the Railway Engineering and Maintenance Encyclopedia (Howson 1942).

Crosstie initial cost.—Josephson (1977) analyzed the initial cost of treated wood and of concrete crossties for heavily traveled mainline tracks (table 22-22). He found that wood ties with conventional tie plates and spaced on 19-½-inch centers have an installed cost of $34 each of $110,500 per mile; concrete ties on 24-inch spacing were predicted to have an installed cost of $60.50, or $159,720 per mile of track. Thus the wood ties on 19-½-inch spacing, with standard tie plates, cost only 69 percent as much as concrete crossties. If wood ties were spaced 21-¼ inches apart with conventional plates, cost per mile should be $101,400; if these more widely spaced wood ties were equipped with Pandrol fasteners (a system considered superior to conventional spikes), installed cost would be $127,000 per mile.

TABLE 22-21—*Causes leading to removal of treated mainline crossties during 1955 and 1956, related to wood species* (Data from Bescher 1977, based on those of C. J. Code)

Reason for removal	Oak sp.[1]	Pine sp.[2]	Sweetgum and tupelo sp.[3]	Mixed hardwoods[4]	Weighted average[5]
	Percent				
Split	66.6	5.2	38.9	47.1	36.8
Decay	12.2	16.9	38.2	19.3	18.2
Plate cut	9.4	21.9	.8	26.2	15.2
Crushed or shattered	4.1	33.5	4.5	.2	13.6
Spike killed	7.8	5.6	7.2	5.5	6.6
Natural defects	.6	12.4	.6	—	4.6
Derailment or dragging equipment	1.6	1.9	6.4	1.2	2.2
Tamp killed[6]	3.2	.5	.9	.5	1.6
Broken	.4	.2	.7	—	.3
Other	.1	1.9	1.8	—	.9
Total	100.0	100.0	100.0	100.0	100.0

[1]2,504 crossties from five railroads inspected; age of the youngest tie removed was 5 years, the oldest 33 years.

[2]2,270 crossties from three railroads inspected; age of the youngest tie removed was 9 years, the oldest 35 years.

[3]846 crossties from three railroads inspected; age of youngest tie removed was 7 years, the oldest 34 years.

[4]1,029 crossties from two railroads inspected; age of youngest tie removed was 10 years, the oldest 29 years.

[5]6,649 crossties from five railroads inspected; age of youngest tie removed was 5 years, the oldest 34 years.

[6]A tamp-killed crosstie has worn, rounded bottom corners; such a round-bottom crosstie will not restrain steel rails against expansion forces.

TABLE 22-22—*Installed cost of treated wood and concrete mainline crossties* (Data from Josephson 1977)

Item of cost	Wood ties 19-½-inch spacing 3,250 per mile	Concrete ties 24-inch spacing 2,640 per mile
	Dollars/tie	
Ties	14.50	32.00
Hardware	8.00[1]	8.50
Freight to site	1.50	4.00
Installation	10.00	16.00
Total	34.00[2]	60.50[3]

[1]Assumes reuse of two-thirds of the tie plates when relaying the line.

[2]Corresponds to $110,500 per mile.

[3]Corresponds to $159,720 per mile.

Annual cost per mile of mainline track.—Josephson (1977) also computed the annual cost of wood and concrete ties installed in a heavily travelled mainline track (table 22-23). He found that with 25-year life for the conventional wood tie system, annual costs were 77 percent of those computed for concrete ties with estimated 40-year life.

TABLE 22-23—*Annual cost per mile of treated wood and concrete ties at three tie life spans* (Data from Josephson 1977)

System and crosstie life (years)	Annual cost per mile	Cost index[1]
	Dollars	
Wood ties with plates, spikes, and 19-½-inch spacing		
20	11,255	84
25	10,352	77
30	9,815	73
Wood ties with plates, spikes, and 21-¼-inch spacing		
20	10,327	77
25	9,499	71
30	9,007	67
Wood ties with Pandrol[2] fasteners, and 21-¼-inch spacing		
20	12,938	97
25	11,900	89
30	11,284	84
Concrete ties, 24-inch spacing		
30	14,187	106
40	13,394	100
50	13,056	97

[1]With index of 100 for concrete ties at 40-year life.
[2]A fastener and plate system superior to conventionally spiked plates.

Dowel-laminated wood crossties.—The manufacture of a 7- by 9-inch crosstie 8-½ feet long calls for a minimum log diameter of about 13 inches. If such ties are dowel-laminated (no glue) from pieces 4-½ by 7 inches in cross section (fig. 20-12), they can be produced from logs only 8.3 inches in diameter. Tie halves can be dowel assembled when green (figs. 20-13 and 18-104D, bottom), air-dried, and treated as an assembly. More than 150,000 of such ties are in service—some for 20 years, and experience with them has been favorable. Research data on assembly procedures and dowel withdrawal forces are given in Howe and Koch (1976); a comparison of dowelling green versus dowelling dry is given in the text related to figure 20-13. Economic analyses of operations to produce dowel-laminated crossties can be found in Koch (1976b) and in section 28-18.

Crossties from parallel-laminated veneer.—Tschernitz et al. (1979) described the **Press-Lam** process for making crossties (fig. 22-57 bottom) which embodies stored-heat glue-laminating of thick-sliced veneer (0.25 inch or more thick) using the residual heat of the wood as removed from a veneer dryer. The ideal process is envisioned as a continuous conversion of green veneer into crossties. In a laboratory procedure simulating this process, they found that parallel-laminated-veneer railroad ties—from veneer in thicknesses up to 0.4 inch from Grade 3 logs of various hardwood species with or without butt joints (8.5- and 4-foot-long veneer lengths)—possessed physical properties consistent with the current specifications for solid wood ties. Species evaluated were northern red oak, white oak, water oak, sweetgum, black tupelo, hickory, and American beech (*Fagus grandifolia* Ehrh.)

Performance characteristics were being observed in three separate in-track test groups in 1979 (longest time interval, 5 years), at which date all were satisfactory. Creosote preservative treatment was adequate for all species and treating time was only about half that for solid wood ties. Tschernitz et al. concluded that the greatest problem in any manufacturing operation would be the maintenance of glue bond quality and hence shear strength, and that the viability of the product will likely depend on the economics of manufacture, not on the performance characteristics, which seem good. In 1979, the authors computed a manufacturing cost of $16.44 per untreated 7- by 9-inch crosstie.

Recycled crossties.—In the **Cedrite** process old crossties are recycled by reducing them to flakes, adding resin, forming the flakes, and pressing them into a high-density 7- by 9-inch crosstie that weighs 250 pounds (compared to a softwood crosstie which weighs about 160 pounds). Each tie contains two steel bars for reinforcement, one near the top and the other near the bottom; both are out of the spike driving area and reportedly do not interfere with signal circuits. Details of the process have not been published, but initial tests appear promising (Anonymous 1977).

Crosstie manufacture.—Manufacturing alternatives for producing crossties and timbers are numerous. Some of the headrigs available are described in sections 18-9 through 18-11. Drying procedures are described in chapter 20, and treating procedures in chapter 21. Readers interested in economic feasibility studies are referred to sections 28-18 and 28-32 in this text, and to Monahan (1976), Koch (1976b), and Garrett (1969).

Lumber and residue yields in crosstie manufacture.—Monahan (1976) related yields of lumber and residue to **lumber recovery factor** (number of board feet of lumber recovered per cubic foot of log, abbreviated as LRF), when cutting crossties and lumber from 13-inch diameter, 8-foot red oak logs having a density of 63 pounds per cubic foot. From a gross log weight per 1,000 board feet Doyle log scale of 14,063 pounds, he found that lumber recovery varied from 4,889 pounds at an LRF of 4.0 to 9,100 pounds at an LRF of 7.4 (table 22-24). Chapter 27 contains additional data of this nature for a range of log diameters and lengths (see page 3287 and tables 27-100, 27-109, 27-112).

Concrete crossties.—Howe (1979) reviewed the history of concrete crossties in the United States and Canada and found that their use was minimal in North America until 1972. In 1972, however, the Canadian National Railroad installed 10,000 British Rail type F-23 concrete ties in mainline track west of Jasper, Alberta. From October 1973 to December 1974, an additional five major test sections were installed in the United States and Canada. In the fall of 1976, Canadian National contracted for 1,500,000 additional concrete ties, and in 1978, AMTRAK awarded a contract for 1,100,000 concrete crossties to be

Figure 22-60A.—Equipment for placing concrete crossties in the Northeast Corridor mainline track of AMTRAK. (Photo from U.S. Department of Transportation.)

placed in the Northeast Corridor mainline track between Washington and Boston. These concrete crossties (fig. 22-60AB) weigh about 780 pounds each and in 1978 cost about $38 each, FOB manufacturing plant, including fastener components. Opinions regarding annual cost of wood versus concrete crossties vary; one economist believes that installed cost and annual cost of wood ties are both significantly less than those for concrete ties (tables 22-22 and 22-23). Service life for concrete crossties has not yet been established, but may be 40 to 50 years. To adequately support concrete crossties, a very hard ballast—e.g., **trap** rock from the Northeast with specific gravity of about 2.8—is commonly used; ballast depth must be 8 inches or more.

For further discussion of wood versus concrete crossties see: Mechanical Engineering. 1984. The track structure, an interview. Mechan. Engrg. 106(1): 44-47.

Landscape ties.—Landscape architects have found that treated crossties retired from rail lines make good retaining walls in gardens and terraces. Their use has become so widespread that there is a brisk market for timbers sawn particularly for this purpose. Because the landscape tie need measure only about 6 feet long and perhaps 6 by 6 inches in cross section, it can be sawn readily from small pine-site hardwoods. Treatment to inhibit decay is less critical for such timbers than for railroad crossties, and the selling price per cubic foot is frequently significantly higher.

Figure 22-60B.—Concrete crossties spaced 24 inches apart in the Northeast Corridor mainline track of AMTRAK. The crossties rest on trap rock ballast at least 8 inches deep and carry 140-pound rail. (Photo from U.S. Department of Transportation.)

TABLE 22-24—*Yields of lumber and residues from 1,000 board feet Doyle log scale—weighing 14,063 pounds—related to lumber recovery factor*[1] *when cutting crossties and lumber from 13-inch-diameter, 8-foot-long red oak sp. logs*[2] (Data from Monahan 1976)

Component	Lumber recovery factor							
	4.0	4.5	5.0	5.5	6.0	6.4	7.0	7.4
	Pounds							
Bark	1,062	1,062	1,062	1,062	1,062	1,062	1,062	1,062
Chips	6,769	6,158	5,547	4,936	4,325	3,846	3,103	2,906
Sawdust	1,343	1,343	1,343	1,343	1,343	1,343	1,343	995
Lumber[3]	4,889	5,500	6,111	6,722	7,333	7,812	8,555	9,100
	(−22%)	(−13%)	(−3%)	(7%)	(16%)	(24%)	(36%)	(44%)

[1]Lumber recovery factor (LRF) is the number of board feet of lumber recovered per cubic foot of log, measured inside bark.

[2]Density when green of 63 pounds per cubic foot of wood and bark.

[3]Values in parentheses are percentages of lumber yield overrun (or underrun if minus) from Doyle log scale.

MINE TIMBERS

Timbers for use in underground coal mines, primarily to support the roof in an opened coal seam are traditional hardwood products cut in the Appalachian bituminous coal region extending from central Alabama to northern Pennsylvania (fig. 22-61 bottom).

Round and split timbers are used for upright supports, while sawn timbers are used primarily for horizontal supports, mainly headers and half-headers. Sawn wood is also used for mine ties, floor planking, crib blocks, construction and repair, and a number of minor products (fig. 22-61 top).

Knutson (1970) found a direct relationship between the tonnage of coal mined and the volume of wood used in the mines. In 1967 an average of 1.00 board foot of sawn timbers and 0.54 lineal foot of round and split timbers were used for every ton of bituminous coal mined. In that year about 294 million tons of bituminous coal were produced from underground mines in the Appalachian region. To produce this tonnage, an estimated 295 million board feet of sawn timbers and 159 million lineal feet of round and split timbers were used. In 1979, bituminous coal production from the region was about 251 million tons.

Wood usage varies with thickness of the coal seam, nature of the mine roof and floor, purity of the coal, and competition from other types of roof support. The type of machinery used also affects timber usage, e.g., mines equipped with coal conveyors, rather than rail cars, do not use mine ties.

Knutson found that 1967 consumption of mine timbers in Appalachian bituminous coal mines was divided as follows with relative price index indicated:

Product	Measure	Relative price (if ties have index of 100)
	Million board feet	*Index*
Headers	107.4	82
Half-headers	79.4	81
Wedges	25.4	132
Crib blocks	31.3	64
Ties	25.6	100
Miscellaneous timbers	25.9	67

Additionally 159 million lineal feet of props were sold in 1967; a thousand lineal feet of props brought 72 percent of the sales price of a thousand board feet of mine ties.

Knutson (1970) found that most of the round and split prop timbers are 36 to 70 inches long; average length is about 53 inches, and average diameter about 6 inches. Other mine timbers measured about as follows:

Product	Thickness	Width	Length
	Inches		*Feet*
Wedges	⅛-1	4	1
Crib blocks	5	5	2-½
Half-headers	2	8	1-½
Headers	3	8	14
Ties	5	7	6
Miscellaneous	1	10	12

Some coal companies use pressure-treated timbers—particularly ties; the determination of which products are to be treated depends on the expected life of the mine.

Mine-timber specifications.—Coal-mine operators require timbers suitable for the intended use in the mine, manufactured to their standards, and structurally sound. Timson (1978a) summarized (table 22-25 and fig. 22-62) minimum characteristics of roundwood suitable for manufacturing sawn mine timbers and round and split props. Roundwood for mine timber production can be cut from hardwood logging residues. Timson (1978b) found that after a sawlog cut 44 percent of logging residue measuring at least 4 feet long and 4 inches in diameter outside bark was suitable for mine timber production, i.e., 26 percent of the limbwood and 58 percent of the bolewood residue. White oak, chestnut oak, northern red oak, hickory, yellow-poplar, and red maple were among the species studied.

Species preference.—Knutson (1970) found that each mine operator has his preference, but generally uses species available in the locality of his mine. Regional usage is about as follows, for sawn timbers:

Species	Proportion of total
Red oak sp.	55
Hickory	15
Yellow-poplar, basswood, and cucumbertree	15
Beech	6
Miscellaneous hardwoods	4
Pine and hemlock	5

Round and split props are primarily oak, hickory, and beech.

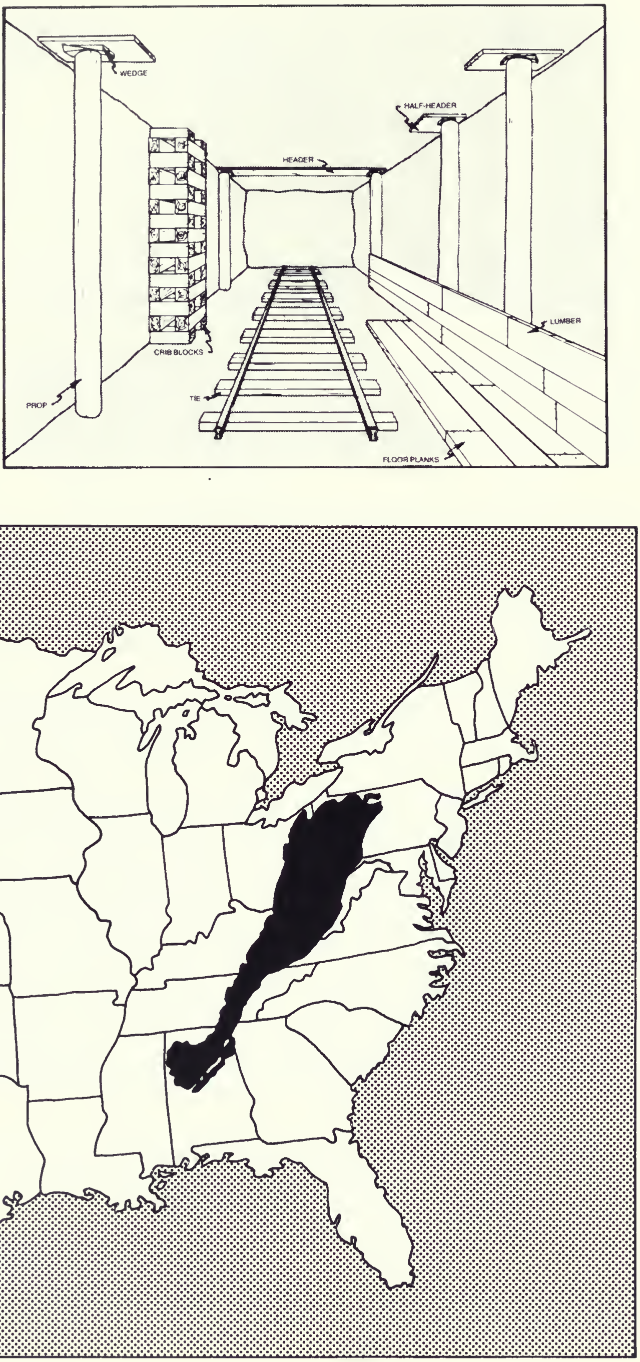
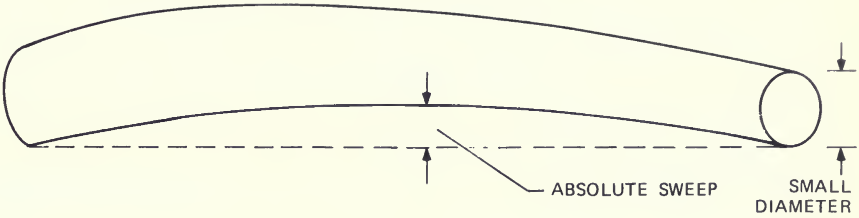


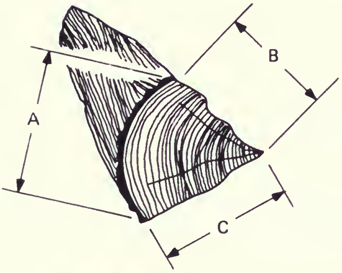
Figure 22-61.—(Top) Examples of timbers used in the underground bituminous coal-mining industry. (Bottom) The Appalachian bituminous coal region. (Drawings after Knutson 1970.)



MAXIMUM ABSOLUTE SWEEP PERMITTED: 1/2 SMALL DIAMETER

EXAMPLE:

SMALL DIAMETER	MAXIMUM ABSOLUTE SWEEP
18 INCHES	9 INCHES
12 INCHES	6 INCHES
6 INCHES	3 INCHES



MORE THAN 1 SPLIT FACE

TWO OF THREE MEASUREMENTS "A", "B", OR "C" MUST EQUAL 1 INCH PER FOOT OF LENGTH: 4-1/2-INCH MINIMUM

1 SPLIT FACE

MEASUREMENT "A" MUST EQUAL 1 INCH PER FOOT OF LENGTH: 4-1/2-INCH MINIMUM

Figure 22-62.—(Top) Maximum sweep in roundwood for sawn mine timbers. (Bottom) Split mine-prop measure. (Drawings after Timson 1978b.)

TABLE 22-25—*Minimum standards for roundwood suitable for manufacture of sawn timbers and round or split props* (Timson 1978b)

Product, mill equipment, and specifications
Sawn products, standard sawmill
Minimum diameter: 7 inches at the small end
Minimum length: 6 feet
Sweep (fig. 22-62): Not to exceed one-half the diameter of the small end, and allowed only in sound pieces without large knots[1,2]
Decay or hollowness: Pieces up to an including 10 inches diameter, none. Pieces 11 inches to 15 inches in diameter, one-fourth diameter. Pieces over 15 inches, one-half diameter.
Surface defects: No surface defects larger than width of one face.[2]
Straight seams allowed, but spiral seams limited to one face.
Sawn products, bolter mill
Minimum diameter: 6 inches at the small end
Minimum length: 2½ feet
Decay or hollowness: None
Sweep: None
Surface defects: None larger than width of one face
Sawn products, special
Minimum diameter: 12 inches at small end
Minimum length: 18 inches
Decay or hollowness: None
Surface defects: None larger than width of one face
Maximum defect: One large defect per piece
Round props
Minimum size: 4½ inches in diameter at small end, and 4-½ feet long. Over 4-½ feet long, 1 inch diameter for each foot of length.[3] Some props shorter than 4-½ feet are sold, but they must be at least 4-½ inches in diameter.
Sweep or crook: Slight.
Decay or hollowness: None.
Maximum knot size: No greater than width of one face and cannot interfere with strength (in compression parallel to grain).
Split props
Some specifications as round props.
End measurement on props with one split surface: Measure between bark and split surface perpendicular to split surface; distance in inches must equal prop length in feet (see fig. 22-62). Minimum, 4-½ inches.
End measurement on props with two or more split surfaces: Measure along split surfaces (bark portion considered a split surface—see fig. 22-62). Each of two surfaces measured in inches must equal prop length in feet. Minimum, 4-½ inches.

[1]A **large knot** has a diameter greater than one-half width of one face.

[2]A **log face** is one-fourth the circumference along the surface of roundwood.

[3]The Federal Mine Safety Law allows no less than 1-inch diameter for each 15 inches of length with a minimum diameter of 4 inches. The minimum standards in this table are based on 1978 practices.

OTHER TIMBERS

Hardwood timbers of various dimensions are commonly used around construction sites in the South and East. Pieces may be as small as 4 by 4 inches and 4 feet in length for temporary support of pipe lines during laying operations, or as large as 12 by 12 inches and 16 or more feet in length for temporary street support during underground construction in cities, e.g., during subway construction in Washington, D.C. In aggregate, significant volumes are sold for such construction uses.

HIGHWAY POSTS

Reid and McKeever (1978) reported that there are about 3.8 million miles of streets and highways in the United States, and that since 1960 the total mileage has been increasing at an average of about 20,000 miles annually. They found that approximately 200 million board feet of lumber and 500 million square feet of plywood (3/8-inch basis) are used annually for highway construction, together with about 325 million board feet of timbers, falsework, piling, fence posts, and guardrail posts. Of these several categories of wood, guardrail posts appear to be the product most suitable for manufacture from pine-site hardwoods. Steel posts are the major competitor for this market, and they dominate it—for reasons not entirely clear.

Impact strength of wood and steel posts.—The widely used semi-rigid **strong-post** guardrail system protects vehicle occupants by transmitting the energy of a vehicle hitting guardrails through the supporting posts to the earth. Infrequently run full-scale crash tests involve a 4,000-pound vehicle that is crashed at 60 miles per hour into a barrier, at an approach angle of 25 degrees. Gatchell and Michie (1974) evaluated the dynamic performance of wood and steel guardrail posts, through use of a pendulum dynamometer. They found that for strong-post guarding systems, red oak 6- by 6-inch posts and southern pine 6- by 8-inch posts provide impact-strength characteristics that are superior to the W6 x 8.5 steel posts commonly used. For use in **weak post** systems (in which the post is intended to break), southern pine 6- by 6-inch posts were equal in impact strength to S3 x 5.7 steel posts. They concluded that in wood-guardrail-post specifications knot-associated grain distortion in the middle third of the tension face should not exceed one-third the width of the tension face. Knots in the outer third of the length of wood guardrail posts have no effect on post impact strength. (See also table 22-26, last column, for impact strengths of round and sawn posts of hickory, oak, and Virginia pine.)

Machine driving of pressure-treated wood posts.—If pressure-treated wood posts are hand set in augered holes, they require more than twice the installation time of machine-driven steel posts. Gatchell (1967ab) was successful in machine driving Osmose-treated 7-inch-diameter southern pine posts and 6- by 6-inch and 6- by 8-inch creosoted red oak posts in rocky and in gravelly substrates. Driving rates ranged from 15 posts per hour on the rocky sites to 30 posts per hour in gravel. The longest average time for driving was 1.7 minutes for the 6- by 8-inch red oak posts driven on the rocky site, the shortest was 0.4 minutes for the 7-inch pine posts on a gravel site. Gatchell concluded that on sites free of large rocks or other obstructions, guardrail contractors can expect to install from 2,500 to 3,500 linear feet (12.5-foot post spacing) of guardrail line per 8-hour shift—about equal to installation time when steel posts are used. Whether sloped or flat, tops of wood posts will not be damaged by the driving machine. For machine driving, posts with blunt bottoms are preferable to those with slopes. Wooden post driving time is proportional to cross-sectional area—the greater the cross-sectional area, the longer the driving time. Gatchell found that wood posts can be driven on any site where steel posts can be driven; they also can be driven on some sites where steel cannot, and where an auger cannot be used.

Damage to wood and steel posts during driving.—The effectiveness of a strong-post guardrail is in part determined by below-ground damage the post may have suffered during machine driving. Gatchell and Lucas (1971) compared damage to flat-bottom, 7-inch-diameter, 6-foot-long southern pine posts treated with water-borne salt preservative, with that suffered by 6B 8.5 steel posts with 6-inch web, 4-inch flange, measuring 5 feet 9 inches long and weighing 8.5 pounds per lineal foot. All posts were driven in a 65-year-old one-lane gravel road providing a variety of sites adverse to machine driving. Two commercial post drivers were used, one with hammer weight of 950 pounds, the other with 800- and 1,200-pound hammers. On both machines, hammer initial free-fall height to the top of a 6-foot post was 8 feet. All posts were driven to 4-foot penetration. Gatchell and Lucas found that both wood and steel posts driven under adverse conditions perform well, but wood resists damage better than steel. Cones of compressed top-layer material beneath flat-bottomed wood posts reduce the energy required for insertion and protect the bottom of the posts. The presence of knots within 3 to 12 inches of the base of a wood post further minimizes any damage that might occur. Results suggested that wood performs better than steel when harder rocks are found in the road base; if rocks resist breaking and do not have wedge-shaped edges, the wood posts displace them without suffering damage.

Comparison of installed costs of wood versus steel guardrail posts.—Gatchell (1967b) found that the installed cost of machine-driven wood posts was significantly less than that of driven steel, as follows:

Post description	Purchase price	Setting cost	Total
	Dollars per post		
Driven treated wood	2.75-2.79	0.35-0.70	3.10-3.49
Hand-set treated wood	2.75-2.79	1.87-2.35	4.62-5.14
Driven galvanized steel	5.25-5.85	.35- .52	5.60-6.37

Strength of roundwood compared to sawn posts of three species.—Doyle and Wilkinson (1969) evaluated the bending-strength of three Appalachian species. Specimens of round and sawn hickory (mostly shagbark and mockernut), oak (mostly scarlet, northern red, and black), and Virginia pine, each type in three sizes, were tested under static and impact bending in green condition, pressure-treated with creosote, and dried (but not treated). A total of 1,020 specimens were tested: 480 round and sawn posts of run-of-the-mill quality, and 540 matching small clear specimens cut from the posts that were static tested. They found (table 22-26) that round posts had higher strength, stiffness, and energy absorbing properties than corresponding sawn posts. Hickory tested highest in average strength, stiffness, and energy absorbing properties, followed by oak, then pine. The modulus of rupture and modulus of elasticity of posts did not increase as much with drying as those of the matching small clear specimens. The creosote preservative treatment did not appreciably affect strength properties of the posts.

FENCE POSTS

In a survey of Piedmont farms in Georgia, Worrell and Todd (1955) found only 12 percent of the farms without fences; length of fence on the other 88 percent ranged from 700 feet to 90,000 feet, and averaged about 18,000 feet per farm. Data on the number of fence posts installed on farms throughout the southern pine region are not published but the number is very large. Annual purchases of fence posts for replacement and new construction are also substantial.

Fence post size.—All treated posts sold by commercial plants are graded by size, i.e., according to the diameter at the small end (top), and the length. Two

TABLE 22-26—*Average modulus of rupture, modulus of elasticity, and impact energy at failure, of round and sawn posts of three species tested in green condition, at 12-percent moisture content, and when pressure treated with creosote* (Doyle and Wilkinson 1969)[1]

Condition and size	Modulus of rupture[2]	Modulus of elasticity[2]	Impact energy[3]
	Psi	*Thousand psi*	*Thousand inch-pounds*
HICKORY (MOSTLY MOCKERNUT AND SHAGBARK)			
Green			
3-inch round	13,430	2,080	47.7
4- by 4-inch sawn	8,350	1,050	61.8
5-inch round	12,580	1,950	134.0
4- by 6-inch sawn	7,480	1,410	107.2
8-inch round	12,050	1,990	—
6- by 8-inch round	6,910	1,320	—
Treated			
3-inch round	14,120	2,130	46.2
4- by 4-inch sawn	9,290	1,530	35.9
5-inch round	12,180	1,820	124.7
4- by 6-inch sawn	8,140	1,500	120.1
8-inch round	10,200	1,570	—
6- by 8-inch sawn	7,520	1,410	—
Dry			
3-inch round	19,500	2,480	60.8
4- by 4-inch sawn	10,500	1,520	37.7
5-inch round	13,460	1,990	130.4
4- by 6-inch sawn	12,140	2,020	85.4
8-inch round	16,540	2,800	—
6- by 8-inch sawn	12,990	1,840	—

See footnote page 2686

TABLE 22-26—*Average modulus of rupture, modulus of elasticity, and impact energy at failure, of round and sawn posts of three species tested in green condition, at 12-percent moisture content, and when pressure treated with creosote* (Doyle and Wilkinson 1969)[1]—Continued

Condition and size	Modulus of rupture[2]	Modulus of elasticity[2]	Impact energy[3]
	Psi	*Thousand psi*	*Thousand inch-pounds*
OAK (MOSTLY BLACK, NORTHERN RED, AND SCARLET)			
Green			
3-inch round	12,030	1,570	33.5
4- by 4-inch sawn	7,590	1,490	31.3
5-inch round	9,300	1,360	97.4
4- by 6-inch sawn	6,000	1,140	49.5
8-inch round	11,560	1,900	—
6- by 8-inch sawn	7,150	1,150	—
Treated			
3-inch round	8,930	1,140	41.0
4- by 4-inch sawn	6,320	1,080	27.5
5-inch round	8,390	1,370	51.3
4- by 6-inch sawn	5,640	1,040	54.8
8-inch round	8,890	1,470	—
6- by 8-inch sawn	5,930	1,160	—
Dry			
3-inch round	7,190	1,020	37.6
4- by 4-inch sawn	10,580	1,630	40.4
5-inch round	8,970	1,540	73.5
4- by 6-inch sawn	8,730	1,260	52.1
8-inch round	9,150	1,680	—
6- by 8-inch sawn	8,220	1,400	—
VIRGINIA PINE			
Green			
3-inch round	8,030	1,340	10.9
4- by 4-inch sawn	5,100	920	7.4
5-inch round	7,880	1,280	15.7
4- by 6-inch sawn	5,250	1,150	35.2
8-inch round	4,440	1,080	96.4
6- by 8-inch sawn	5,920	1,120	97.2
Treated			
3-inch round	7,140	1,180	11.0
4- by 4-inch sawn	6,440	1,150	16.9
5-inch round	7,750	1,430	26.3
4- by 6-inch sawn	4,780	1,070	18.0
8-inch round	7,380	1,290	113.0
6- by 8-inch sawn	4,870	1,020	60.9
Dry			
3-inch round	11,290	1,460	7.3
4- by 4-inch sawn	7,060	1,250	10.7
5-inch round	12,050	1,860	19.6
4- by 6-inch sawn	6,410	1,250	16.5
8-inch round	9,540	1,510	79.5
6- by 8-inch sawn	8,760	1,580	47.7

[1]Each value is the average for five posts (four in a few cases). Specific gravities of the posts static tested averaged as follows (based on ovendry weight and green volume): hickory 0.69, oak 0.58, and pine 0.48.

[2]Center-point loaded in bending with span-depth ratio of 14.

[3]Struck with a pendulum hammer 24 inches above ground level.

broad classes are recognized: corner or brace posts, and line posts. Corner or brace posts are commonly 8 feet long, sometimes longer. Line posts are sold in three lengths: 6, 6.5, and 7 feet. Corner and brace posts are graded according to even-inch diameter classes: 3-4, 5-6, 6-7, and 7-8 inches. Standard grades for diameters of line posts do not exist, but the most popular treated posts are only about 3 inches in diameter (Worrell and Todd 1955).

Species preference and durability.—Historically black locust (*Robinia pseudoacacia* L.) has been the preferred species for untreated fence posts, with white oak, post oak, and eastern red cedar (*Juniperus virginiana* L.) also much used. In recent years treated southern pine posts predominate, but, as discussed in section 21-4, many pine-site hardwoods can be effectively treated with preservatives for use as fence posts. Natural durability of southern woods employed as fence posts varies widely; estimates of useful life (years) by the Tennessee Valley Authority (1964) and Worrell and Todd (1955) follow (see also table 21-18):

Species	TVA	Worrell and Todd
Black locust	15	17 (heartwood)
Eastern red cedar	18	17 (heartwood)
Sassafras (*Sassafras albidum* (Nutt.) Nees)	11	10 (heartwood)
Mulberry (*Morus rubra* L.)	—	10 (heartwood)
White oak	11	8 (incl. post oak)
Chestnut oak	4.8	—
Hickory	4.7	—
Red maple	4.0	—
Black tupelo	3.4	—
Red oaks	2.8 (black oak)	3
Sweetgum	—	3
Yellow-poplar	2.8	—

Life of treated fence posts is summarized in tables 21-17 and 21-19.

Strength of hickory, oak, and pine fence posts.—Table 22-26 affords the following comparison of creosote-treated roundwood posts measuring 3 inches in diameter:

Statistic	Hickory	Oak	Virginia pine
Modulus of rupture (psi)	14,120	8,930	7,140
Modulus of elasticity (psi)	2,130,000	1,140,000	1,180,000
Impact energy (inch-pounds)	46,200	41,000	11,000

Machine-driving of fence posts.—Neetzel and Christopherson (1964) found that for maximum post firmness and straightness, with minimum expenditure of driving energy, machine driven fence posts should be pointed on the large (butt) end. Blunt-ended posts could, however, be satisfactorily machine driven. In their evaluation, they used 3-inch-diameter, creosote-treated, southern pine posts driven to a 24-inch depth in deep loam soil (both wet and dry), with a 200-pound hammer. Fourteen to 22 hammer blows were generally required.

POLES AND PILING

In the South and Southeast, markets for poles and piling are dominated by southern pine which is readily pressure-treated and obtainable in lengths and diameters usually required; some oak piling is sold, however. Hickory and oak roundwood has outstanding strength, stiffness, and ability to absorb impact energy (table 22-26, see 8-inch roundwood), but these hardwoods are not as readily treated as pine, and pine-site hardwood trees do not commonly yield long straight stem sections.

RIVER-BANK AND ROAD MATS

Since before World War II, U.S. Army engineers have constructed **wood mattresses** to control erosion of dikes and high banks of alluvial soil at bends in the Mississippi River below Cairo, Ill. Davis (1937) found that they annually consumed in excess of 15,000,000 board feet of pine and mixed hardwoods—mostly 1- by 4-inch boards. These wood mattresses are woven into great sections from 40 to 100 feet wide and many times as long. When spiked and wired together, they are sunk at critical points. The weaving of the mattress is done on a barge which moves downstream as work progresses. The bank on which the mattress is laid is given a gradual slope of not more than a foot downward for every 3 feet horizontally. After the mattress is sunk into place, the bank is paved with stone down to about the waterline covering the upper edge (apron) of the mattress. Stone cast from the barge is used to sink the outer part. The entire wood structure is anchored to the shore with cables.

Logging mats have been, and continue to be, occasionally used in place of gravel on temporary logging roads in purchased stumpage tracts, and at loading decks, trailer set-out areas, chip-van concentration areas, and on localized soft spots. These logging mats, made primarily from 4/4 oak lumber, are hand nailed into 18- to 30-inch-wide, 16-foot-long assemblies. First two or three 16-foot-long 1 by 6 or 1 by 8 runners are laid on the ground spaced to yield the 18- to 30-inch width and then narrow slabs cut to 18- to 30-inch lengths are nailed on 4-inch centers across the 16-foot boards. The assembly is then turned over, and the nails clinched. The mats are then placed end to end in dual arrangement, with crosspieces uppermost, to support the wheels of trucks. Because mats are used before major rutting occurs, they lie relatively flat. Boyer,[12] who provided this description, noted that after tracts are cut about 60 percent of the mats are reusable; the major problem in using such mats is flat tires from nails remaining in the bottom boards after crosspieces have broken. Boyer's analysis indicates 12 such reusable mats might be substituted for 60 tons of gravel at a saving of about $270; gravel used on a road bed becomes a permanent part of the tract, whereas the mats are removable.

Oil well drillers operating in bottomlands of Louisiana and Mississippi use significant volumes of 4/4 and 8/4 hardwood mats of similar construction.

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[12]Boyer, R. L. 1977. Logging mats—an alternative to high-cost gravel. Paper presented at Spring Meeting of the American Pulpwood Association, Appalachian Technical Division, Williamsburg, Va., May 18-19. 2 p.

STRUCTURAL LUMBER

Two-by-4-inch, 8-foot studs for wall construction are a major lumber commodity in the United States and Canada. Also, 7- to 8-foot 2 by 6's, 2 by 3's, and 2 by 2's are much used. Traditionally these products have been cut from softwoods. In the Midsouth and the Southeast studs made with chipping headrigs from southern pine veneer cores and small logs are particularly competitive. Most are dried at high temperatures (230°-240°F). If they are high-temperature dried in narrow loads under heavy top load restraint to the moisture content at which they will equilibrate in use, e.g., 9 percent, they can be relatively crook-free (Koch 1969a, 1971a, 1974). Even greater freedom from crook can be obtained if live-sawn oversized blanks are dried at high temperature before they are edged and machined to final dimension, as demonstrated by Koch (1966ab, 1967a, 1968, 1969b).

Should demand require, some widely available hardwoods such as yellow-poplar, sweetgum, black tupelo, red maple, and sweetbay can also be successfully manufactured into almost warp-free studs by edging and ripping live-sawn flitches after they have been kiln-dried at high temperature.

In West Virginia Koch and Rousis (1977) showed that more conventional manufacture of yellow-poplar studs, i.e., sawing to usual dimensions and kiln-drying at low temperatures without restraint, resulted in less than half of the pieces meeting Stud grade requirements. Considering knots alone, 90 percent of the pieces would have graded Stud or better at 19 percent moisture content; this proportion was reduced to 34 percent, however, by consideration of crook as well as knots.

Hallock and Bulgrin (1978) eliminated most crook in yellow-poplar studs by live sawing logs into 7/4 flitches which were dried and then ripped into studs. This technique, which is similar in some ways to that Koch developed for southern pine, has been termed SDR (Saw, Dry, and Rip; fig. 22-63). In their experiment, they dried the studs on a mild schedule to a 15-percent moisture content.

Maeglin and Boone[13] showed further benefits from high-temperature drying in combination with the SDR process. They dried 7/4 yellow-poplar flitches cut from trees 8 to 12 inches in dbh for 28 hours at 240°F dry-bulb temperature and 190°F wet-bulb temperature, followed by about 44 hours of equalizing at conditions set for 10 percent equilibration moisture content—200°F dry- and 188°F wet-bulb temperatures. At the end of this schedule, stud moisture contents averaged 12 percent with range from 9 to 15 percent. Flitches ripped to width after drying, and planed to net dimensions of 1.5 to 3.5 inches had average crook of about 1/64-inch; none of the 417 studs were rejected from Stud grade for exceeding ¼-inch crook. Compared with conventionally sawn yellow-poplar studs dried on a mild kiln schedule, the SDR studs dried at high temperature averaged 86 percent less crook, 43 percent less twist, and 34 percent less bow.

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[13]Maeglin, R. R., and R. S. Boone. 1979. High quality studs from small hardwoods by the S-D-R process. Paper presented at 33rd Annual Meeting, Forest Products Research Society, San Francisco, July 8-13. See also Boone and Maeglin 1980.

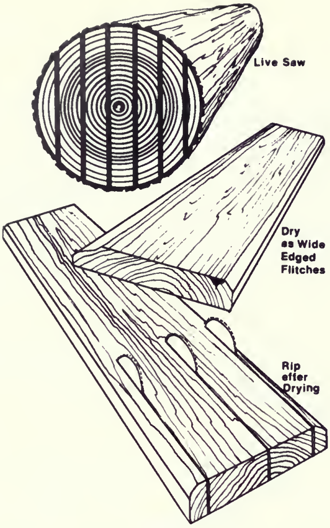

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Figure 22-63.—Manufacturing system, termed SDR, designed to control crook in hardwood studs. Logs are live-sawn into flitches; these flitches are dried and then ripped to yield studs. (Drawing after Harpole et al. 1981.)

Conventionally sawn yellow-poplar studs, even when dried at high temperatures, had average crook of nearly ⅛-inch.

Maeglin et al. (1981) found that small yellow-poplar sawlogs converted to studs by the SDR process yielded 84 percent more product value than if sawn into 4/4 boards. See table 22-27 for volume yields, and table 22-28 for grade yields.

TABLE 22-27—*Lumber yields from 10 8-foot-long yellow-poplar logs sawn by three methods to two thicknesses* (Maeglin et al. 1981)[1]

Statistic	7/4 SDR[2]	7/4 CON[3]	4/4 boards[4]
Log diameter inside bark at small end, inches	7.5	7.5	7.4
Log volume, cubic feet	26	26	25
Scribner Decimal C volume, board feet	127	128	124
Nominal lumber tally, board feet	218[5]	215[6]	156
Lumber recovery factor	8.5	8.5	6.2

[1]Data based on logs sampled from four states: North Carolina, Tennessee, Virginia, and West Virginia.

[2]SDR means live sawing, drying, ripping. Data based on 40 logs per state.

[3]CON means centered-cant sawing. Data based on 40 logs per state.

[4]Boards were cut using the cant method and full taper sawing; logs were rotated to recover highest grade possible. Data based on 10 logs per state.

[5]Of the total volume of SDR studs, 62.6 percent were 2 by 4, 21.4 percent 2 by 3, and 16 percent 2 by 2 inches.

[6]Of the total CON studs, 81.9 percent were 2 by 4, 14 percent 2 by 3, and 4.1 percent 2 by 2 inches.

TABLE 22-28—*Grade yields of boards and studs by percentage of volume for small 8-foot-long yellow-poplar logs sawn by three methods to two thicknesses* (Maeglin et al. 1981)

Board thickness, sawing method, and lumber grade	Yield
	Percent
7/4 studs by SDR method	
Stud	99
Economy	1
7/4 study by CON method	
Stud	88
Economy	12
4/4 boards by cant method	
Select	0
1C	2
2A	18
2B	36
3C	44

Harpole et al. (1979) analyzed the economics of carrying the SDR idea one step further, i.e., to live saw 8/4 flitches, from 8- to 12-inch logs, edge them to fullest possible width, edge glue them into wide panels, and then rip the wide panels to desired width for structural joists and planks. This is a variation of a technology that was very widely practiced by the white pine (*Pinus strobus* L.) wood box industry of New England in the 1930's and 1940's. Harpole et al. found that this system, used to increase the amount of wide-width dimension lumber (2- by 10-inch and wider), yielded a 12- to 13-percent increase in volume over more conventional sawing procedures and justified the additional investment required.

See also sections 28-12 and 28-22 for summaries of economic feasibility studies of structural-lumber manufacture from yellow-poplar.

Research suggests that straight, dry, well-manufactured yellow-poplar structural lumber, if available at competitive prices, is potentially acceptable to lumber users. Schick (1978) and Schick and Grinell (1979) found that in West Virginia, lumber wholesalers, retailers, homebuilders, and architects responded positively toward potential distribution and use of yellow-poplar framing lumber, but with some important reservations. Recent acceptance by the American Lumber Standards Committee of the structural grading rules for yellow-poplar proposed by the Northern Hardwood and Pine Manufacturing Association (1978) should overcome one major problem. Inclusion of such lumber in promotions of the National Forest Products Association, and acceptance by the various regional and local building codes should clear the way for wide acceptance of yellow-poplar framing lumber.

Other hardwood structural grading rules accepted by the American Lumber Standards Committee are for cottonwood (*Populus deltoides* Bartr. ex Marsh), aspen (*Populus tremuloides* Michx.), and red alder (*Alnus rubra* Bong.). Readers interested in the procedure whereby stress-graded structural lumber achieves official acceptance in the market should find Galligan's (1977) explanation useful. Koch (1981) found that estimated strength ratios of yellow-poplar 2 by 4's were not good predictors of their modulus of rupture.

STRUCTURAL PLYWOOD

Consumption of softwood plywood in the United States increased from 2.7 billion square feet (3/8-inch basis) in 1950 to about 20 billion square feet in 1978. During the same timespan, consumption of hardwood plywood more than doubled to about 4 billion square feet (fig. 29-14).

Of the 182 softwood plywood plants operating in the United States in 1978, 60 were in the southern pine region—all 60 built since 1963 (Whitman 1979). Such extraordinary expansion suggests that demand for structural panels may eventually outrun the available supply of softwood veneer logs. Construction of plants to make composite structural panels of southern pine veneer over flake cores (see discussion related to table 24-2 and figs. 24-50 through 24-52) would greatly increase the square footage of panels that can be manufactured from available pine veneer.

Another possibility for expanding structural panel production is use of hardwood veneers. Veneer for this purpose need not be of appearance grade and could be rotary peeled in large volumes from 4-foot bolts of hardwood that grow on southern pine sites (fig. 18-252). Ideally such veneers should be strong and stiff, but of moderate weight; additionally, they should glue readily. The Hardwood Plywood Manufacturers Association (1971) has provided a structural design guide for hardwood plywood, and the American Plywood Association (1974) has published a product standard. O'Hallaran (1979) described procedure used in developing performance-based specifications for structural panels; by laboratory and field work, these procedures establish criteria for structural adequacy, dimensional stability, and durability during one year of weathering.

The oaks and hickories, which comprise more than half the volume of hardwoods growing on pine sites, are strong and stiff—but they are dense and difficult to glue into exterior-grade panels (Stern 1947b; Craft 1970, 1971, 1975). Lighter pine-site hardwoods such as sweetgum, yellow-poplar, red maple, sweetbay, and black tupelo peel and glue readily, but have less strength and stiffness than southern pine of comparable thickness. See table 24-31 for modulus of elasticity and tensile strength of 1/6-inch-thick, rotary-peeled sweetgum, white oak, black tupelo, and yellow-poplar veneers harvested in three southeastern areas.

The gluing problem can be partly resolved by using sweetgum or yellow-poplar (or other of the readily glued low-density species) for inner plys and red oak or hickory for faces (Craft 1975). (For further discussion of glueing technology see: Sellers, T. and J.R. McSween. 1983. Glueing Structural Plywood from Medium-density Southern Hardwoods. Plywood Research Foundation, Tacoma WA. 15p.)

Plywood manufacturers prefer to use 8-foot lathes for both face and core veneers—the core veneers are reduced to 4-foot length with splitter knives. To accommodate the small crooked logs typical of pine-site hardwoods, greater utilization of 4-foot veneer logs is desirable and, in the eyes of some manufacturers, practical (fig. 18-252). Such 4-foot veneers can be end-scarfed to obtain needed 8-foot lengths. A thousand square feet of three-ply 3/8-inch-thick panel with oak faces and sweetgum or yellow-poplar core would weigh about 115 pounds more than this amount of loblolly pine plywood, which weighs about 1,100 pounds at 8 percent moisture content. Five-ply, 5/8-inch-thick plywood with 1/8-inch oak faces and sweetgum or yellow poplar inner plys would weigh about the same as an all southern pine panel of equal thickness.

Lutz and Jokerst (1974) studied the problem of using hardwoods for structural plywood and concluded that, in general, new plywood products have been readily accepted if they conform to existing standards such as PS 1-74 for Construction and Industrial Plywood (American Plywood Association 1974). This standard provides quality control and aids in acceptance by code authorities. The standard lists five groups of species in which group 1 has highest strength, and group 5 is the weakest. Domestic hardwoods in each of these groups, as listed in PS 1-74, are:

Group 1—American beech, sweet and yellow birch, sugar maple, and tanoak.

Group 2—Black maple, sweetgum, and yellow-poplar.

Group 3—Red alder, paper birch, and bigleaf maple.

Group 4—Bigtooth and quaking aspen, eastern cottonwood, and black cottonwood (western poplar).

Group 5—Basswood and balsam poplar.

Not appearing in the foregoing list are the eastern and southern oaks, hickories, red maple, black tupelo, or sweetbay. Amendments are made to Product Standard PS 1-74 by a standing committee; it is a voluntary standard developed by manufacturesrs, distributors, and users in cooperation with the Office of Engineering Standards of the National Bureau of Standards.

The first step, therefore, would be to have these species added to the proper group in the standard, by formal request to the standing committee. Oak-sweetgum or oak-yellow-poplar plywood should qualify for C-D panels and for structural II panels which permit groups 1, 2, or 3 species in face, back, and all inner plys. Structural I panels, however, are at present limited to group 1 species in all plys.

Yield of structural veneer from trees of four southern hardwoods.—See table 12-5 through 12-10 for average yield of dry 1/6-inch, rotary-peeled veneer by grade and tree-diameter class for yellow-poplar, sweetgum, white oak, and black tupelo. Veneer grades tabulated are those defined by Product Standard PS 1-74.

Yield of veneer from grade 3 Appalachian oak logs.—Craft (1970, 1971) processed through a southern pine sheathing plywood plant a mill-run sample of factory grade 3 Appalachian oak logs cut to 8-1/2-foot lengths and averaging 11.7 inches in diameter at the small end. The sample logs scaled 3,567 board feet Doyle scale, or 4,933 board feet International 1/4-inch scale. The yield of usable veneer was 222 cubic feet, the equivalent of 2.18 square feet of ⅜-inch panels per board foot of log input, Doyle scale; or 1.50 square feet of ⅜-inch panels per board foot of log input, International ¼-inch scale. Of the total input log volume (inside bark) of 808 cubic feet, percentage yields on a cubic basis were as follows:

Product	Percent of input volume
Usable grades C and D veneer	27
Green chippable waste, including cores	55
Dry waste	18
	100

Craft made all-oak plywood in thicknesses of ⅜-inch to ⅞-inch that had satisfactory appearance (fig. 22-64) and production economics, but which failed to pass the vacuum pressure soak test for plywood sheathing glue lines. It performed well in field tests, however; after 6 years use in commercial applications, no delaminations were observed (Craft 1975).

Gluing of oak faces to less dense hardwood inner plys.—Jokerst and Lutz (1974) found that ⅛-inch northern red oak face and back veneers could be bonded to a ⅛-inch eastern cottonwood (*Populus deltoides* Bartr. ex Marsh.) core in a cure time of 4 minutes—possibly less if plywood were hot-stacked (after pressing) for 4 hours, as is the custom with southern pine plywood. Bonds so made with a 70-percent solids, furfural-extended hot-press phenolic adhesive satisfied glue-line requirements for exterior-type plywood. Spread rate was 80 to 83 pounds of adhesive per thousand square feet of double glue line; platen pressure was 175 psi, platen temperature 300°F, open assembly time was minimal, and closed assembly time was 9 minutes. After a year of exposure to the weather in Madison, Wis., these plywood panels had no delamination; shear strength and wood failure did not change substantially from tests made before exposure (Jokerst et al. 1976).

For exterior-type plywood, specimens subjected to a standard vacuum-soak test[14] must average 85 percent or more, wood failure in the glueline. Craft (1975) approached, or exceeded, this standard of phenolic glueline quality with red oak and hickory faces and backs glued to hardwoods of lower density, as follows (sweetgum and sweetbay should also have worked well, but were not included in the trials):

[14]In the vacuum-soak treatment small plywood specimens, prepared to stress gluelines in shear when gripped at the two ends in a tension machine, are submerged in 120°F water and subjected to a vacuum (15 inches of mercury) for 30 minutes. Following release of the vacuum, specimens continue to soak for 15 hours at atmospheric pressure in water. The water is not permitted to cool below 75°F. At the end of the 15-hour soak, specimens are sheared when wet in a tension machine, dried, and the percentage of wood failure evaluated.

Species of face and back veneers and of inner-ply veneers	Wood failure
	Percent
Red oak	
Red maple	87
Sycamore	82
Black tupelo	80
Yellow-poplar	80
Hickory	
Black tupelo	92
Red maple	88
Beech	85

No combination of white oak or of chestnut oak face and back veneers, however, yielded average percent wood failure above 55 percent, regardless of species of inner plys.

Weight of hardwood plywood.—Carpenters prefer light panels; they are accustomed to the weight of loblolly pine plywood which compares with hardwood plywood as follows (Craft 1975):

Face-ply species and inner-ply species	Three plys of 1/8-inch	Five plys of 1/8-inch
	Pounds per 4- by 8-foot panel at 8-percent moisture content	
Loblolly pine		
Loblolly pine	35.2	58.6
White oak		
White oak	45.6	76.0
Red oak		
Yellow-poplar	38.9	57.6
Red maple	41.1	64.0
Black tupelo	41.0	63.9
Hickory		
Yellow-poplar	42.5	62.0
Red maple	44.7	68.4
Black tupelo	44.6	68.3

Face glued blockboard.—Blockboard is a form of **lumber-core plywood,** the latter a product that has for years been used in the United States and Canada in furniture and cabinet manufacture. **Face-glued blockboard** is distinguished from lumber-core plywood in that gluelines are found only between face veneers and the core; the core strips in blockboard are not edge glued as they are in lumber-core plywood. In Europe, face-glued blockboard panels are used for industrial shelving, storage units, packing cases, doors and partitions, bench tops, and even as combination subflooring underlayment (Bowyer 1979a). Bowyer (1979a) constructed face-glued blockboard from 0.1-inch elm face veneers and 0.8-inch-thick aspen core strips in short lengths; the core strips were 1.5 or 3 inches wide. He concluded that such blockboard has dimensional stability properties very similar to softwood plywood, and that low-density

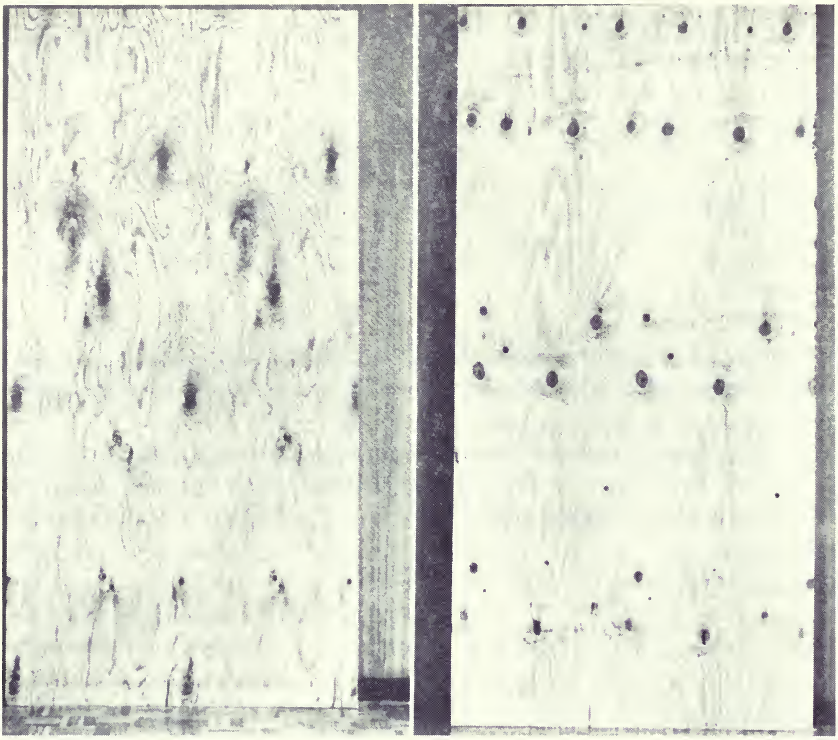

Figure 22-64.—(Left) Grade D back of a typical plywood sheathing panel made from factory grade 3 Appalachian oak logs. (Right) Grade D back of a typical southern pine sheathing plywood panel. (Photo from Craft 1970.)

hardwood blockboard, if 0.9 inch thick, could meet or exceed strength properties of ¾-inch thick Douglas-fir plywood; a hardwood blockboard panel of 0.9-inch thickness would weigh about 13 percent more than a ¾-inch panel of Douglas-fir plywood.

The hardwood, face-glued, three-ply blockboard panels made by Bowyer (1979a) had linear expansion, when conditioned first at 50 percent relative humidity and than at 90 percent, as follows:

Direction of measurement and width of core veneer strip	Linear expansion (50 to 90 percent RH)
Inches	*Percent*
Parallel to grain of face veneer	
1-½	0.087
3	.076
Perpendicular to grain of face veneer	
1-½	.076
3	.094

Three-quarters-inch-thick, five-ply Douglas-fir plywood subjected to the same cycle, had linear expansion of 0.071 percent parallel to the face grain and 0.031 perpendicular to the face grain; face plies were 1/16-inch thick, crossbands 7/32, and center ply 3/16. Performance after accelerated aging tests, however, suggest face-glued blockboard should not be used for exterior application even if hot-press bonded with phenolic resin (Bowyer 1979b).

Bowyer (1979a) concluded from a brief economic analysis that manufacture of hardwood face-glued blockboard would likely be profitable if the product were marketed as industrial shelving or as combination subfloor-underlayment. See also Bowyer and Stokke (1982).

Fraser (1975) illustrated and described a Finnish plant that produces endless 4-foot-wide sheets of three-ply face-glued blockboard with a single-opening traveling hot press. The panel, which has scarf-jointed 2-mm-thick birch veneer faces and backs glued to pine core strips, is cut to market size from the continuous sheet.

LAMINATED BEAMS AND LUMBER

It is difficult to glue dense southern hardwood veneer into plywood that will yield 85 percent wood failure when sheared after being subjected to the vacuum-soak test described in footnote 14. This does not mean, however, that laminated dense hardwoods such as white oak are precluded from severe service. On the contrary, laminated white oak has served admirably in such diverse and demanding applications as keels and frames of wooden ships of the U.S. Navy (Kuenzel 1950, 1952; McKean et al. 1952), and in laminated flooring for truck beds. Hickory, another dense wood, is laminated to ash for extraordinarily tough and serviceable baseball bats (McDonald 1951).

The structural uses of laminated hardwoods are many. In addition to laminated truck trailer and railcar flooring described later, laminated oak is being used for stairway railings, restraining structure around tanks in the holds of liquid methane tankers, for foundations under large cryogenic tanks holding methane and ammonia, and for decorative structural members in residences and commercial buildings.

General guidelines for laminating lumber can be found on pages 1158 through 1175 of Agriculture Handbook 420 (Koch 1972). Guidelines for laminating, edge gluing, and end gluing southern hardwoods are being prepared by T. Sellers of Mississippi State Forest Products Laboratory, Mississippi State, Miss., in a state-of-the-art report written as a companion volume to this text. For fabrication procedures, the interested reader should find the comprehensive work by Freas and Selbo (1954) useful. Steps in fabrication include organization of laminae, spreading, layup, curing under pressure, and finishing.

The introduction of nondestructive testing techniques to evaluate the strength of individual laminae has led to several publications describing systems to position laminae efficiently in beams (Koch 1964ab, 1967bc, 1971b; Koch and Bohannan 1965; Koch and Woodson 1968; Bohannan and Moody 1969; Moody and Bohannan 1970; Moody 1974, 1977). Industry has, to an increasing degree, adopted the principle of placing laminae having the highest modulii of elasticity in the outer, most highly stressed region of each beam. Because eastern hardwoods vary significantly in modulus of elasticity (table 10-6) it is possible to place laminae in beams according to species. For example, the hickories, cherrybark oak, and water oak, when dry, have modulus of elasticity greater than 2 million psi; black tupelo and hackberry average only about 1.2 million psi.

Techniques for applying glue to laminae with roll spreaders are simple and well developed. For structural laminated beams, glue is usually spread on both mating surfaces because of the long assembly periods required for layup. Application of glue to both mating surfaces permits longer assembly times—both open and closed, but particularly closed—than application of glue to only one surface.

As an alternative to the roll-spreading technique, Hann et al. (1971) reported that a phenol-resorcinol glue of high viscosity could be advantageously extruded in a ribbon pattern on oak laminae. Advantages for the ribbon spread—which is accomplished by pumping glue through orifices as the lumber passes below—include cleanliness of operation, accurate control of spread rate, little waste of glue, and little solvent evaporation; by this system glue is spread only on one surface.

Following glue appliction and beam layup, pressure is uniformly applied for a time which varies with both press temperature and glue. Most heavy laminated beams and arches are pressed several hours (or overnight) in massive clamps temporarily arranged to manufacture only a few of each structure. For 1- and 2-inch oak lumber, experience indicates that a specific pressure of about 150 to 250 psi is required (Freas and Selbo 1954).

Descriptions of presses utilizing the stored-heat principle to laminate small beams and decking have been provided by Marra (1956), Malarkey (1963), Hann et al. (1971), FPL Press-Lam Research Team (1972), and Jokerst (1972).

Mann (1954), Syme (1960), and Anonymous (1962) reviewed fast-cycling batch equipment designed to edge-glue and laminate with radio frequency heating, and Carruthers (1965) described a continuous laminating machine for beams that uses radio frequency energy to cure the gluelines. Miller and Cole (1957), Clark (1959), Carruthers (1963), and Miller and George (1965) have reviewed gluing problems associated with the use of radio frequency energy to cure gluelines.

The following paragraphs present data that are specific to lamination of oak—the species group of major importance among the hardwoods that grow on southern pine sites, and briefly discuss strength of beams laminated from mill-run oak and the possibilities of manufacturing two-ply lumber for furniture dimension stock and for highway sound barriers.

Flat-grain white oak versus vertical-grain for lamination.—Selbo (1960) fabricated laminated white oak beams consisting of 13 laminations of ¾- by 9-¾-inch boards bonded with phenol-formaldehyde adhesive. Some beams had all vertical-grain boards; in others, vertical-grain and flat grain were alternated. Both were subjected to 4 to 5 years of salt-water soaking and weathering exposure. Selbo concluded that adequate and durable glue bonds can be obtained in both types of construction, but vertical-grain oak laminations have a tendency to develop cleavage parallel to the glue lines when subjected to severe exposures, and therefore may be less desirable than flat-grain oak for use in exterior service.

Effect of laminae thickness and width on glue-line durability.—Selbo (1948a) glue-laminated white oak beams from laminae 4, 8, 14, and 24 inches wide, that were ⅛-, ¼-, ⅜-, ¾-, 1, and 1-⅝ inches thick. After bonding with a phenol-formaldehyde adhesive designed for curing at intermediate temperatures and conditioning for 2 weeks, the beams were end-coated and exposed unprotected for 3 years to outdoor conditions, or to 3 years of continuous salt-water soaking, or alternate soaking in a 4-percent salt solution and drying. He found that glue bonds of good durability could be obtained with all laminae within the size range tested. The thickness and width of the laminae, within these limits, apparently had no significant effect on the strength and durability of the glue bonds.

Effect of laminae thickness on beam strength.—Beams glue-laminated from thin laminae are usually significantly stronger than those made of thick laminae if they are cut from knotty wood or wood with areas of cross grain. With thin laminae, knots and localized areas of cross grain are more randomly distributed within the beam and therefore weaken it less than if concentrated in thick laminae or one-piece beams (Nearn and Norton 1952; Koch 1967b, p. 10; Schaffer et al. 1972; Braun and Moody 1977). With clear straight-grained white oak, however, Finnorn and Rapovi (1959) found that laminae thickness, in the range from ¼- to ¾-inch, did not affect modulus of rupture or modulus of elasticity of straight or curved laminated beams. Preston (1950) found that 1/40- and 1/60-inch-thick clear yellow-poplar laminae were compressed (densified) during pressing and therefore had 16 and 26 percent higher tensile strength than 1/10-inch laminae; also Preston found that modulus of elasticity in bending was increased by decreasing laminae thickness.

Safe bending radius for white oak laminae.—(See section 19-3).

Effect of water soaking on strength of laminated beams.—Laminated white oak beams 1.75 inches wide, 3.75 inches deep, and 45 inches long comprised of six ⅝-inch-thick essentially clear boards were fabricated by Freas and Werren (1959) and tested in bending when at 11 to 12 percent moisture content; bending properties of these dry beams were compared with those of matched beams salt-water soaked for 3 months to a moisture content of about 40 percent and tested wet. They found that the decrease in modulus of elasticity after salt-water soaking averaged about 26 percent; modulus of rupture decreased about 41 percent.

Effect of preservatives on shear strength.—Selbo (1959) found that block-shear strengths of northern red oak laminated with resorcinol and phenol-resorcinol adhesives from preservative-treated northern red oak boards were 4 to 16 percent less than in untreated controls. Two oil-borne and three waterborne preservatives were used in the test, which lasted 3 years, during which time specimens were conditioned at 80°F and 65 percent relative humidity. In all specimens, shear strength declined slightly during the first three months, but thereafter remained generally constant.

Strength of laminated oak beams.—Modulus of rupture and modulus of elasticity of laminated beams depends on wood species, grade, moisture content, arrangement of laminae, and beam size. Nemeth (1974) described an experiment to develop a laminated oak beam product utilizing the grade and species of oak available in Arkansas. He tested two-ply specimens made of red and white oak 1- by 4-inch lumber classified in nine groups according to strength reducing characteristics. Data so obtained were used to place laminae in core and faces of the beams and predict beam mechanical properties. For 12-inch-deep beams laminated at 16-percent moisture content with the grades of oak lumber available, modulus of elasticity averaged 1,749,000 psi and modulus of rupture 4,894 psi with computed allowable extreme fiber stress in bending of 1,750 psi. (See sec. 10-4 for species-average strength values for clear wood.)

Gluing green oak.—In usual practice, wood to be glue-laminated is conditioned to the moisture content it will attain in use—generally near 10 percent—before it is planed just prior to glue application and lamination. For some applications such as lamination of oak planks into crossties, however, it would be useful to glue green wood into assemblies. In an effort to accomplish this, Murphey et al. (1971) dried surfaces of green northern red oak lumber by application of high voltage, air at 300°F, platens at 350°F, and infra-red lamps. They found that hot air and platen drying produced highest joint strength when a resorcinol adhesive was used. Urea, melamine, and casein adhesives either failed or produced lower strength joints. Surface drying with hot air yielded joints with higher shear strengths than did platen drying.

Two-ply laminated hardwood lumber.—Suchsland (1980) proposed that yields of hardwood furniture dimension lumber could be increased substantially by manufacturing two-ply lumber. (See discussion related to figure 22-2.) He concluded that there would be added processing costs due to lamination, but in many ways manufacture would be simplified. In the sawmill, emphasis would shift from quality recovery to volume recovery. Live sawing would be favored and lumber grading could be simplified. The roughmill in which dimension parts are manufactured could be more automated, since defects would not have to be detected and removed.

TRUCK TRAILER FLOORING[15]

The U.S. Department of Commerce (1975) estimated that 191,262 truck trailers were shipped from U.S. manufacturers in 1974. Of these, 127,460 units, or 67 percent, were van-type trailers. Manufacturers estimated that approximately 90 percent of the van trailers, 115,600 units in 1974, incorporated laminated or solid wood planking as the primary flooring material. The other ten percent primarily were refrigerated units with extruded aluminum flooring. Also, 36,834 platform or flatbed trailers, incorporating wood floors were shipped in 1974.

Total truck trailer shipments in 1979 numbered 209,522 units (U.S. Department of Commerce 1980), an increase of 10 percent over 1974 levels; production of van and platform trailers with wood floors therefore also increased, to about 167,000 units.

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[15]Text under this heading is taken, with minor editorial changes and permission of the authors, from Fergus et al. (1977).

Almost all van and platform trailers are 8 feet wide (outside dimension) and from 26 to 50 feet long, with an average length of 40 or more feet. Standard truck flooring is 1-1/16 to 1-⅝ inches thick with 1-¼ and 1-⅜ the most commonly used thicknesses. The standard "board" width is 12 inches, with the boards running continuously for the length of the trailer (fig. 22-65 top). Assuming a 1-⅜-inch-thick floor and a 40-foot average length, 300 square feet (34.4 cubic feet) of wood flooring is required for each van or platform trailer. This aggregates to a national market of an estimated 57,000,000 square feet (6,530,000 cubic feet) per year of 1-⅜-inch finished floor material.

The average cost to produce a trailer was approximately $7,000 in 1975. The material cost of wood flooring averaged $320 per trailer—about $1 per square foot.

Oak performs well according to several industry spokesmen and it is the principal; species used. Southern pine is also used, but to a lesser extent.

Manufacturing processes.—Laminated oak flooring for the truck trailer industry is typically produced from #1, #2, or #3A common hardwood lum-

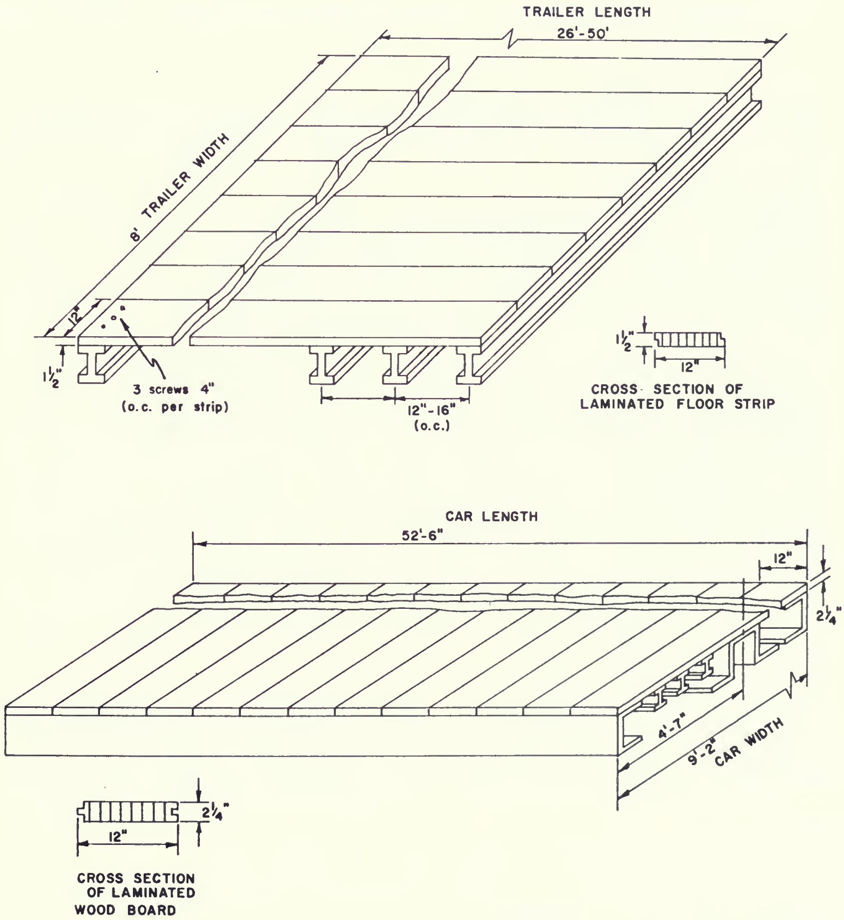

Figure 22-65.—(Top) Truck trailer glue-laminated wood flooring. (Bottom) Railcar flooring. (Drawing after Fergus et al. 1977.)

ber. With log-run raw material resources, manufacturers resell the upper grades, using the #1 common and lower material for flooring. Steps in the manufacturing process are:

1. Rough plane 4/4 or 5/4 lumber.
2. Rip lumber to desired thickness of deck. i.e., 1-⅜ inches.
3. Plane ripped strips to 0.880 or 1 inch.
4. Cut out defects.
5. End match strips with hook joint.
6. Turn rippings on edge and face laminate with a melamine fortified urea adhesive in a continuous lay-up operation.
7. Cure laminated flooring in a hot press.
8. Crosscut continuous ribbon to the desired length of the trailer.
9. Rip the large panels into 12-⅜-inch-wide floor boards.
10. Apply surface and edge detail with planer-matcher or molder. Usually a shiplap or tongue and groove joint is machined on the board for edge matching. A 1/16-inch **crusher bead** is also machined on one edge to insure spacing between planks adequate to prevent buckling on wetting.
11. Finish cross cut as necessary.

The five most important material characteristics considered in the design of trailer flooring are strength, durability, nailability, coefficient of friction, and weight to strength ratio.

Strength.—Van trailer flooring is normally supported on, and fastened with self tapping machine screws to steel junior I-beams, 12 to 16 inches on center and must be capable of supporting concentrated, moving fork lift loads of up to 18,000 pounds over these spans. Engineering requirements dictate that in actual service the flooring product should weigh less than 5.0 pounds per square foot and support a concentrated load of at least 9,000 pounds (the load on one of two forklift wheels) over 12-inch spans without excessive deflection or failure. As an example, using a simple span beam analog for analysis and based on practical deflection limitations for fork life operations, a 0.1-inch deflection is the maximum allowable over a 12-inch span. Under these assumptions, a wood-base material would need a minimum stiffness (EI) property of 346,000 pound inches squared per inch and an ultimate bending strength of greater than 8,650 psi to support the load. In general, a thin flooring material with a high modulus of elasticity value is desired, because thinner floor materials provide more volume in the van trailer for pay loads.

Durability.—The strength and durability of the glue line for laminated wood flooring is normally established by means of wet and dry block shear tests and cyclic delamination tests. ASTM, AITC, or other teting standards are used to evaluate these properties, although no one particular standard is used by all concerns. Most corporate standards are modified by experience with delamination and glue-bond failure in actual service. Average shear value of a sample tested according to ASTM Test D905-49 should probably be at least 800 psi and delamination should represent less than 15 percent of the total glue line area in AITC Test 110.

Surface wearing characteristics of flooring materials are not generally tested in the laboratory. Almost all failures in wood-base trailer flooring are due to the puncture or rupture of floor strips by fork lift traffic. Service life equal to that of laminated oak is generally acceptable. Truck van trailer flooring, because it is usually exposed to the weather on the bottom, must be resistant to salt and corrosion. For platform trailers, because the wood flooring is exposed on both top and bottom, laminated wood flooring is used exclusively. This is one reason why nailable steel is not expected to be used in any quantity for trailer floors.

Dimensional stability is normally not a problem in trailers utilizing 12-inch-wide floor panels so long as they are installed at between 10 and 12 percent moisture content. A 1/16-inch machined crusher bead ensures an edge spacing gap to accommodate subsequent swelling across the board and prevent buckling. One reason why large panel sizes have not been favored is the increased problem with dimensional stability.

Nailability.—Shifting of cargo during transportation is a critical problem in the trailer industry. Life safety and property loss considerations dictate that cargoes must be sufficiently tied down to prevent movement and subsequent damage. This is normally done by nailing hold-downs or dividers directly to the floor system. Thus, it is necessary that the floor material possess good nail withdrawal strength, and yet, the density must be low enough to facilitate nailing operations. One general complaint about tropical hardwood species (e.g., apitong) is that nailing characteristics are poor.

Coefficient of friction.—Trailer flooring materials must provide a certain degree of friction to avoid sliding of fork lifts during loading and unloading operations. When slippery material such as aluminum or steel are employed, it is necessary to use an antiskid paint to protect against sliding. In general, untreated laminated oak and southern yellow pine provide good skid resistance. (See section 9-4 for a discussion of friction coefficients.)

Weight-to-strength ratio.—Limited load carrying capacities of bridges and roadbeds require limits on total weight of trucks and trailers. The payload is the total legal weight minus the dead weight of the trailer. Any additional trailer weight reduces net allowable cargo load. Thus the weight-to-strength ratio of a flooring material is probably its most critical property and the primary advantage of laminated oak, southern pine, and extruded aluminum for truck trailer flooring. The high weight-to-strength ratio of nailable steel (about three times that of laminated oak) eliminates it from consideration for this market.

Trend.—Fergus et al. (1977) concluded that the low weight-to-strength ratio of laminated oak and laminated southern pine establish these products as the major competitors for truck trailer flooring. With good wear resistant properties and high coefficient of friction, laminated wood products should continue to dominate this market, although extruded aluminum will continue to be used in refrigerated trailers.

RAILCAR FLOORING[16]

The same process used to make truck trailer flooring is employed to produce laminated oak railcar flooring (fig. 22-65 bottom) except that this flooring is crosscut to an average length of 9 feet 2 inches, the width of the freight car. Three-ply vertically laminated southern pine is also used for railcar flooring.

Requirements for railcar flooring are basically the same as for truck trailer floors, but weight-to-strength ratios are less critical. Railcars and railroads are designed for load carrying, and payloads are little affected by dead weight. Although heavier railcars increase energy requirements, these costs have been considered insignificant.

An additional concern in railcar flooring is combustibility. Noncombustible materials are preferred to reduce damage from fires started by hot boxes or sparks from cast iron brake shoes. Wood flooring treated with fire-retardant chemicals reduces the probability of fire damage, but treatment increases cost of railcar manufacture.

Because the life of a freight car is specified to be 40 years, wood flooring in such cards must be completely replaced at least twice during the life of the car, since its life is usually 10 to 15 years.

Fergus et al. (1977) concluded that although laminated wood flooring has long been standard, nailable steel may the primary railcar flooring in the future. This trend, however, may be blunted by the reported[17] favorable comparative performance of laminated wood flooring. Current trends show rapidly decreasing use of wood in new railcars except for specialty cars such as coin-steel cars or in captive operations where the high cost of replacing wood floors over the life of a railcar can be absorbed by the parent company. Some laminated wood flooring will continue to be used for replacement of existing wood floors, but Fergus et al. predict that by the year 2000, or soon thereafter, this market will be almost entirely eliminated by the use of nailable steel.

The major reasons cited for preferring nailable steel to wood-base flooring products are:

- No break-through of forklifts and heavy loads.
- No damage from repeated nailing.
- No decay.
- No splintering or roughening from abrasive freight, pinch bars, or handling equipment.
- Stronger car all around as it acts as a structural part of the car.
- No fear or damage from hot box fires if equipped with friction bearings.
- No contamination from previous loading, although caulking material may absorb flour, sand or other materials.
- No fear of fire from sparks caused by cars having wood flooring and cast iron brake shoes.

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[16]Text under this heading is condensed from Fergus et al. (1977).

[17]Nemeth, L. F. 1976. Performance of a laminated wood and heavy duty nailable steel boxcar floor deck. Wood products. R & D Dept. Potlatch Corp. Reported at Ann. Meet., For. Prod. Res. Soc., July.

PARALLEL-LAMINATED VENEER

The possibility of laminating lumber from sliced or rotary-cut veneer has interested researchers and industrialists for many years, because of the potential for increased yield and uniformity of strength. Thick knife-cut veneer entered the scene when Lutz (1962) reported laminating ¼-inch-thick sliced white oak dried in a conventional veneer dryer.

Since 1967 interest has largely centered on rotary-peeled rather than sliced veneer, because rotary-peeling is a well-understood, simple, fast process in which veneer recovery is high. From work commencing in 1963, Koch (1967b) found that parallel-laminated rotary-cut veneer could be glued without difficulty into uniformly strong beams, and that butt joints did not seriously weaken the beams if laminae were thin and the joints staggered (see also Koch and Woodson 1968; Koch 1971b). In joists or beams with glue-joint planes vertically arranged, modulus of elasticity was about average for the species when low- and high-grade laminae were mixed and placed randomly. The 95-percent exclusion limit for modulus of rupture averaged higher if laminae were ½-inch thick rather than 1 inch thick.

From 8-ply, 12-inch-deep joists made in 1965 from 1/6-inch, rotary-peeled veneer, Koch (1973) concluded that logs too short for conversion to sawn structural lumber could be rotary-peeled advantageously, and the resulting veneer randomly laid up, and parallel-bonded into wide, long slabs with staggered butt joints placed in a controlled pattern. Such slabs, when gang ripped to obtain planks of desired widths, would yield joists or other structural lumber, having fairly uniform modulus of elasticity approximately equal to that for outer wood of the species. Moreover, in planks loaded as joists, distribution of defects within the several plies is random; modulus of rupture therefore varies less from piece to piece than in similar-size joists sawn from solid wood. With this system, yield per cubic foot is substantially increased, as peeling wastes less wood than sawing. Moreover, rafters and joists of any length can be made from short logs of fairly small diameter.

The literature on parallel-laminated veneer is primarily oriented toward softwoods, but principles elucidated also apply to hardwoods. Readers interested in properties of softwood parallel-laminated veneer will find the following references useful:

Reference	Subject	Species
Luxford (1944)	Strength of glued laminated rotary-cut veneers	Sitka spruce
Koch (1964ab, 1967bc, 1971b, 1973, 1975, 1976c)	Effects of veneer orientation, thickness, and joint placement on bending properties; economics	Southern pine
Koch and Woodson (1968) .	Placement of veneer by elastic modulus	Southern pine
McGowan (1971)	Parallel-to-grain tensile properties	Douglas-fir
Bohlen (1971, 1972ab, 1973ab, 1974, 1975)	Yield of product; bending, tensile, and shear strength	Douglas-fir

Reference	Subject	Species
Young (1972)	Industrial trials	Douglas-fir
FPL Press-Lam Team (1972, 1977)	Description of Press-Lam process and state of development	Southern pine and Douglas-fir
Jokerst (1972)	Stored-heat adhesive cure	Southern pine
Moody (1972)	Tensile strength of lumber laminated from ⅛-inch veneers	Southern pine and Douglas-fir
Moody and Peters (1972)	Strength properties	Southern pine
Schaffer et al. (1972)	General feasibility of the Press-Lam process	Southern pine and Douglas-fir
Civil Engineering (1972)	Structural applications of micro-lam lumber	Douglas-fir
Echols and Currier (1973)	Flatwise bending properties	Douglas-fir
Tschernitz et al. (1974)	Treatability	Douglas-fir
Gilb (1974)	Patent on truss joints with pin connectors	—
Hancock (1976)[18]	Manufacturing case history	Douglas-fir
Koehl (1976)	Joists with plywood webs	Douglas-fir
Strickler et al. (1976)	Duration of load characteristics	Douglas-fir
Harpole (1976ab; 1978)	Economic analysis, yield analysis	Softwoods and hardwoods
Braun and Moody (1977)	Beams with laminated-veneer tension lamination	Douglas-fir
Harpole and Aubry (1977)	Economic analysis	Douglas-fir
Youngquist et al. (1977)	Crossarms	Douglas-fir
Anderson and Harpole (1978)	Economic analysis	Southern pine
Mills (1978)	Market for long-span joists	Southern pine
Neubauer (1978)	Column strength	Douglas-fir
Kunesh (1978)	Strength, stiffness, and structural applications	Douglas-fir
Casilla and Chow (1979)	Fingerjointing of laminae	Western hemlock
Youngquist and Bryant (1979)	Production and marketing feasibility	Softwoods and hardwoods
Jung and Day (1981)	Strength of fasteners in parallel-laminated veneer	Douglas-fir

[18]Hancock, W. V. 1976. The production of LVL—a case history. 7 p. Paper presented at the seminar—Parallel laminated veneer for structural and specialty products, Oct. 4-5, Univ. Wis.

Hardwoods that grow on southern pine sites have important potential as the raw material from which to manufacture products of parallel-laminated veneer. An economic case can be made for utilizing very small oak and hickory stems in a small-scale operation to produce sawn veneer for parallel lamination into high-price furniture. (See section 28-2, an economic analysis). For major impact on utilization of the hardwood resource, however, products made from parallel-laminated veneer must likely utilize rotary-peeled veneer and be sold as structural commodities.

Two- or three-ply pallet deckboards of rotary-peeled oak are one possibility. Hann et al. (1971) described laboratory procedures for manufacturing such deckboards, and Kurtenacker (1975a) found that they performed adequately in use. Pallet parts, however, sell for significantly less money per ton than do long, wide joists of high strength.

Wellwood and Hyslop (1980) analyzed the economic feasibility of manufacturing such joists in Canada from aspen (*Populus tremuloides* Michx.), and concluded that plant investment could be recovered in about 4 years—possibly less. Schaffer and Moody (1977) examined the potential of manufacturing stress-graded laminated lumber from eastern hardwoods in the United States and indicated probability of both technical and economic success. See section 28-32 for an economic analysis of such an operation.

Even higher prices per ton are obtainable if the high-strength properties of parallel-laminated veneer are exploited in the manufacture of light-weight I-beam joists having tension and compresson chords of parallel-laminated veneer. (See sections 28-21 and 28-31 for economic analyses of manufacture of such I-beams with laminated-hardwood-veneer chords.)

Youngquist and Bryant (1979) identified the following additional products as potentially suitable for manufacture from parallel-laminated veneer: window and door headers, ridgepoles in manufactured housing, mobile-home truss chords, truck and container decking, and scaffold planking. Tschernitz et al. (1979) have studied the manufacture of crossties from thick hardwood veneer; see preceding section *Crossties from parallel-laminated veneer* and figure 22-57 bottom.

One of the most promising potential uses for parallel-laminated hardwood veneer was early identified by Yao (1973) as furniture. A specific case is structural frames for upholstered furniture which require the strength generally found only in lumber. Text discussion related to figures 20-16 and 20-17 describes manufacture and properties of frame stock laminated from northern red oak veneer, and an economic analysis of the manufacture of laminated frame stock is provided in section 28-16. (See also Hoover et al. 1978, 1979, and Eckelman et al. 1979.)

A pioneering commercial enterprise in Stelle, Ill., manufactures parallel-laminated hardwood-veneer cants for remanufacture; the material is available in lengths to 8 feet, widths to 34 inches, and thicknesses to 4 inches (Mace 1977).

All factors considered, manufacture of parallel-laminated hardwood-veneer products should become a significant segment of the eastern hardwood industry. Availability of equipment particularly suited for the rapid economical production of rotary-peeled veneer from small hardwood bolts (fig. 18-252) is an important key to such manufacture.

WOOD-DISK PATIOS

An attractive and serviceable patio surface can be constructed of treated wood disks cut at least 3 inches thick from hardwood logs 12 inches and larger in diameter (fig. 22-66). Bois (1967) described procedures for excavating the patio area about 7 inches below desired finish grade, outlining it with 4/4 form boards, spreading and tamping dampened sand to a 4-inch depth within the patio area outlined by the form boards, placing the treated disks on the sand and in close contact with each other, and then filling spaces between disks with tamped crushed or natural stone of ½- to ¾-inch size.

The disks must be treated with preservative before laying, to prevent early loss through rot. Bois suggested soaking freshly cut green disks at least 24 hours—preferably 48 hours, in tubs filled with pentachlorophenol in mineral spirits. After the disks are in place and have dried somewhat, so that checks have developed, they should be sprayed with the preservative solution, thoroughly drenching bark and sapwood. He recommended that, for long life, the patio should receive such spray treatment annually.

A double-diffusion process for treating, in which the green disks are first soaked overnight in a 4-percent sodium fluoride solution and then in a 4-percent copper sulfate solution, is even more effective in prolonging patio life.

Figure 22-66.—Site for 20- by 40-foot patio was bulldozed out of a steep slope and framed with retaining wall of native stone. Some 200 preservative-treated oak disks, 3 inches thick, were used. (Photo from Bois 1967.)

22-11 WOOD STRUCTURES

Pioneers in the Appalachian region routinely built houses, commercial buildings, and a great variety of farm structures of round and hewn white oak posts and beams. Oak was also much used for floors, walls, and millwork; and structures were commonly roofed with split white oak shakes. Log cabins of oak were also common. Since pioneer days, however, hardwood has lost favor as the primary material for structures. Softwood studs, joists, rafters, and sheathing now are predominant. There remain, however, some structures for which hardwood can be competitive. Following are some references relating to a few of these structures:

Subject	Reference
Horse stalls from oak, hickroy, or ash	Cooper and Landt (1973)
Poultry coops from oak, elm, and ash	Miller (1978)
Red oak shade shelters for hogs	Cooper and Barham (1970)
Slotted hickory floors for swine	Walters et al. (1970)
Recreation structures from low-grade hardwood	Cooper and Caraway (1975)
Picnic structures and tables of oak and hickory, and their markets	Cooper (1963); Sesco (1969)
Log houses (usually not hardwood, but information is applicable to hardwood)	Dunfield (1974); Carlson (1977); Rowell et al. (1977)
Stackwall house in which logs 24 inches long are stacked at right angles to the wall	Park (1978)
Pole house construction	American Wood Preservers Institute (n.d.)
Hardwood use in mobile homes	Martens and Koenick (1970); Dickerhoof (1978ab)
Conventional houses and demand for them	Anderson (1970); Marcin (1977)
Survey of codes and standards for light-frame construction	Sherwood (1980)
Related to ships and boats	
• Preservative-treated, laminated red oak minesweeper	Anonymous (1957)
• Laminated and steam-bent white oak launch frames	Luxford and Krone (1962)
• Durability of resorcinol glue in boat gusset joints	Selbo (1948b)
• Seasoning, storage, and handling ship planking	Peck (1945)
• Small boat building	Gardner (1977)

22-12 HANDCRAFT PRODUCTS

Among the hardwoods that grow on southern pine sites are numerous species favored for manufacture of handcrafted articles. Bentwood products such as the handmade chair described in section 28-2 are readily made from white oak, southern red oak, hickory, or ash. Sweetgum, white oak, and hickory turn readily. Carved sculptures can be beautifully executed in ash and oak. Other species also have special qualities needed in particular craft articles. Readers interested in the manufacture of handcrafted articles will find useful references listed on the initial page of chapter 18.

Marketing of handcrafted products is usually difficult for artisans not experienced in wholesale and retail selling. Kallio and Lindmark (1972) described the operation of a cooperative formed to stimulate the manufacture and sale of handcrafted products in a rural area of Kentucky. The cooperative, which has minimal dues, maintains 30 to 40 active participants who provide inventory for, and manage, a retail store and wholesale outlet. A shop is also provided with 20 work stations with room for 27 trainees and craftsmen.

22-13 CHEMICALLY MODIFIED WOOD

Treatments to modify properties of wood are summarized in Koch (1972, p. 1128-1143). Only two of these treatments will be discussed here—wood-plastic composites and impregnation with polyethylene glycol. See also sub-section STABILIZATION TREATMENTS in section 21-5 and figure 21-12.

WOOD-PLASTIC COMPOSITES

Vinyl monomers can be used to stabilize wood dimensionally and improve its mechanical properties without impairing desirable aesthetic qualities. Unlike deep-colored phenol-based, theremosetting polymers, the vinyl polymers are clear, colorless, hard thermoplastic materials. Polymerizing the vinyl monomers in the void spaces of the wood does not discolor the wood or alter in any way its eye-appealing nature. The feel of the surface of a wood-vinyl plastic object is like wood—in textile terminology, it has a good hand. Hardness is greatly increased by the treatment.

Vinyl monomers can be polymerized or cured in the wood by radiation or by heating with free radical catalysts. Beall and Witt (1974) provided data on bending properties of white ash and red oak sp., impregnated when kiln-dry with methyl methacrylate, and polymerized by radiation. Their specimens measured 1- by 1- by 16 inches and were broken in bending after equilibration to 6 percent moisture content. Modulus of rupture, fiber stress at proportional limit, and modulus of elasticity were all increased significantly by the treatment (table 22-29). In spite of the difference in loading (61 percent for white ash, and 31 percent for red oak), mechanical properties of treated specimens of the two species did not differ significantly.

TABLE 22-29—*Mechanical properties of small static-bending specimens of white ash and red oak impregnated with methyl methacrylate and cured, compared with untreated controls*[1] (Beall and Witt 1974)

Species and treatment	Modulus of rupture	Fiber stress at proportional limit	Modulus of elasticity
		Psi	
White ash			
Untreated control	15,200	6,870	1,410,000
Treated (61% loading)[2]	23,900	11,100	2,200,000
Red oak sp.			
Untreated control	16,000	7,600	1,560,000
Treated (31% loading)[2]	20,400	10,500	2,100,000

[1]Specimens were tested at 6-percent moisture content; each value is the average for 16 specimens of clear wood measuring 1 by 1 by 16 inches.

[2]Ratio of polymer to ovendry wood mass.

Siau et al. (1978) vacuum-impregnated with methyl methacrylate specimens cut from 6-inch-diameter trees of 22 hardwood species grown on southern pine sites (listed in table 3-1). They found that fractional volumetric retentions of monomer, and cured polymer, were related to longitudinal air permeabilities and the anatomical structure of the species. Siau et al. concluded that the five diffuse porous woods (red maple, yellow-poplar, black tupelo, sweetgum, and sweetbay) are very suitable for the production of wood-polymer composites. Difficult-to-treat, and unsuitable for wood-polymer composites were hackberry, white oak, post oak, blackjack oak, black oak, and low-permeability cherrybark oak. Permeable cherrybark oak, the remaining red oaks, and the ashes, elms, and true hickory were moderately permeable and appeared moderately suitable for manufacture of wood-polymer composites.

PRODUCTS STABILIZED WITH POLYETHYLENE GLYCOL

The polymers of dihydric alcohols are polyethers with an oxygen atom separating the hydrocarbon groups and with reactive hydroxyl groups only on the ends; up to molecular weights of 6,000, they are highly soluble in water. Because of the low vapor pressure of polyethylene glycol (PEG), it remains in the cell walls when wood impregnated with it is dried; this bulking action prevents the wood from shrinking. PEG-bulked wood feels moist when relative humidity is above 70 percent because of its hygroscopicity, but certain polyurethane finishes tend to reduce this. The treated wood is highly stable to changes in humidity, but in water the PEG is leached out with time. Treatment causes a slight loss in abrasion resistance and bending strength, but toughness is essentially unaffected when the wood contains about 45 percent PEG. With many woods, the anti-shrink efficiency is about 80 percent. PEG treatment is used where wood must have dimensional stability to prevent cracking and checking. Art carvings can be preserved in this manner.

Merz and Cooper (1968) provided data specific to black oak. They treated freshly sawn, green heartwood blocks measuring 1.5 inches long the grain, 3 inches in the tangential direction, and 1.5 inches in the radial direction. Treatment consisted of soaking the blocks in a 50-percent water solution of PEG 1000 held at 140°F. Observations of wood stability were made at intervals up to 384 hours of treatment. They found that a 96-hour treatment reduced tangential and volumetric shrinkage by about 65 percent and radial shrinkage by 68 percent. Longer treatments reduced shrinkage even more, but not sufficiently to be of practical significance. Warping of the blocks was inconsequential after 96 hours; some hairline checks were observed, but their occurrence was not related to treatment time. The blocks absorbed PEG in amounts equivalent to 44 percent of their dry weight after 96 hours, and only an additional 14 percent in 228 more hours.

Englerth and Mitchell (1967) suggest that stabilized low-cost bowls can be made from permeable 8-inch-diameter green log sections that are free of splits. By their procedure, one end of the log is sawn smooth and a turning-lathe faceplate securely screwed to it. The exterior of the green wood is shaped to oversize contour and the interior hollowed, leaving the wall ⅜- to ½-inch thick. This rough-turned bowl is soaked in PEG for about 3 weeks. It is then dried to about 7 percent moisture content, refastened to the lathe faceplate, and finish turned until the walls are ⅛- to ¼-inch thick, and the bottom about ¾-inch thick. To complete the bowl, polyurethane varnish is applied to the sides, the excess base thickness cut off, and the bottom varnished.

Procedural details for making other PEG-treated products can be found in Mitchell (1972).

22-14 PULPWOOD AND PULPCHIPS

By 1978 pulpwood consumption in domestic mills had increased thirteenfold since 1920, rising from 6.1 million cords to 78.6 million cords (6.2 billion cubic feet). The 1978 volume data includes 45.9 million cords of roundwood and 32.7 million cords of chips and sawdust obtained from slabs, edgings, veneer cores, and other residues of primary manufacturing plus an unknown quantity of forest residues. In addition, export demand increased almost 24 times to 11.8 million cords (0.7 billion cubic feet). As a result of such growth, about half of the cubic volume from domestic forests is used as pulpwood. By 2030, consumption of pulpwood in U.S. mills is projected to be about 180 million cords (U.S. Department of Agriculture, Forest Service 1980).

Softwoods have long been preferred for pulp and paper products because of their longer fiber and lighter color. In recent decades, however, use of hardwoods has increased rapidly. In 1950 less than 15 percent of the pulpwood used in U.S. mills was hardwood, but by 1978, hardwoods comprised more than 25 percent of the total. Such trends resulted from technological improvements in pulping, availability of substantial volumes of hardwood at lower costs per ton of fiber, improvement in properties of many grades of paper and board with the addition of hardwood pulps, and rising competition and prices for softwood timber. The trend toward increased use of hardwoods will be hastened by a favorable supply situation; the proportion of hardwood fiber used in U.S. mills should continue to rise, reaching about 32 percent in 2000 and 38 percent in 2030 (U.S Department of Agriculture, Forest Service 1980).

Harvesting, manufacture, use, measurement units, and prices of pulpwood and pulpchips are discussed elsewhere in this text, as follows:

Subject	Text reference
Harvesting and storing	Chapter 16
Economics of forest residue chip harvesting	Section 28-9
The chipping process	Sections 18-9, 18-24, and 18-25
Pulping	Chapter 25
Chip yields	See Index under heading *Pulp chips*
Chippable residues	See Index under heading *Yields and measures, residues*

Subject	Text Reference
Pulpwood prices	Figure 29-41AB
Pulpchip prices	Figures 25-2 and 29-42
Pulp mill locations	Figure 25-1
Pulpwood consumption and production	Figure 29-5ABC

22-15 ENERGY WOOD[19]

Fuelwood consumption in 1976 was about 18 million cords or 1.4 billion cubic feet; this total included approximately 330 million cubic feet of roundwood from growing-stock trees and 270 million cubic feet of primary plant byproducts. Total volume was equivalent to about 21 million tons of dry wood. Additionally, some 10 million tons (dry basis) of bark was consumed for fuel in 1976.

RESIDENTIAL USE OF FIREWOOD

Roundwood was the major source of energy in the United States until the 1880's. Fuelwood use dropped sharply in the first half of the present century, replaced by fossil fuels and electricity. Difficulties in fossil fuel supply during World War I, The Great Depression, and World War II brought renewed interest in wood, but these episodes had little effect on the rapid decline of fuelwood consumption. By 1970, less than 2 percent of all households in the United States used wood as their primary fuel for heating and less than 1 percent as their primary cooking fuel.

With the unprecedented, and continuing, rise in the price of fossil fuels and electricity (figs. 29-49 and 29-50), an increasing number of households (estimated at 912,000 in 1976) is using wood as a primary source of heat. Much greater numbers are using wood for supplementary heat or for esthetic purposes. In 1976, 58 percent of all new single-family homes built had one or more fireplaces, as compared to 44 percent in 1969. The number of wood stoves, not included in the figure for fire places, has also risen substantially. Thus, it is projected that residential use of wood fuels, especially from roundwood, will increase steadily from 6 million cords in 1976 to some 26 million cords in 2030. Demands may rise much beyond this projected level, unless major new fossil-fuel discoveries are made, or alternative sources of oil and gas, such as tar sands, oil shale, and geopressurized salt domes, become sufficiently developed before then to reverse this trend.

INDUSTRIAL AND COMMERCIAL USE OF FUELWOOD

Of the nearly 800 million cubic feet (11 million tons, dry basis) of wood byproducts used as fuel in 1976, about 90 percent went to produce steam heat

[19]Text under this heading is condensed from U.S. Department of Agriculture, Forest Service (1980).

and electricity at wood processing plants. Additionally, pulpmills used about 5 million tons, dry basis, of bark removed from roundwood pulpwood and 61 million tons of spent liquor solids for fuel. Wood processing plants in the future are likely to use as fuel nearly all their bark and most of their wood byproducts not sold for wood pulp or particleboard furnish. Should fossil fuel prices continue rising, some plants will bring in nearby forest residues, or urban residues, to supplement mill fuels. Some mills will sell excess power to utility companies.

Currently, a small amount of mill wood byproducts and bark is used for producing heat or steam power at other manufacturing plants or at institutional or commercial buildings. There is much interest in the possibility of increasing the use of wood for such purposes—especially as an outlet for forest residues and wood from cull trees, thinnings, and dead trees. It is difficult to predict the eventual extent of such use.

In 1978, wood and bark provided all or part of the fuel requirements of some 10 or 12 utility plants in the United States. The ultimate magnitude of fuelwood use by steam-electric plants will depend on many factors, such as price trends for coal and oil in comparison to fuelwood, practical aspects of developing assured long-term fuelwood supplies, problems in collecting and storing very large quantities of wood or bark, and advantages or disadvantages of the various fuels in meeting emission control standards. The National Energy Act of 1978 provides incentives for cogeneration and use of fuels other than oil and gas in steam-electric facilities. Because fuelwood requirements of even small steam electric plants are very large, the potential impact of a single such installation on local timber supply could be great. If many were developed, there would be major impacts on timber resources, and especially hardwood resources, over large areas. Projections of timber demand for steam-electric utilities cannot be predicted reliably because of indeterminate factors affecting such demand.

Because the eastern hardwood resource is underutilized and is available from private landholdings adjacent to large populations, this resource will be especially attractive for fuel. Harvesting, processing, and marketing of hardwood for fuel are discussed elsewhere in this text, as follows (see also index under heading *Fuelwood*):

Subject	Text reference
Heat of combustion of wood and bark	Table 9-12
Technology of burning and other processes for obtaining energy from wood	Chapter 26
Harvesting technology	Chapter 16
Moisture content of wood and bark	Table 8-2
Drying of chips	Figures 20-18AB
Drying of roundwood and splitwood	Figures 20-15 through 20-17
Economics of—	
• Harvesting fuel chips	Section 28-9
• Harvesting forest residue in bale form	Section 28-7
• Operating a diesel tractor on wood gas	Section 28-1
• Hardwood pyrolysis	Section 28-10
• Wood charcoal production with a Herreshoff furnace	Section 28-20
• Hardwood gasification	Section 28-6
• Ethyl alcohol production (large scale)	Section 28-33
• Ethyl alcohol production (small scale)	Section 28-5

22-16 OTHER PARTICULATE WOOD

Wood in particulate form has numerous uses in addition to energy, paper, and fiberboard production. For many of these uses, particle form is critical; metallurgical chips, flakes for structural panels, excelsior, and wood flour (see section 18-26) are examples of such products. Products for which particle form is less critical include mulches, and poultry and animal litter (see sec. 13-7).

METALLURGICAL CHIPS[20]

In the electric smelting processes (fig. 22-67) that extract or reduce metals from their ores, **woody reductants** in the form of **metallurgical chips** (fig. 22-68) are used, as are other reductants such as coal and coke. Electric smelting is a continuous process in which a mixture of ore and reducing agents—wood chips, coke, and coal—is added into the top of an electric furnace at regular intervals. Carbon electrodes submerged in the mix melt the material, which is periodically tapped from the bottom of the furnace.

During smelting oxygen in the ore is combined with carbon from the reducing agents, thereby freeing the metal. The carbon and the oxygen form carbon dioxide, which escapes from the furnace as gas.

Wood constitutes 10 to 75 percent by weight of the furnace mix. This proportion varies according to the origin and particle sizes of the ore, the type and quality of the alloy being produced, the furnace design, the moisture content and size of the wood particles, and the artistry of the smelter operator. The metallurgy of electric smelting depends upon art as well as upon science. Hence the use of wood chips appears to reflect the individual metallurgist's or smelter's convictions as well as technological and economic considerations.

Although wood chips provide some of the carbon for chemical reaction, their primary usefulness in the charge is due to their bulk. Some of the reasons metallurgists cite for the use of wood in the charge are:

- To provide a large surface area for chemical reaction to take place more completely and at improved rates.
- To maintain a porous charge, thereby promoting gentle and uniform—instead of violent—gas venting.
- To help regulate smelting temperatures.
- To keep the furnace burning smoothly on top.
- To reduce conductivity.
- To promote deep electrode penetration.
- To prevent bridging, crusting, and agglomeration of the mix.
- To make possible the smelting of finely divided raw materials without sintering.
- To reduce dust, metal vapor, and heat loss; and as a result to improve working conditions near the furnace.

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[20]Text under this heading is condensed from Wartluft (1971).

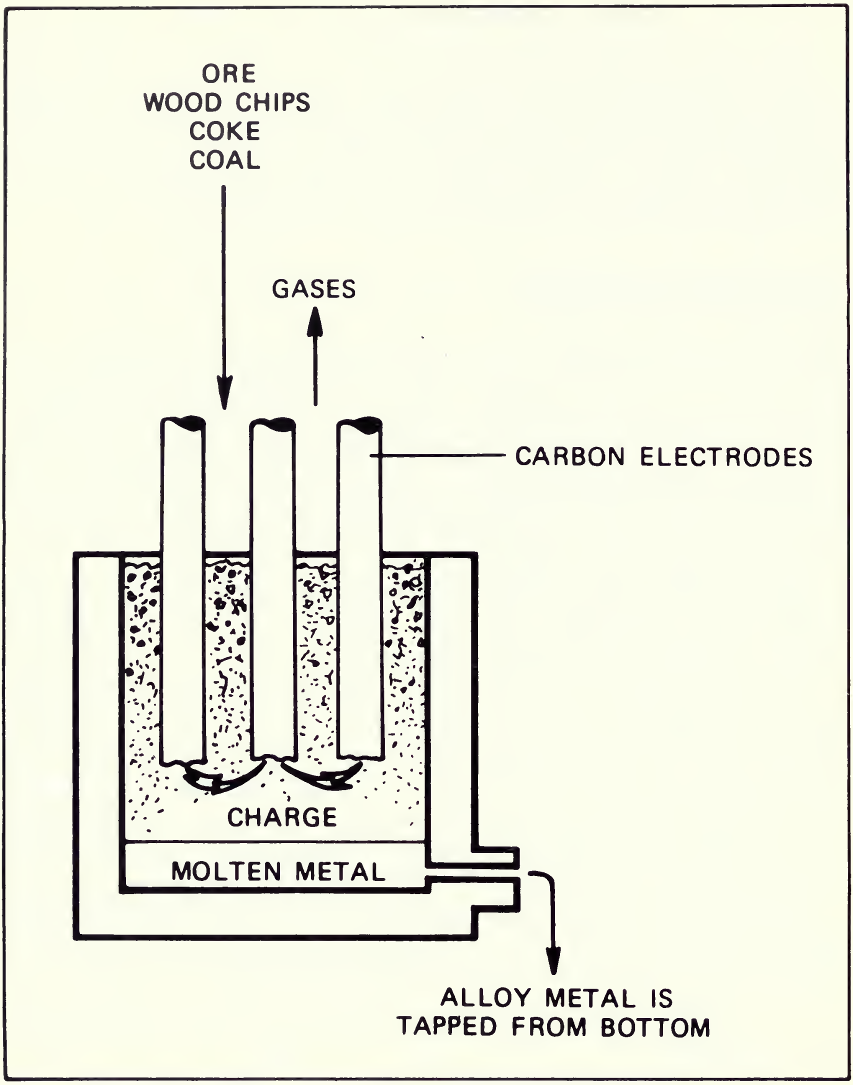

Figure 22-67.—Diagram of a submerged-arc electric furnace. The ore, wood chips, coke and coal—introduced at the top of the furnace—are mixed in varying proportions to produce the alloy desired. (Drawing after Wartluft 1971.)

Annual demand.—The electrometallurgical industry consumed about 796,000 tons (green weight) of wood in 1970—about enough to operate a 500-ton-per-day pulpmill for a year. In 1970 59 percent, 480,000 tons, was consumed by plants in the Ohio and Tennessee River Valleys (fig. 22-69). Consumption varies from 6,000 to 78,000 tons per plant per year. Average annual consumption per plant is 36,000 tons. In 1970, bark residues represented about 5.3 percent of the total amount of woody reductants consumed. Of these bark residues, 30,400 tons (green basis) were hardwood bark and 12,000 tons

Figure 22-68.—A comparison of metallurgical chips and pulp chips. (Photo from Wartluft 1971.)

were pine bark. Wartluft (1971) concluded that demand for metallurgical chips should increase at about 6 percent a year. His publication lists the names and locations of 22 plants that used metallurgical chips in 1970.

Wood species and form.—Hardwoods are preferred because they last longer in the furnace. Most ferro-alloy plants prefer green wood, although some buy dry wood to reduce transportation costs. Metallurgical chips should be free of decay and also of foreign material that might impart impurities to the alloys being produced. Because bark frequently carries dirt, it is undesirable. However, in 1970 16 of the 22 plants in the United States accepted limited proportions of bark.

Chip size is the most important specification. In the Ohio and Tennessee River Valleys, desired particle size ranges from 2.5 inches square and 0.5 inch thick to 8 inches square by 1 inch thick. Chips larger than these, as well as some very stringy hardwood barks, are excluded primarily by the plant's materials handling equipment. Small particles, including sawdust, generally are of no benefit because they burn too fast.

Chip manufacture.—For a review of the technology of manufacturing large chips, see: Antezana, L.F. 1985. Maxi-chippers. *In* Proceedings of the symposium "Comminution of wood and bark" held October 1-3, 1984, Chicago, Illinois; available from the Forest Products Research Society, Madison, Wisconsin.

See also, section 18-24.

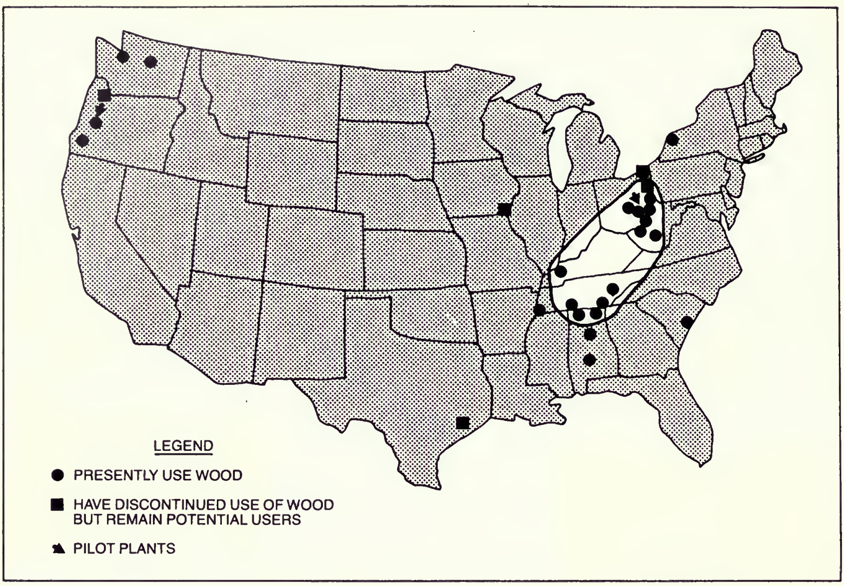

Figure 22-69.—Location of electrometallurgical plants in the United States that used wood chips in 1970 and those that have discontinued use. Wartluft's (1971) study was concentrated in the Ohio and Tennessee Valley region (circled area).

FLAKES FOR STRUCTURAL PANELS

Mechanical properties of structural panels of hardwood flakes bonded with thermosetting resins are extremely sensitive to the dimensions and density of the flakes. These relationships are explained in chapter 24. Manufacture of flakes for structural boards is discussed in section 18-25. Present demand in the South for such flakes is minimal, but by year 2000—probably earlier—there will likely be numerous flakeboard plants in operation that will consume significant quantities of southern hardwood flakes. The economic feasibility of such plants is discussed in Koch (1978), and in sections 28-14, 28-19, 28-23, 28-24, 28-25, 28-26, 28-27, 28-28, 28-29, 28-31, and 28-32.

EXCELSIOR[21]

During the first two-thirds of this century, **excelsior**—thin ribbon-like strands of wood—was sold in considerable volume. In 1939 excelsior production of 53 plants in the United States totalled about 122,000 tons. Production in 1946 in the Lake States was significantly greater than in 1939. Value of excelsior produced annually in the United States declined from about $5 million in 1958 to about $3 million in 1972; by 1977, however, shipments amounted to about $7 million (fig. 22-70).

[21]Text under this heading is condensed from U.S. Department of Agriculture, Forest Service (1956).

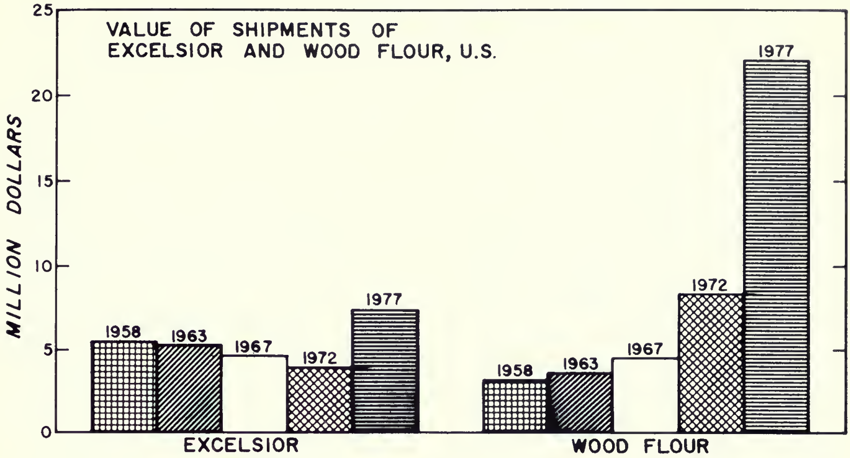

Figure 22-70.—Value of shipments of excelsior and wood flour in the United States, 1958-1977. (Data from Bureau of the Census.)

Excelsior is used for protective packing material, low-priced padding in upholstery and mattresses, filtering material, animal bedding, and toy stuffing. It may also be used as a filler in cement and magnesite boards. Excelsior is usually cut from species that are light in weight and color, soft, tough, straight-grained, absorbent, and free of odor. For some uses slight odor is not objectionable, and excelsior having some resin is acceptable. For use as packing and upholstery, excelsior must be resilient and expand readily after compression.

At one time or another excelsior has been made from most native woods except the hardest and most pitchy species. The bulk of commercial excelsior, however, has always been produced from cottonwood (*Populus deltoides* Bartr. ex Marsh), aspen (*Populus tremuloides* Michx.), southern pine, and basswood (*Tilia Americana* L.). In the late 1950's cottonwood and aspen accounted for about 50 percent of the total production, southern pine 40 percent, basswood 8 percent, and other woods 2 percent.

The transportable limit for excelsior wood, because of costs, is about 50 to 100 miles. Bolts are usually cut 37 or 60 inches long, and must be free from growth defects and reasonably straight-grained. They are peeled by hand or machine, usually at the time of cutting, and stacked at roadside to dry for 3 to 6 months before being transported to a plant where they are stacked in the yard or stored under cover to complete the drying. A shed may contain 3,000 to 5,000 cords or more in various stages of drying. The wood is not allowed to dry longer than 2 years, to avoid decay, which renders it worthless for excelsior use. Well-seasoned bolts are trimmed and cut to the proper lengths for excelsior making. Following are typical specifications:

> Wood to be sawed 5 feet long, peeled clean of bark; sticks to be straight, sound, free from large knots, and not less than 4 inches at the small end. Pieces 4 inches to 7 inches not to be split; bolts 7 inches to 11 inches to be split once; from 11 inches to 14 inches quartered; and over 14 inches split in proportion.

Excelsior machines, which may be horizontal or upright, carry a number of small knives mounted in a heavy frame to score parallel lines along the grain of the face of the bolt; a slicing knife then shaves the surface (like a carpenter's plane) to the depth of the score marks, thus producing the individual strands of excelsior. In both horizontal and upright machines, the bolt is held firmly between two rollers that automatically feed it into the knives. The upright machine is made in single units or in batteries of two or four machines. Horizontal equipment is usually installed in units of four or more machines. Excelsior must be carried away from the machine as it is cut, to prevent clogging.

The average machine cuts from 800 to 1,200 pounds of excelsior in an 8-hour day. A cord of dry wood yields 1,800 to 2,000 pounds of excelsior, varying with the dimensions and quality of the bolts, the grade of the product, and the kind of wood. Waste in manufacture is approximately one-fourth of original wood volume. Much of this waste wood is used in bailing or as fuel.

Excelsior is graded according to the thickness and width of the strands and the kind and color of the wood. Standard excelsior is 18 inches long or the length of the stick, 0.01 inch thick, and is divided into width classes as follows: fine, 1/26-inch wide; medium, ⅛-inch wide; and coarse, 7/32-inch wide. Certain special grades of excelsior, classified as "wood wool", vary in dimensions according to specifications, but strands are usually 0.005 inch thick and 1/32-inch wide. Wood wool is made as thin as 0.002 inch and as narrow as 1/64-inch. Material of this type is manufactured only for special purposes. Coarse excelsior varies from 0.012 inch to 0.02 inch in thickness and from 1/32- to ¼-inch wide. Probably 80 to 90 percent of the output of excelsior is of the standard and coarse grades.

Excelsior is sold by the ton. It is ordinarily packed in bales weighing about 100 pounds, but may be packed in bales weighing 200 pounds or more.

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23

Fiberboards

This chapter is a condensed version, reprinted here with the permission of the authors, of U.S. Dept. of Agriculture, Agriculture Handbook 640, "Fiberboard manufacturing practices in the United States," by Otto Suchsland (Michigan State University) and George E. Woodson (Louisiana Tech University). The contributions to this project by these two Universities and their Experiment Stations are acknowledged. The project was performed under Cooperative Agreement No. 19-323 of the U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station.

CHAPTER 23
Fiberboards

CONTENTS

Chapter 23
Fiberboards[1]

23-1 INTRODUCTION

Fiberboards comprise one category among numerous reconstituted products (fig. 23-1) made from southern hardwoods, including plywood (secs. 22-9 and 22-10) particleboard and flakeboard (ch. 24), and paper (ch. 25). Fiberboards differ from plywood and flakeboard in that they are composed of cellular-size particles bonded together with little or no adhesive. Paper, also made from cellular-size particles, is continuously formed wet into thin sheets and dried continuously over hot rolls (fig 25-19); fiberboard, however, may be formed dry as well as wet (fig. 23-2), is usually 1/10- 3/4-inch thick, and is usually (except for insulation board) platen pressed.

Fiberboard was first made in this country by the **wet process** (fig. 23-2 top). **Dry-process** boards (fig. 23-2 bottom) were developed more recently as an extension of the particleboard industry.

Fiberboards are also classified by density. **Insulation board,** wet-formed in thicknesses from ⅜- to ¾-inch, has lowest density. **Medium-density fiberboards (MDF)** are made by both wet and dry processes in intermediate densities. MDF-wet, with thickness range from ¼- to ½-inch, is generally used as siding for buildings. MDF-dry, in thickness from ⅜-inch to 1 inch, competes with particleboard as core material in furniture panels. High-density fiberboard, manufactured in thickness from 1/10- to 5/16-inch, is called **hardboard;** although there are significant differences in hardboard-wet and hardboard-dry, they compete for the same markets.

The foregoing classification of fiberboards differs from definitions of voluntary product standard ANSI/AHA A-135.4 promulgated by the American Hardboard Association (U.S. Department of Commerce 1973a, 1982), which defines hardboard as any fiberboard (wet or dry) pressed to a density of 31 pounds per cubic foot (specific gravity 0.50) or greater. Thus this standard does not recognize MDF as a separate classification, nor does it include MDF-dry, which is manufactured and traded under a different standard developed under the auspices of the National Particleboard Association. In the trade MDF-wet is called hardboard, and the MDF-dry is called medium-density fiberboard. Insulation board is defined as a fiberboard ranging in density from 10 to 31 pounds per cubic foot, corresponding to a specific gravity range from 0.16 to 0.50 (U.S. Department of Commerce 1973b; American Society for Testing and Materials 1978).

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[1]Chapter 23 is greatly condensed from Suchsland and Woodson (1985), readers needing additional information on the subject should consult the source document.

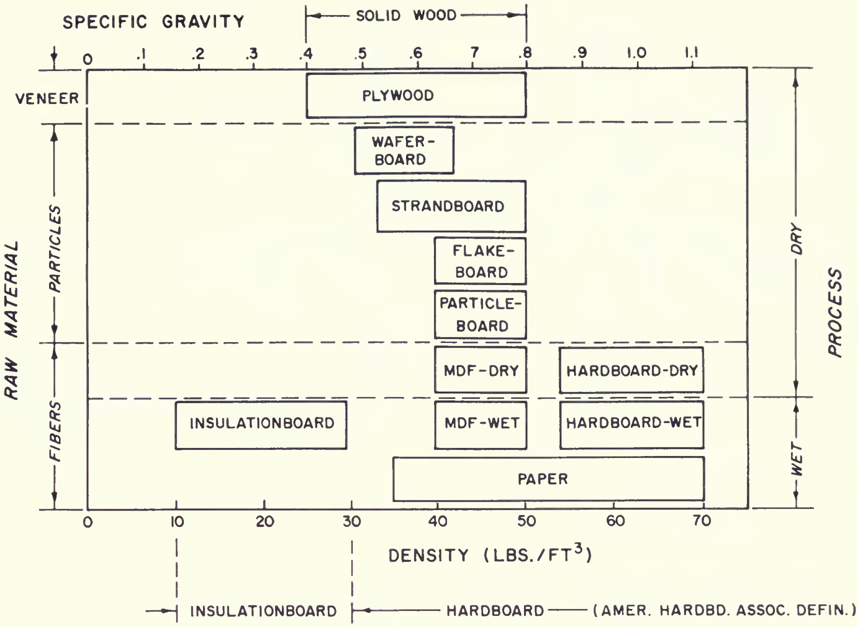


Figure 23-1.—Classification of reconstituted wood products by particle size and product density. MDF means medium-density fiberboard. (Drawing from Suchsland and Woodson 1985).

23-2 THE INDUSTRY

Insulation board manufacture began in the United States during World War I. The first hardboard plant was built in 1926. Medium density fiberboard (MDF-dry was developed in about 1965, and its manufacture expanded rapidly during the 1970's.

The fiberboard industry, with the possible exception of the MDF-dry component, is mature, and its growth has slowed (figs. 29-11, 29-12B, and 29-13). Southern hardwoods can be effectively used in fiberboards and the availability of these woods has influenced, and will continue to influence, plant location. Future growth is correlated with the housing market (figs. 23-3 and 29-4).

INSULATION BOARD

Insulation board is produced in 12 plants (table 23-1), 7 of which are in the South; only 1 is in the West. In the southern plants, hardwood usage varies with location and season; in plants designed to accept hardwoods, and in seasons sufficiently dry to log hardwood bottoms, the furnish may contain up to 90 percent hardwood. Between 1972 and 1981 only one insulation board plant opened; six plants shut down between 1960 and 1981. Annual capacity and production are shown in figure 29-11. Insulation board products are classified as

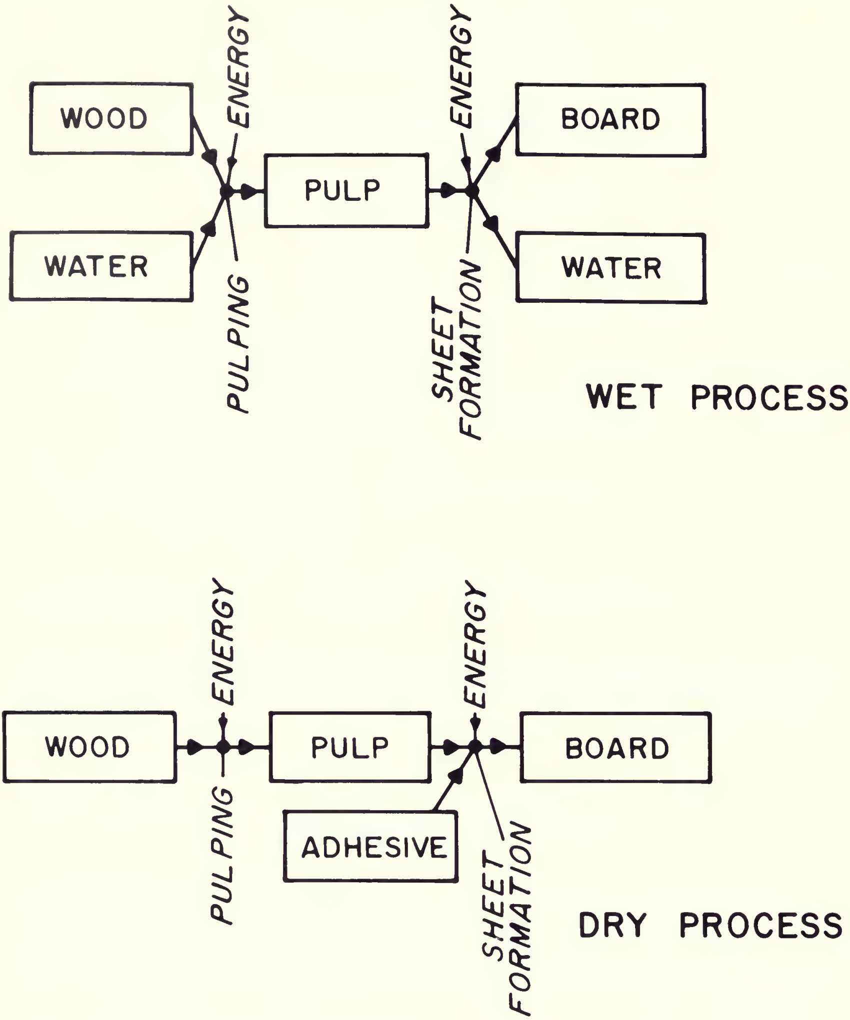


Figure 23-2.—Schematic representation of wet and dry fiberboard processes. (Drawing from Suchsland and Woodson 1985.)

exterior, interior, and industrial; the exterior products account for about half the tonnage manufactured (fig. 23-3). The market for sheathing, a major exterior product, is expected to decline because of competition from gypsum board and foil-backed structural-foam panels. Stricter flame-spread restrictions in building codes, which favor mineral board and plastic substitutes, are also expected to reduce use of interior building board and mobile-home board.

Exterior.—Exterior-class boards are categorized as follows: **sheathing,** a low-price board used in house construction for its moderate insulation value, noise-control properties, and bracing strength; **roof decking** is laminated with water-proof adhesive from sheets of insulation board to provide insulation and a finished interior ceiling surface; **roof insulation** provides insulation but not a

TABLE 23-1.—*Insulation board plants in the United States, 1977* (U.S. Environmental Protection Agency 1979, updated in 1983 by Suchsland and Woodson[1])

Company	Location	Annual capacity (½-inch basis)[1]	Other products manufactured
		Million square feet	
Armstrong Cork	Macon, Ga	400[2]	
Boise Cascade	International Falls, Minn.	210	Hardboard
Celotex	Marrero, La.[4]		
	L'Anse, Mich.[3]	737	
	Sunbury, Penn.[3]		
Flintkote	Meridian, Miss.	200	
Georgia Pacific	Jarratt, Va.[3]	210	Hardboard (1978)
Huebert Fiberboard	Boonville, Mo.	50	
National Gypsum	Mobile, Ala.	192	
Temple Industries	Diboll, Tex.	220	Hardboard
U.S. Gypsum	Lisbon Falls, Me.		
	Pilot Rock, Ore.[3]	271	Hardboard (all facilities)
Total		2,400	

[1]These are approximate capacities as they depend upon product mix. Figures quoted are for mills operating 24 hours/day, 6⅔ days/week, 50 weeks/year.

[2]Understated due to heavy tile production. If operated as a sheathing mill, capacity would increase 20 percent.

[3]No effluent.

[4]Utilizes bagasse.

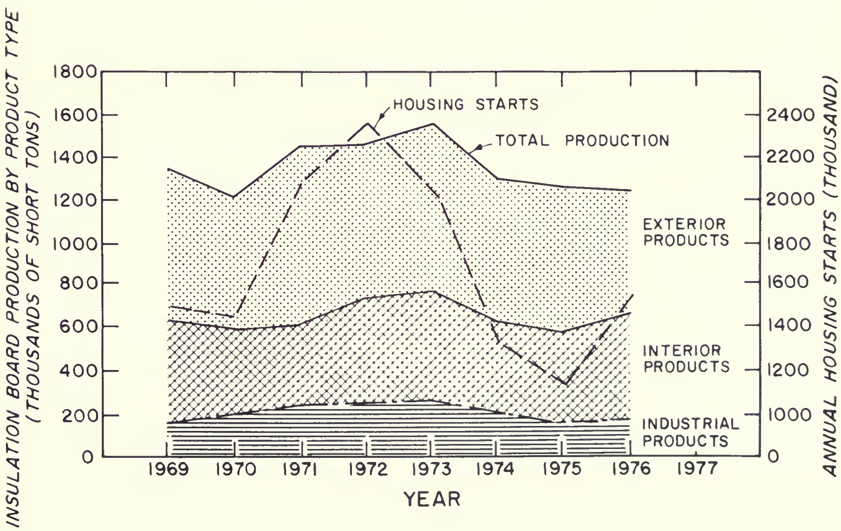


Figure 23-3.—Production of insulation board, by classification, in the United States. (Drawing after U.S. Environmental Protection Agency 1979.) Insulation board shipments in 1981 were 2.575 billion square feet ½-inch basis. (Current Industrial reports, U.S. Dept. of Commerce, Bureau of the Census, MA26A (81)-1.)

ceiling surface; aluminum-siding **backer board** is used to improve insulation of aluminum siding.

Interior.—Building board is a general-purpose board for interior construction. **Ceiling tile** is embossed for decorative interior use, usually to improve architectural acoustics. **Sound deadening board** is employed to control noise levels in buildings.

Industrial products.—Industrial insulation boards include mobile-home board, expansion-joint strips, and boards for the automotive and furniture industries.

HARDBOARD

Excluding those that manufacture MDF-dry, there are 23 plants manufacturing hardboard in the United States, 9 of which are in the South and 7 in the West (table 23-2). No new plants have been built since 1971, but several have expanded significantly. (See figs. 29-12ABC for growth of annual capacity and consumption and import and export data). An analysis of the economic feasibility of building a new hardboard siding plant to utilize southern hardwoods can be found in section 28-30.

Like insulation board, hardboard markets are tied closely to housing markets. Development of methods to simulate natural wood-grain patterns on hardboard has permitted it to capture about 20 percent of the **interior paneling** market. **Hardboard siding** is probably the most economical exterior wall cladding available and it should continue to be competitive. **Industrial board** includes products for the automotive, furniture, and construction industries; consumption of such board has increased modestly in the last decade.

MEDIUM-DENSITY FIBERBOARD (MDF-DRY)

MDF-dry is produced in 12 plants (table 23-3), seven of which are in the South; all have been built since 1965. The first plant was designed to produce exterior siding, but was soon converted to manufacture core stock for furniture panels. Most of the output of the entire industry is sold for this purpose. MDF-dry competes successfully with particleboard, a lower cost core material, because MDF has more uniform structure and its machined edges can be finished without edge banding. Industry experts expect MDF-dry to make further inroads in the particleboard market, and annual production should continue to grow at about 10 percent a year. MDF-dry production in 1975, 1976 and 1977 was 215.5, 280.0, and 441.4 million board feet, ¾-inch basis. Production trends are graphed in figure 29-13 top.

TABLE 23-2.—*Hardboard plants in the United States, 1982*. (Data from American Hardboard Association)[1]

Parent company	Mill location	Annual capacity: Total hardboard (⅛-inch basis)	Siding (surface basis)	Siding (tonnage)
		Thousand square feet	*Thousand square feet*	*Tons*
Abitibi-Price	Alpena	549,000	—	—
	Roaring River	577,500	165,000	131,175
Boise Cascade	International Falls	702,812	200,804	133,535
Celotex	Paris	192,000	64,000	53,680
Champion	Catawba	230,000	77,000	61,000
	Dee	84,000	—	—
	Lebanon	107,000	—	—
Evans	Corvallis	138,500	—	—
Forest Fiber	Forest Grove	114,136	26,088	30,132
Georgia Pacific	Conway	208,000	—	—
	Jarratt	210,000	60,000	57,000
Masonite	Laurel	1,610,000	( )	—
	Towanda	652,000	(variable)	—
	Ukiah	600,000	( )	—
Superior	Superior	160,000	—	—
Superwood	Duluth	350,000	—	—
	N. Little Rock	175,000	—	—
	Bemidji	105,000	—	—
	Phillips	96,000	—	—
Temple-Eastex	Diboll	477,858	136,531	98,985
U.S. Gypsum	Danville	230,000	—	—
	Pilot Rock	50,000	—	—
Weyerhaeuser	Klamath Falls	420,000	120,000	96,000
Total		8,038,806	849,423	661,507

TABLE 23-3.—*Medium-density fiberboard plants (MDF-dry) in the United States, 1983* (Dickerhoof and McKeever 1979, updated by authors, 1983)

State	City	Company name	Annual production capacity
			Million square feet, ¾-inch basis
Alabama	Eufaula	LA.-Pacific	60.0
Arkansas	Malvern	Willamette Ind.	46.0
California	Rocklin	LA.-Pacific	75.0
Montana	Columbia Falls	Plum Creek Lumber Co.	80.0
North Carolina	Moncure	Weyerhaeuser Co.	60.0
	Spring Hope	Masonite Corp.	74.0
Oklahoma	Broken Bow	Weyerhaeuser Co.	70.0
Oregon	Medford	Medford Corp.	80.0
South Carolina	Holly Hill	Holly Hill Lumber Co.	68.0
	Marion	Celotex Corp.	57.0
Virginia	Bassett	Bassett Industries	22.0
New Mexico	Las Vegas	Montana de Fibra	80.0[1]
Total			692.0

[1]Under construction, 1983; not included in total.

23-3 SOME CHEMICAL ASPECTS

Pulping processes are classified as mechanical (sect. 25-5), semichemical (sect. 25-6), or full chemical (sect. 25-7). Only mechanical pulps, in which fibers are separated by frictional force or by steam pressure, are used to make fiberboards; no chemicals are added to dissolve intercellular lignin. Several important chemical reactions do occur, however, during mechanical pulping and subsequent manufacturing steps.

Acid hydrolysis during the pulping stage causes a breakdown and subsequent loss of part of the hemicelluloses. Acidity necessary for such hydrolysis is developed by simultaneous formation of acetic and formic acids from wood carbohydrates. The hydrolysis reaction not only reduces pulp yield, but loads process water with biodegradable sugars which may create pollution problems.

Condensation, in which two or more molecules combine, with the separation of water, is important in the curing of phenolic resins used in fiberboard manufacture. This reaction takes place at elevated temperature in the hot-pressing phase of manufacture, to form a permanently bonded three-dimensional network in the fiberboard. Even without resin binders, cell wall components may undergo condensation reactions to form bonds within the fiberboard.

During fiberboard pressing and heat treatment, pyrolysis releases volatiles, and further degrades products of hydrolysis from the pulping stage, and subsequently forms condensation products. These reactions darken the board and reduce its hygroscopicity. The volatiles may cause pollution problems.

Control of pH is necessary at two stages of wet-process fiberboard manufacture. Mechanical pulp leaving a refiner has a pH of less than 4 (slightly acidic); to more efficiently remove dissolved solids, pH in the pulp washer is increased to about 5 by adding fresh water or caustic soda. After addition of sizing chemicals such as waxes and asphalt to resist water, and phenolic resins and drying oils as binders, the pH is reduced (often by addition of sulfuric ascid) and then aluminum sulphate or paper makers, alum ($Al_2(SO_4)_3$) is added as a precipitator. The aluminum ion, reacting with the sizing material, forms an insoluble precipitate on the fiber surface which reduces water absorption and improves fiber bonding.

In dry-process fiberboard manufacture there is no control of fiber pH except that provided by catalysts added to resins just prior to resin application.

Bonds between fibers in insulation board and in paper, both of which are wet-formed, are enhanced by close contact resulting from water surface tension as the water evaporates; addition of an adhesive to these products is usually not necessary. Most fiberboards, however, require addition of an adhesive, which in liquid form contacts and interacts with surfaces of mating fibers, developing a cohesive strength similar to that of the fibers it bonds together. Resin adhesives such as urea-formaldehyde and phenol-formaldehyde are irreversibly solidified by chemical reactions from a change in pH or the heat of hot pressing, or both. Phenol-formaldehyde resins are used in the manufacture of hardboard, and urea-formaldehyde resins for MDF. Phenol-formaldehyde resins form water-proof and boil-proof glue lines. Urea-formaldehyde bonds have considerable water resistance but are not considered exterior-type. Regardless of glue-line quality, swelling of fibers during exterior exposure can cause permanent strength loss.

Even without the use of the resin adhesives, bonds can be established between fibers, although the mechanism of such bonding is not clearly understood. Lignin-rich fiber surfaces, perhaps reacting with pentose hydrolysis products, or perhaps softened by interaction of heat and water content, bond in some wet-formed boards. Lignin bonds in dry-formed boards are more difficult to achieve.

23-4 RAW MATERIAL

SPECIES

Approximately half of the fiberboard plants in the United States are located in the South (tables 23-1, 23-2, and 23-3). Many of these plants use southern pine, but southern hardwoods are also widely used—notably in several MDF plants and in the large hardboard facility at Laurel, Miss.

The second insulation board plant in the United States was built in 1931 in Greenville, Miss. and used 100-percent cottonwood (it was later converted to use mineral fibers only). Most industry experts believe that softwoods make better wet-process insulation board than hardwoods, however, although softwoods require longer chip steaming cycles and more energy for mechanical pulping than do hardwoods. Long, soft coniferous fibers drain well and provide a strong pulp; fiber distribution within insulation board mats is not a problem as it is with hardboards.

For hardboards made by the wet process hardwoods are preferred because their short fibers cause fewer high-density spots arising from uneven fiber distribution, a defect termed **cockle.** Very short fiber elements (fines), however, promote development of cockle because they resist water drainage. Also, hardwoods make very springy fibers that release water more quickly than softwood fibers from wet mats, allowing faster line speeds, and shorter drying and press cycles. Dry-formed hardboards and medium-density fiberboards are less sensitive to species characteristics than wet-formed boards.

In the North, aspen is a preferred species for hardboard and MDF. Cottonwood, willow, and yellow-poplar in the South compare favorably with aspen as fiberboard furnish except that willow makes a darker board. These woods have longer and stronger fibers than most southern hardwoods, yielding strong mats less subject to handling damage during manufacture—a factor particularly important in the S2S, wet hardboard process.

Medium-density southern hardwoods such as elms, ashes, hackberry, black tupelo, and sweetgum vary considerably in color (figs. 5-4 through 5-16) and when used in mixtures may produce more large fiber bundles (shives) and a greater range in fiber-bundle diameters than a single-species furnish. More uniform defibration of mixtures can be accomplished through adjustment of cooking cycles and increasing energy input to primary disk refiners. Maintenance of uniform species composition is required for close control of board properties (fig. 23-4)—an idea easy to express but difficult to execute.

Oak species are the most difficult to incorporate successfully into fiberboards—particularly as whole-tree chips. Oak bark is highly acid and interferes with the settling of suspended solids in waste-water treatment systems, and wears out dust pipes in the dry process. Oak chips steam-cook quickly, are readily overcooked, and yield a short-fibered slow-draining pulp. Pure oak hardboards and insulation boards are brittle. Oak is therefore mixed with other species. A hardboard siding, for example, is being successfully manufactured from a 50-50 mix of oak and southern pine. In the North, a 50-50 oak-birch mixture is used to manufacture a paper-overlaid S1S hardboard.

Hickory species are about as difficult to incorporate as oak.

WOOD DENSITY AND BOARD PROPERTIES

Except in insulation board, fiberboard density is determined by the degree of compaction of the mat during pressing. High hardwood specific gravity will generally result in higher bulk density of the fiber and, at a given board density, a lower compaction ratio (board density/wood specific gravity). But low compaction ratios lead to poor contact between fibers and lowered strength. In dry-formed hardboard, therefore, strength properties are negatively correlated with wood specific gravity and with mat bulk density (fig. 23-5). Wood specific gravity has little effect on dimensional stability, however.

FIBER LENGTH

Fiber length has little effect on the mechanical properties of dry-formed hardboard, but does affect dimensional stability in the plane of the board. Long fibers promote board stability during water absorption or desorption. Long fibers also yield strong mats, which are needed for high-speed handling.

Length of fibers may also be a factor controlling their orientation in fiberboards. Short fibers are much more likely to develop a vertical or Z-component

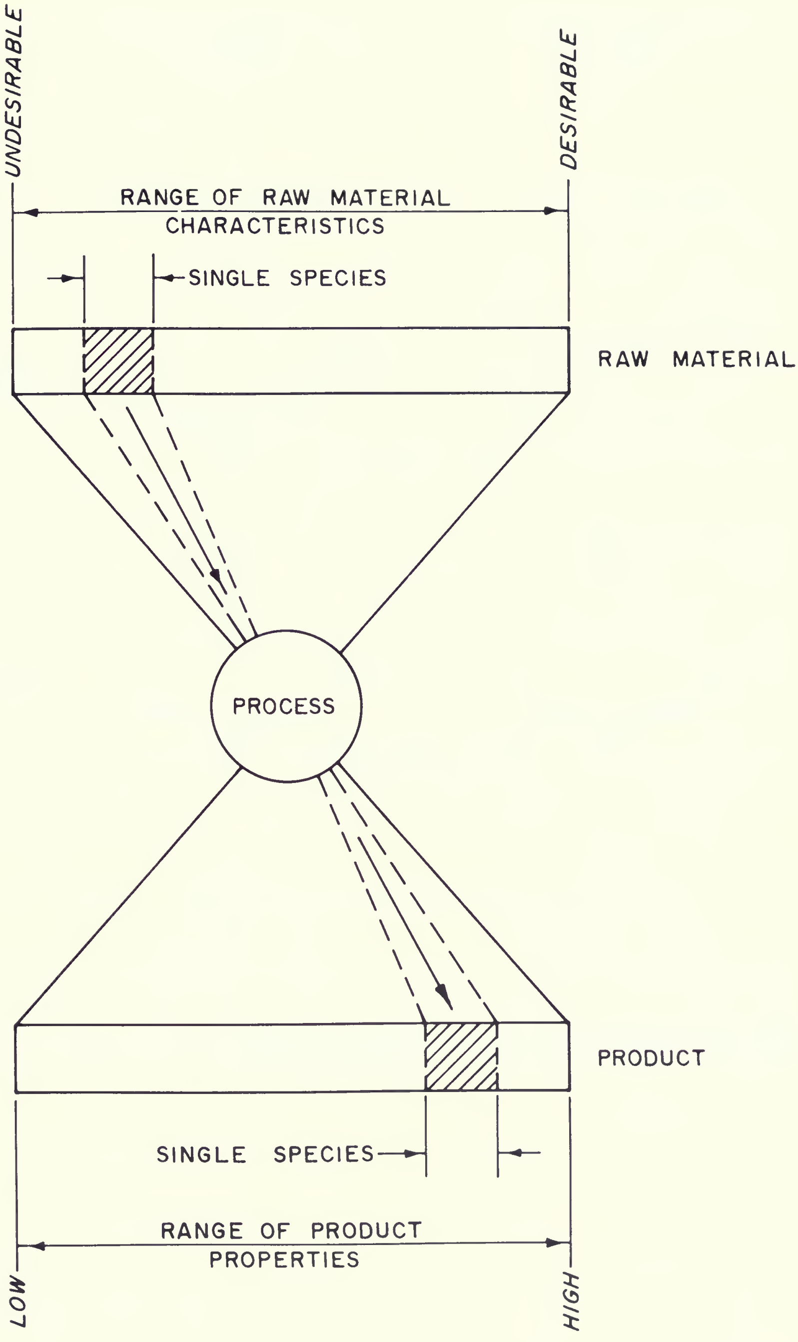


Figure 23-4.—Schematic illustration of the advantage of single-species furnish in the manufacture of fiberboard, compared to a varying and uncontrolled mixture of species. A fiber furnish from a closely controlled, unvarying, homogenized mixture of species can yield a product with a narrow range of properties, however. (Drawing from Suchsland and Woodson 1985.)

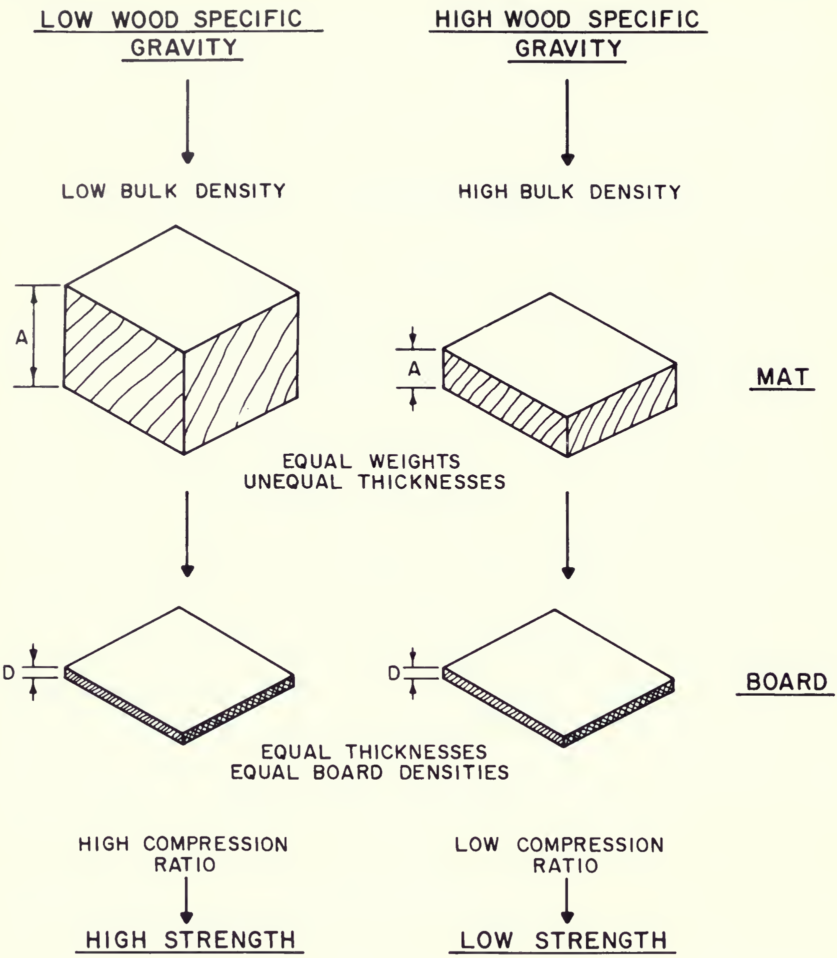


Figure 23-5.—Strength properties of dry-formed fiberboards related to wood specific gravity. (Drawing from Suchsland and Woodson 1985.)

of orientation than are longer fibers (fig. 23-6). Long fibers are more easily aligned, by electrical or mechanical means, in one of the principal board dimensions, to enhance board properties in the direction of alignment.

WOOD FURNISH

In preference to more expensive roundwood, southern fiberboard plants increasingly use residue chips from sawmill and veneer plants, and whole-tree forest-residual chips. Bark-free sawmill chips must be screened to remove their fines content and blended in inventory to maintain a uniform species mix. Whole-tree chips contain considerable bark (table 17-6) which not only weakens boards and contributes significantly to waste-water contamination, but contains grit that accelerates wear of refiner plates and conveyors.

Whole-tree chips will not yield highest quality hardboard substrates for high-gloss finishes, but are suitable for embossed boards permitting surface imperfections from bark and shives.

Sawdust, which is cheaper than pulp chips, can be incorporated in fiberboards but board strength is diminished. To compensate for such strength loss, board density can be increased; e.g., a sawdust component of 20 percent of total furnish would require a board density of about 71 pounds per cubic foot. Such high densities can cause major processing difficulties such as blistering during pressing.

Bark may also be incorporated in fiberboards, but strength properties of resulting boards will be diminshed and color darkened. Strength properties are not the sole quality indicators for many board uses, however, and boards containing considerable percentages of sawdust and bark are manufactured.

23-5 PREPARATION OF RAW MATERIAL

Mechanical pulping with defibrators and refiners requires wood in homogeneous form, i.e., pulp chips, fed at a uniform and continuous rate. The technology for preparing and handling these pulp chips is extensive; interested readers are referred to other sections of this text for aspects of the subject as follows:

Subject	Reference
Roundwood harvest	Chapter 16
Merchandising decks for tree-length wood	Sect. 16-6
Raw-material measurement	Chapter 27
Debarking of roundwood	Chapter 17
Chipping	Sect. 18-24
Whole-tree chipping	Sects. 16-5 and 16-10
Chip debarking and cleaning	Sect. 17-7
Chip handling	Sect. 16-16
Deterioration of chips during storage	Figs. 11-21 through 11-24 and related text, Sects. 16-16, 16-17, and 25-9

The steps in preparing wood for defibration are summarized in figure 23-7.

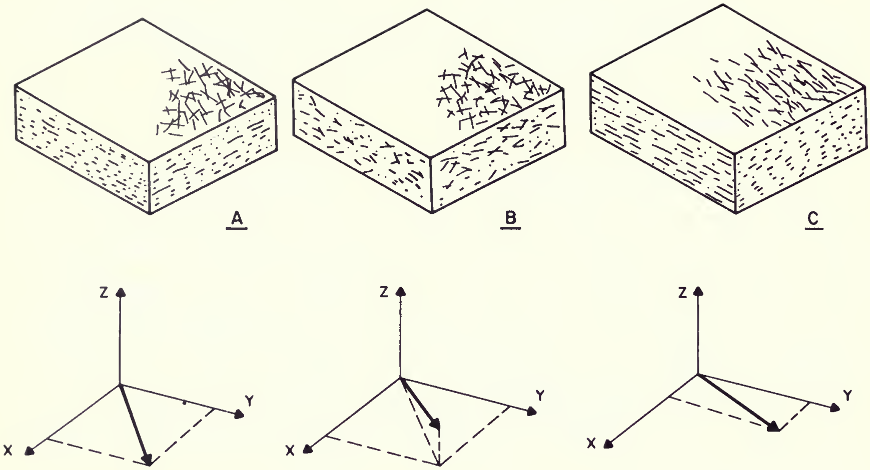


Figure 23-6.—Orientation of fibers in fiberboard. A. Random in plane of board, no vertical component. B. Random in plane of board, small vertical component. C. Oriented in y direction, small x component, no vertical component. (Drawing from Suchsland and Woodson 1985.)

23-6 PULPING PROCESSES

For manufacture into fiberboard, hardwood chips are pulped mechanically. The pulping process may be aided by thermal softening of the lignin-rich middle lamella, but no chemicals are added to dissolve lignin or other wood components. Thermal softening may, however, increase water solubility of hemicelluloses, thus lowering pulp yield for wet-process board to values significantly less than 100 percent. High temperatures or prolonged thermal treatment, while more effectively promoting natural bonding during fiber mat consolidation, increase dissolved sugars in process effluent water.

Mechanical pulping is energy intensive, typically accounting for about half of the total energy expended in fiberboard manufacture. It is generally accomplished in two stages. In the first, and most energy intensive stage, chips are reduced to fiber bundles; the second stage completes fiberization and reduces variations in resulting pulp.

Pulping method and applied energy affect degree of fiberization; incomplete fiberization yields fiber bundles, while over refining may cause broken or split fibers. Desired characteristics of the pulped fiber vary with fiberboard product. The three primary pulping methods appropriate for hardwood fiberboard production are as follows:

- Masonite explosion process
- Atmospheric disk refining
- Pressurized disk refining

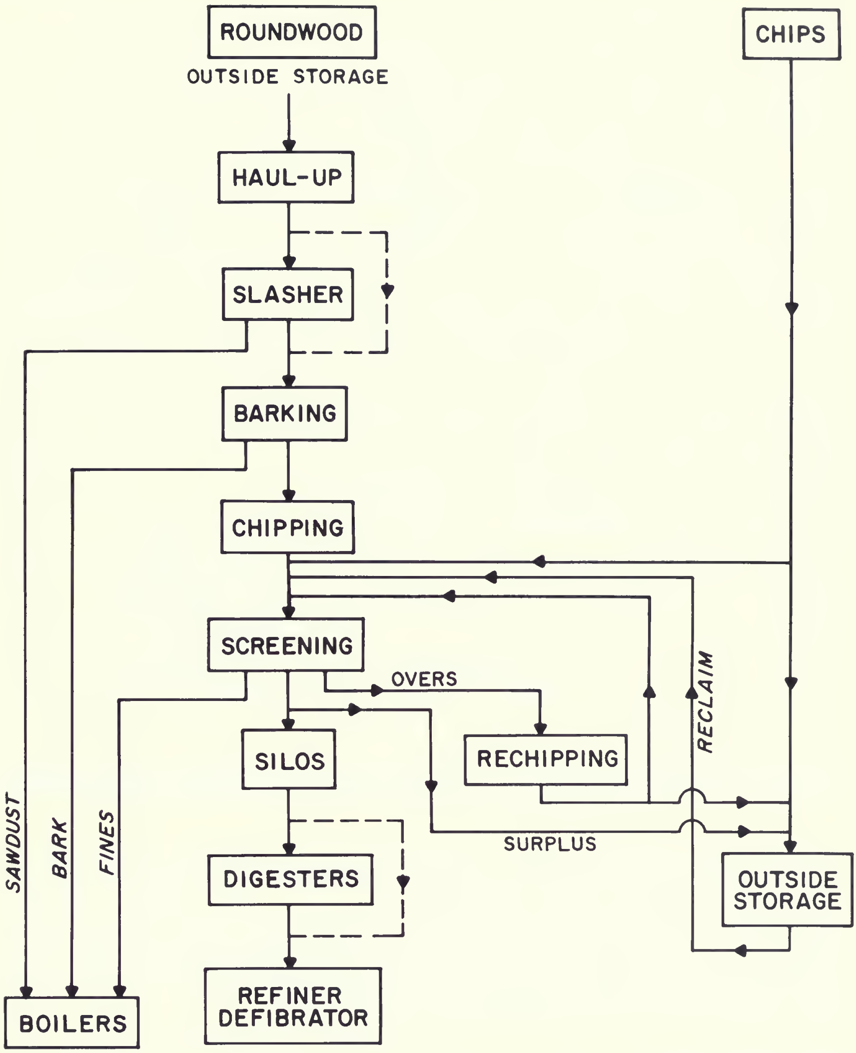


Figure 23-7.—Wood preparation for fiberboard manufacture. (Drawing after Lamarche 1969.)

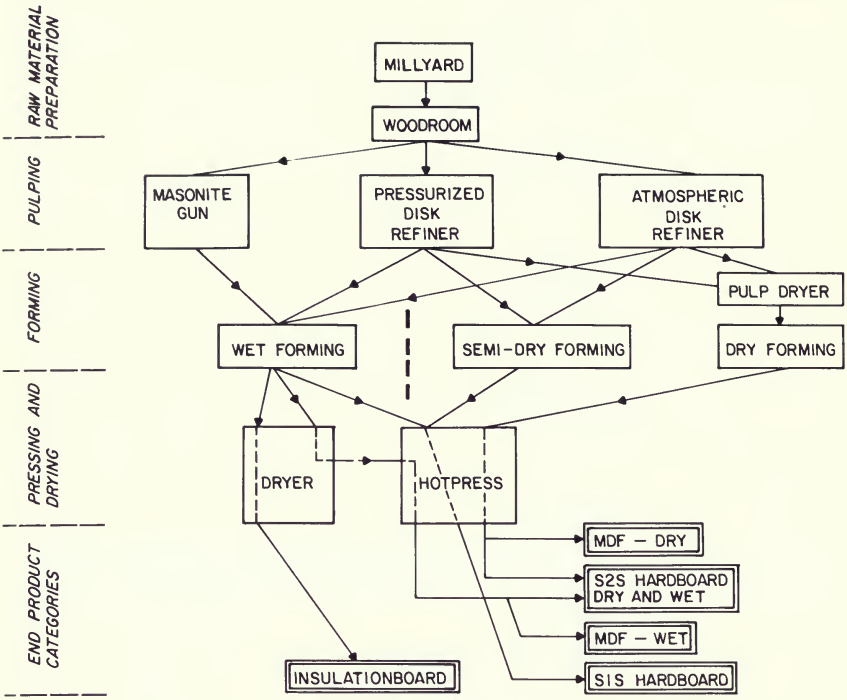


Figure 23-8.—Schematic summary of pulping, forming, and drying processes yielding the five major fiberboard products. (Drawing from Suchsland and Woodson 1985.)

Figure 23-8 summarizes the range of fiberboard processes and products. A plant could produce any or all of the products shown; most, however, produce only one or two because each product requires specific pulp characteristics, generally different from requirements for other fiberboard products. Pulp freeness is one of the most important pulp characteristics.

PULP FREENESS

In wet fiberboard processes water must be removed after its service as a conveying and distributing medium in sheet formation. Much of this water drains by gravity through the **fourdrinier** screen while the mat is being formed; what remains must be converted to steam in subsequent drying or hot pressing. A pulp that drains quickly is a **free** pulp or a **fast** pulp; one that drains water slowly is less free or a **slow** pulp. Fast pulps allow faster line speeds and therefore greater plant productivity. Slow pulps provide more intimate fiber-to-fiber contact and stronger bonds. Two types of freeness testers are in wide use in North America:

- The Canadian Standard Freeness Tester (CSF), standard in North America for paper pulp and described by TAPPI Standard T-227, is a device into which the pulp sample (3 g in 1,000 ml of water) is placed. The mechanism is devised so that water from the pulp will overflow through a side orifice into a calibrated container yielding a numerical value from 0 to 1,000 ml; the higher the number, the faster the pulp.
- Insulation board and hardboard plants in the United States generally use the TAPPI Standard SFMC draining tester, which measures the number of seconds to drain a pulp sample (10.6 g in 1,000 ml of water) through a 40-mesh screen. The higher the number the slower the pulp. Water has a drainage time of 1.5 seconds, S1S hardboard pulp 15 to 20 seconds, and insulation board pulp 50 to 60 seconds.

Freeness can be correlated, by experiment in each mill, to processing characteristics; it is therefore an important parameter useful to control product quality. In general, the larger the surface area of a weight of pulp (**specific surface**), the slower the pulp. Pulp specific surface can be increased by more extensive refining to make fibers more ribbon-like and to **fibrillate** (shred) their ends. Fibrillation of fibers yields a slow pulp but promotes hydrogen bonding, important in the manufacture of insulation board. Wet-formed hardboards do not rely on hydrogen bonding for their strength, and because of their much thicker mats, require fast-draining or free pulps.

Dry fiberboard processes do not require draining water from mats, and for these processes freeness is not monitored.

MASONITE PULPING PROCESS

The Masonite pulping process, originally used on southern pine but now applied to southern hardwoods at the company's Laurel, Miss. plant, uses the heat of steam to soften the chips and its explosive force to defibrate them. Only the Masonite Corporation uses this process for the manufacture of pulp for fiberboard. (See concluding paragraphs of sect. 26-7 for use of a similar process to make animal food.) In all other mechanical pulping processes, fiberization is accomplished by abrading or cutting tools.

The Masonite gun.—The Masonite gun—so called because of the explosive nature of the defiberizing phase—is shown in cross section in figure 23-9 as it was described by W. H. Mason in 1927. The gun has not changed much in the intervening years, although its operation is now automated. It is a pressure vessel measuring about 5 feet high and 20 inches in inside diameter with a capacity of about 10 cubic feet to accommodate about 200 pounds of chips admitted from the top. The tapered bottom end is equipped with a slotted port and quick-opening discharge valve.

After charging with chips, low-pressure steam (350 psi, 450°F) is admitted to heat the chips to about 375°F, and maintain them at this temperature for 30 to 40 seconds. High-pressure steam (1,000 psi, 540°F) is then admitted over a 2- or 3-second period and pressure held for about 5 seconds. The hydraulically actuated discharge valve is then quickly opened and the chips explode due to sudden

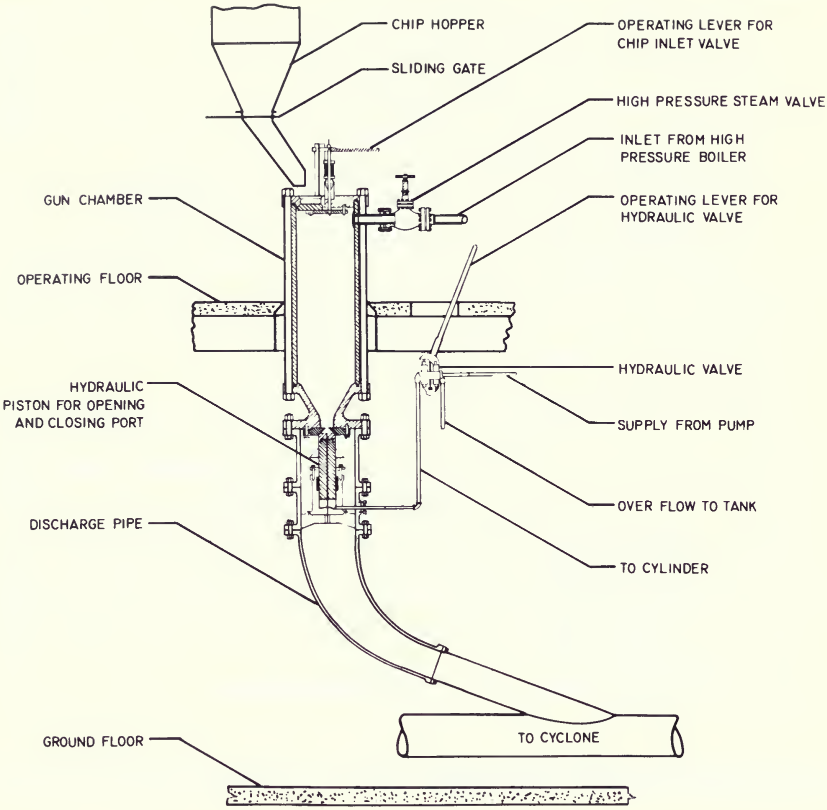


Figure 23-9.—Cross section of Masonite gun. (Drawing after Mason 1927.)

release of internal pressure; at the same time they are forced by the expanding steam through the slotted bottom port plate where they are shredded into fiber bundles. Steam and fibers are separated in a cyclone. The entire cycle from chip charging to fiber discharge requires about 60 seconds.

Effect on wood.—In the Masonite process the foregoing pressure program, while typical, can be varied considerably. Part of the wood substance becomes soluble, and the lignin bond is chemically and physically weakened, allowing fibers to separate on decompression; fibers also darken from thermal degradation. The dissolution of part of the wood substance is due to hydrolysis of the hemicellullose under the catalytic action of acetic acid. The hemicellulose breaks down to water-soluble sugars (hexoses and pentoses) which are removed from the pulp by washing. The degree of hydrolysis and the extent of wood losses can be controlled by modifying the gun cycle. The catalyzing effect of acetic acid, which is believed to be generated by cleavage of acetyl groups of hemicellulose at steam pressures between 300 and 400 psi, is reflected as a sudden rise in the hot water extractability (fig. 23-10).

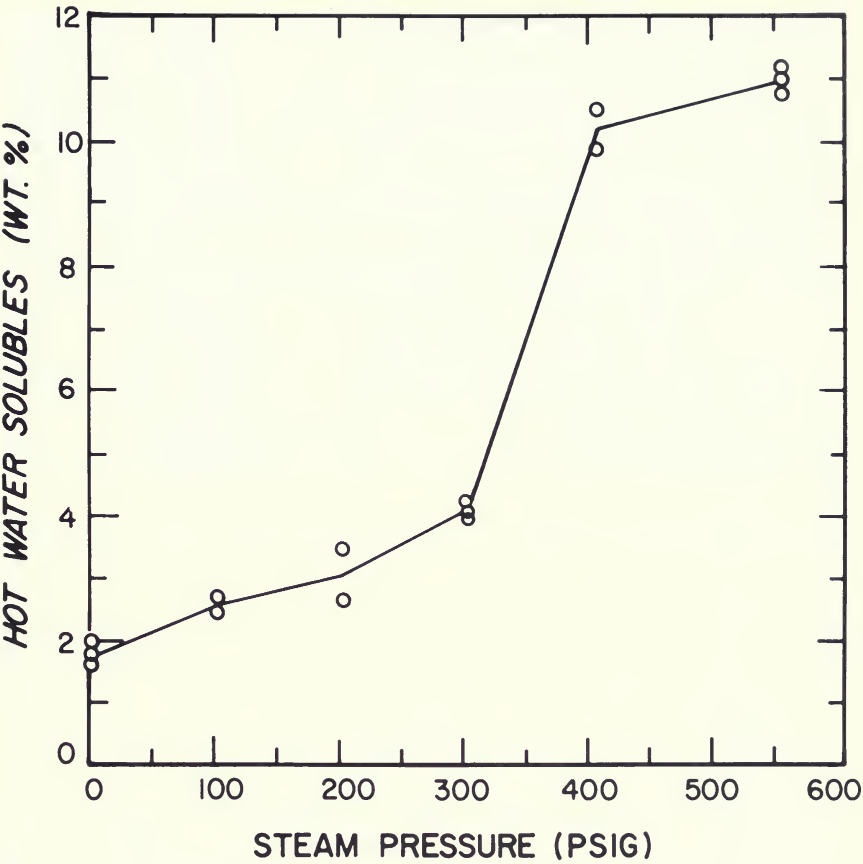


Figure 23-10.—Hot-water extractability of wood chips (percent of ovendry weight) as a function of saturated steam pressure (gage) used in the preheat segment of the Masonite cycle. (Drawing after Spalt 1977.)

Yield.—Yields by the Masonite process decrease with increasing temperature or heating time (fig. 23-11) and have been reported as low as 65 to 70 percent, but more recently between 80 and 90 percent.

Pulp characteristics.—Koran (1970) found that Masonite-process jack pine (*Pinus banksiana* Lamb.) fibers were dark, stiff, little collapsed, with smooth surfaces enveloped by a continuous network of primary wall heavily encrusted with lignin, and in many areas covered by thick layers of middle lamella substance. They are not fibrillated and further refining does not produce the fibrillation necessary for hydrogen bonding in paper manufacture; they are therefore unsuited for paper. For the same reason, however, these fibers make a very free pulp well suited for wet-formed hardboard. The low yield of Masonite mechanical pulp and its rather high energy requirement may cause its gradual replacement with disk-refined pulp.

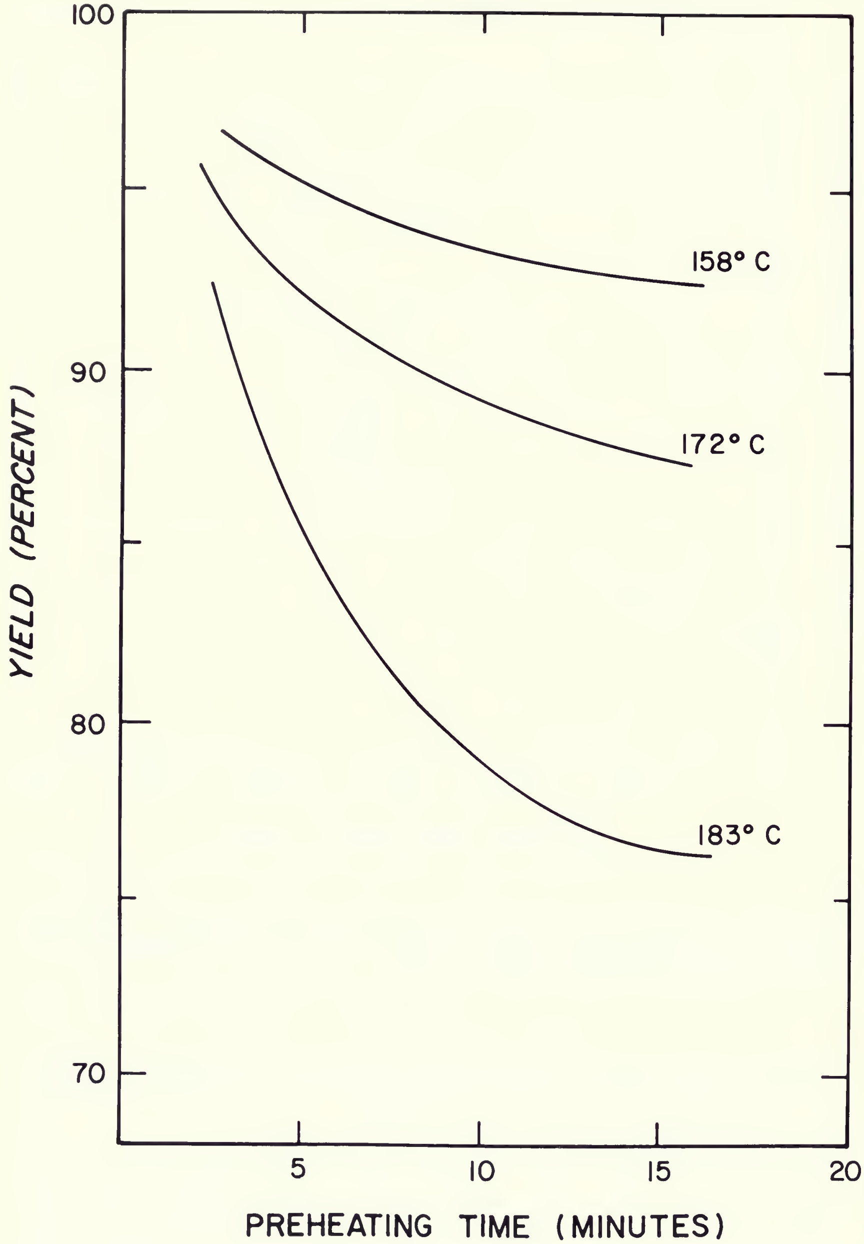


Figure 23-11.—Effect of preheating time and temperature on pulp yield by the Masonite process. (Drawing after U.S. Environmental Protection Agency 1974.)

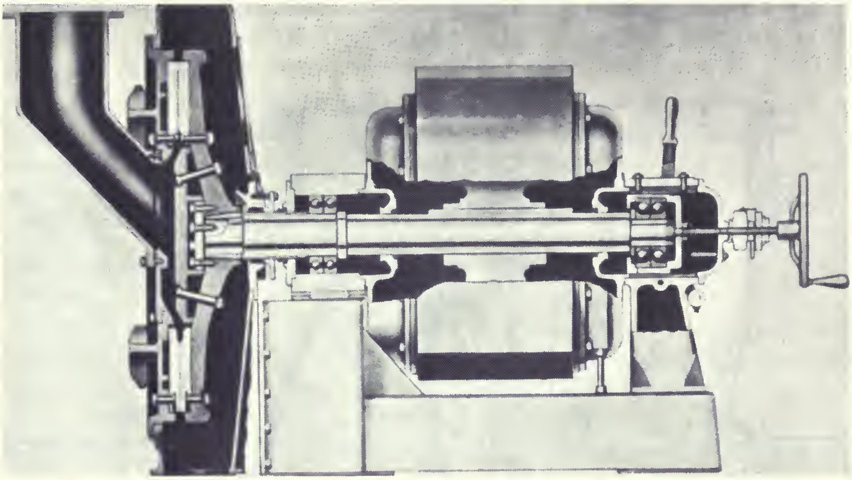


Figure 23-12.—Cross section through a single-revolving-disk refiner. (Drawing courtesy of The Bauer Bros. Co.)

DISK REFINING

Southern hardwoods, which have not been successfully stone-ground on a commercial scale, are readily fiberized in disk refiners. Whereas stone grinders must be fed with roundwood, disk refiners are designed to operate on chips—a form of wood more conveniently conveyed and stored. Also, disk refining allows a variety of continuous-flow chip pre-treatments such as water soaking, steam cooking, and chemical digestion, permitting great latitude in pulp manufacture. In disk refiners chips are sheared, squeezed, cut, and abraded as they are forced through a narrow gap between two textured disks, one or both of which rotate. Resulting pulps are generally superior to stone-ground wood. Most fiberboard pulp is produced by disk refiners.

Single- and double-disk refiners.—The general design of disk refiners is discussed in section 18-27. A **double-disk** refiner in which the two disks counter-rotate is shown in figure 18-282, and the action of single- and double-disk machines is compared in related discussion. See figure 18-283 for illustration of profiled cutting elements (disks); these ring segments are bolted to disk or housing. Figure 23-12 shows a **single-disk** refiner with one stationary and one rotating disk.

Primary refiners are used to break down chips into fiber bundles, and secondary refiners, which require one-tenth or less of total pulping energy, complete fiberization; the **secondary refiners** are also called "pump-through" machines (fig. 23-13). Both single-disk and double-disk refiners are used in primary chip breakdown. Secondary refiners are mostly of single-disk design.

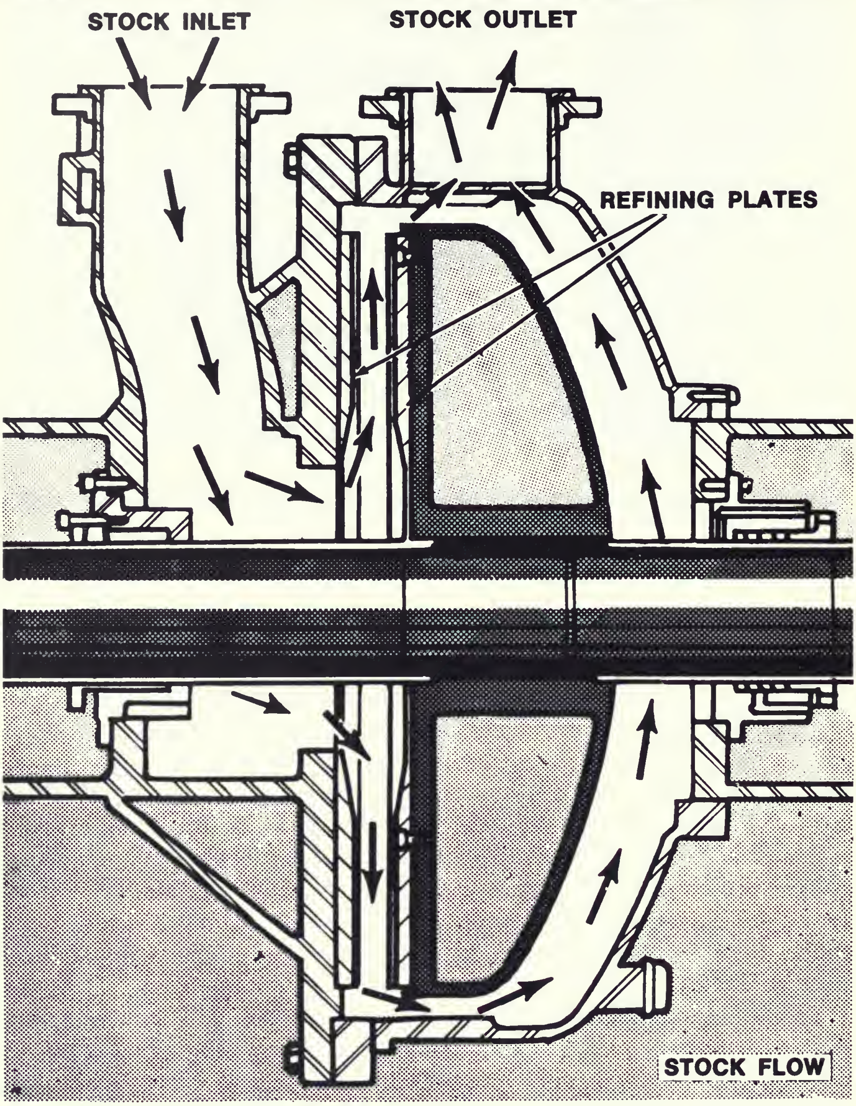


Figure 23-13.—Single-revolving-disk pump-through refiner. Arrows indicate stock flow. With 24-inch disk driven by 200 hp at 514 to 900 rpm, pulp capacity is about 50 tons/day. With 32-inch disk, driven at 450 to 600 rpm by a 400 hp motor, pulp throughput is rated at up to 100 tons/day. (Drawing and data from The Bauer Bros. Co.)

Atmospheric disk refiners.—Green chips fed to disk refiners operated at atmospheric pressure may receive no pre-treatment, they may be steamed or soaked in water at atmospheric pressure and temperature, or they may be cooked in steam or water at elevated pressures and temperatures. Hardwood chips having no pretreatment produce a slow pulp, with a large proportion of broken fibers and fiber bundles. Such hardwood pulp can be used in dry-process fiber-board where lignin bonds between fibers do not significantly contribute to board strength, and in wet processes where slow drainage is not a problem and where surface quality requirements are not very critical. Untreated chips give maximum pulp yield and minimum pollution of process water. However, the pulping of untreated chips is very energy intensive.

Steaming or water soaking hardwood chips at atmospheric pressure and temperature produces more flexible fibers with fewer breaks; this slightly improved pulp forms (felts) better and yields a stronger mat. One northern hardwood siding mill produces most of its pulp (80 percent aspen; 15 percent birch, oak, ash, and jackpine; 5 percent recycled paper) on atmospheric refiners without cooking.

Cooking chips in steam or hot water at elevated pressure and temperature darkens them, reduces their yield, and increases pollution of process-water. Specific refining energy is reduced, however, and resulting fibers are strong and pliable. This method is considerably used in the manufacture of high-quality wet-formed S1S and S2S fiberboard. Cooking vessels (**digestors**) can be designed for batch or continuous discharge.

A **batch digester** to feed an atmospheric refiner is typically a corrosion-resistant vessel designed for pressures up to about 300 psi. The one illustrated (Fig. 23-14) is about 3 feet in diameter, 20 feet tall, and holds about 120 cubic feet of chips. With bottom ports closed the digester is filled with green chips through the top port. Then, with top and bottom ports closed, the bottom steam valve and top blow-down valve are opened so the digester fills with steam while being purged of air. After purging, the blow-down valve is closed and steam pressure built to desired level and held for prescribed time. Pressure is then reduced by opening the blow-down valve and when pressure has dropped to 25-50 psi the chips are blown into the chip bin by opening the bottom port. The steam escapes to atmosphere through large-diameter blow stacks and cooked chips are conveyed to primary refiners.

A wet-process hardboard mill reports the following cycles for such a batch digester[2]:

Hardboard type	Species	Steam pressure	Cooking time
		Psi	*Minutes*
S2S	*Populus* sp.	180	2
S1S	50/50 oak/birch	150	½

Should the oak component exceed 60 percent, then cooking time must be reduced; and if the oak component is less than 40 percent, cooking time should be increased. With 100 percent southern pine chips the cook might be extended to 6 minutes at 190 psi.

[2]Eustis, O. B. 1980. State of the art of the fiberboard industry. Unpublished manuscript.

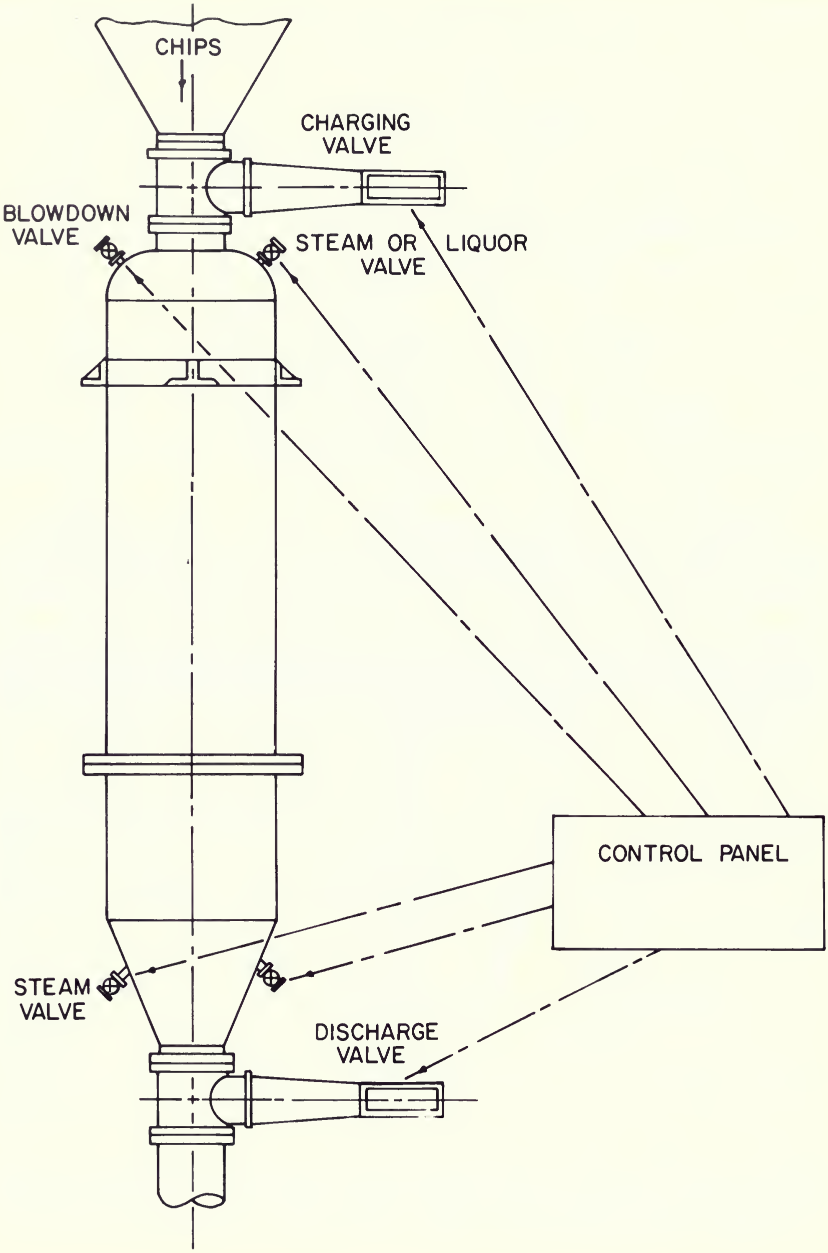


Figure 23-14.—Rapid-cycle batch digester. (Drawing after Textor 1957.)

Horizontal **continuous digesters** (fig. 23-15) are typically made in sizes up to 40 inches in diameter and 40 feet in length. The dwell (cycle) time is controlled by a variable speed feed screw which moves the chips through the pressure cylinder. Rotary valves charge and discharge chips into and from the digester at constant rate. Steam is admitted to the pressure cylinder to maintain cooking conditions continuously.

For uniformity of pulp quality refiners should run at full load, force-fed with chips at a constant controllable rate. Single- or double-screw (fig. 23-16) and coaxial (fig. 23-17) **force feeders** are typically aranged so that they have a constant oversupply of chips; surplus chips are recirculated back to chip bins.

Pulp quality is difficult to define and often can be expressed only in terms of fiberboard properties. Important parameters include freeness, fiber-length distribution, and springiness. The dominant operating variable is throughput rate which affects **specific energy,** the energy required per unit weight of pulp produced. Figure 23-18 illustrates the interrelationships between specific energy and various pulp and sheet properties. In the experiment from which figure 23-18 was derived, the factors in parentheses were held constant; arrows indicate relationships between variables; e.g., freeness is changed by increasing or decreasing energy input, which in turn affects pulp properties as indicated by the arrows.

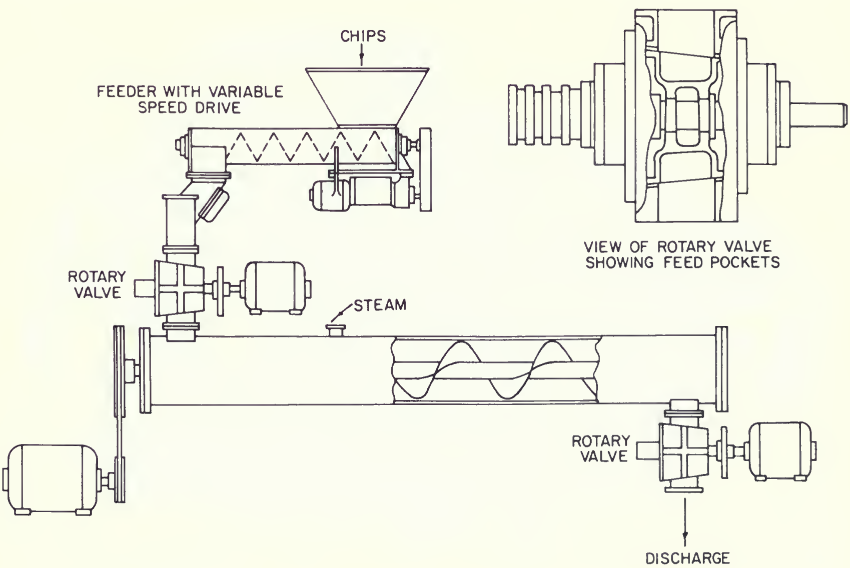


Figure 23-15.—Grenco continuous digester. (Drawing after Textor 1957.)

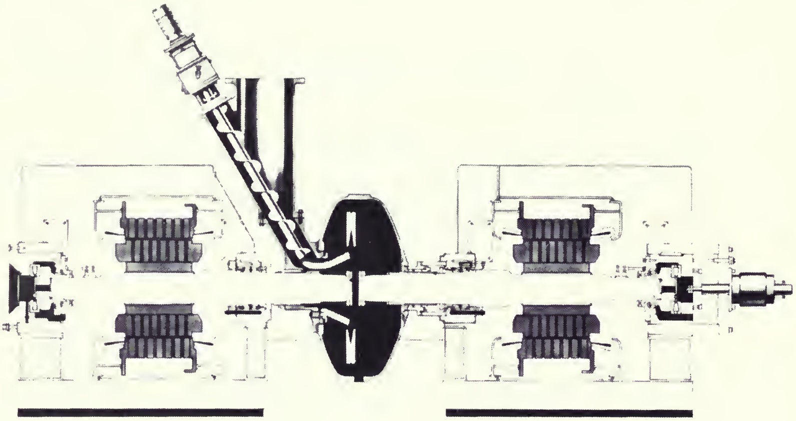


Figure 23-16.—Twin-screw feeder. (Drawing courtesy of The Bauer Bros. Co.) For detail of disks, see Figure 23-21.

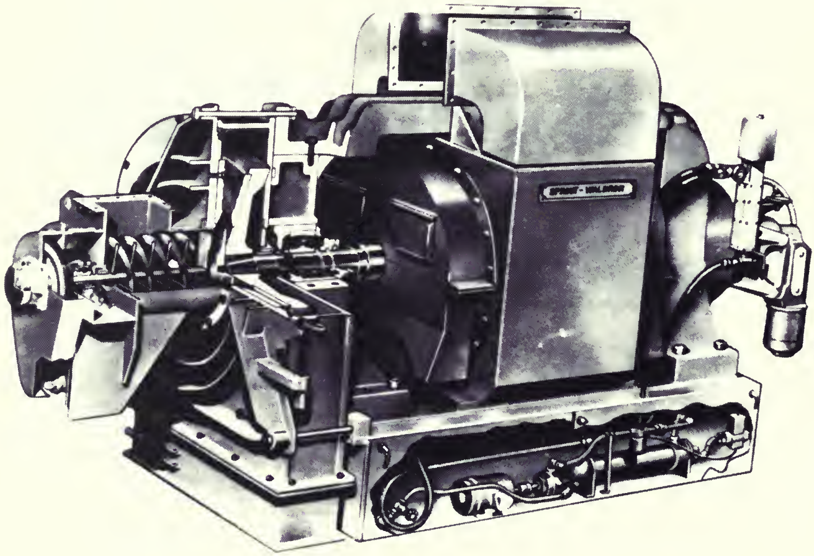


Figure 23-17.—Coaxial feeder. Stock inlet is at top left; steam outlet is at bottom center; stock exits at right to refiner. (Drawing courtesy of Sprout Waldron.)

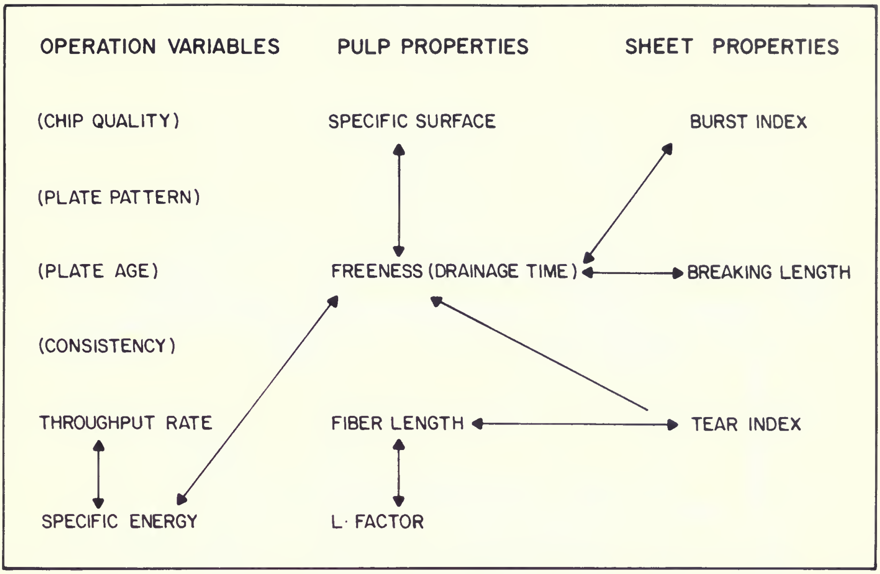


Figure 23-18.—Interrelationships between specific energy and other pulp and sheet properties. (Drawing adapted from Johnson and El-Hosseiny 1978.)

Freeness of pulp on the forming machine is the primary indicator for controlling refiner operation. Freeness can be increased by opening the plate gap, which also increases throughput and decreases specific energy. Typical specific energies for three major classes of fiberboard are about as follows:

Product	Specific energy
	Hp days/ton of pulp, ovendry basis
Dry-formed fiberboard	10-11
Insulation board	20-30
S1S and S2S wet-formed hardboard	20-30

Pressurized refining.—Pressurized refiners, of which the Asplund defibrator (fig. 23-19) is the prototype, refine chips in an atmosphere of saturated steam under pressure. They are comprised of preheater, disk mill, and infeed and outfeed devices that maintain internal steam pressure. Figure 25-20 depicts the significant drop in power required to fiberize hardwood and softwood chips when internal refiner temperature exceeds 300 to 340°F. This reduction of power is attributed to softening of lignin, easing mechanical separation of fibers along the middle lamella.

Process sequence in an Asplund Defibrator (refer to fig. 23-19 for machine-component numbers) begins at the chip infeed chute (1) where green chips (2) are screw fed (3) to form a moving conical non-rotating, compact plug (4) sufficiently dense to block escape of steam from the preheater (6). The plug falls apart as it enters the steam atmosphere of the preheater which is about 10 feet high with inside diameter of about 2 feet. After a minute or less in the preheater,

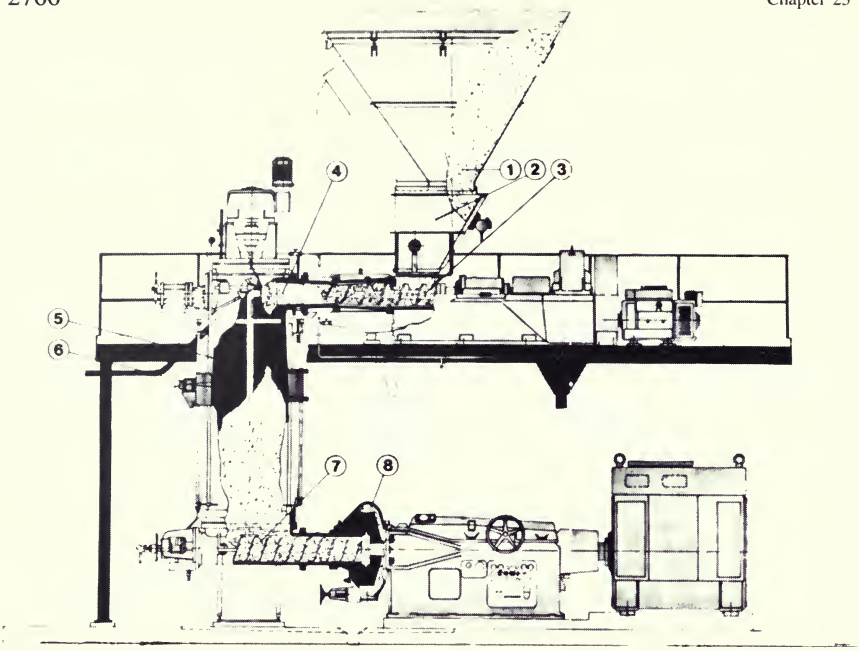


Figure 23-19.—Asplund pressurized disk refiner. See text for explanation of numbered components. (Drawing courtesy of American Defibrator, Inc.)

determined by level control, a conveyor screw (7) at the bottom of the preheater removes the softened chips and feeds them into the center of the single-revolving-disk mill (8). A gap, variable from 0.008 to 0.016 inch, is maintained between the stationary disk and the revolving disk. Pulp is discharged from disk periphery to atmospheric pressure through valves or blow pipes that permit only minimal steam loss. Total dwell time in the system depicted (fig. 23-19) is about 1 minute for fiber suitable for wet-process hardboard. Basic specifications of such machines are as follows (maximum disk speed is about 1,800 rpm):

Disk diameter	Minimum motor size	Capacity
Inches	*Hp*	*Tons/24 hours*
20	270	10-15
24	400	15-20
32	1,100	20-70
36	1,600	50-100
42	3,400	75-200

Defibrator pulp is only slightly darker than the parent wood, consists of individual fibers with undamaged walls, and is free, springy, and bulky. Defibrator pulps are used for both wet- and dry-formed hardboard and for medium-density fiberboard. Like Masonite pulp, defibrator pulp cannot be fibrillated and is, therefore, unsuited for paper manufacture unless the equipment is used in conjunction with chemical treatments of wood chips (see sects. 25-5 and 25-6).

The **Sprout-Waldron** pressurized refiner (fig. 25-21 bottom), like the Asplund is a single-revolving-disk machine with capacities up to 200 tons per day

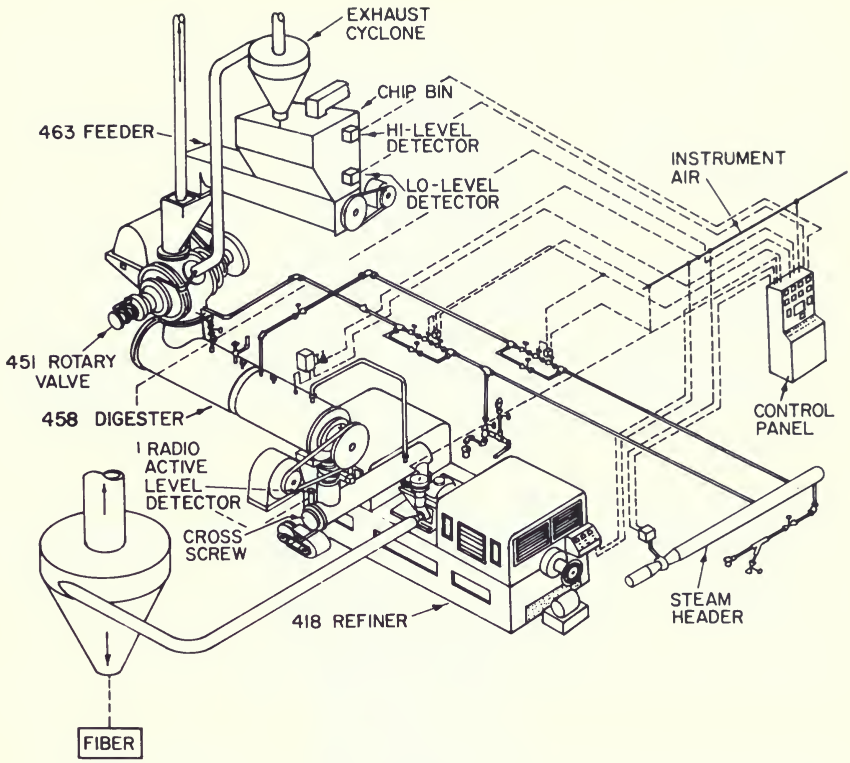


Figure 23-20.—Bauer 418 pressurized refining system. (Drawing courtesy of The Bauer Bros. Co.)

for the 36-inch unit and 400 tons per day for the 42-inch unit. Pulps are similar to defibrator pulps, and are suitable for both wet- and dry-formed hardboard and for medium-density fiberboard.

The **Bauer** 418 pressurized refiner (figs. 23-20 and 23-21) was an important element in the development of dry-formed medium-density fiberboard during the 1960's. It is a double-disk mill (both disks revolve, counter-rotating), and produces a fluffy, bulky pulp which requires considerable compression—a prerequisite for the favorable gluing conditions—when densified to medium board densities. Such fiber is too fluffy to make good wet-formed fiberboard.

All three of the machines just described are currently being used to manufacture pulp for dry-process board of medium and high density. In such pulps freeness can be disregarded, but low fines content, controlled particle-size distribution, and low bulk density (below 2 pounds per cubic foot) are of primary importance.

Pulp consistency, plate design, and refiner selection.—Pulp consistency, the percent dry weight of fibers in the pulp slurry of fiber and water, interacts with degree of refiner-plate wear to affect pulp freeness. Mihelich et al. (1972) found that with new plates, increasing consistency (measured at refiner dis-

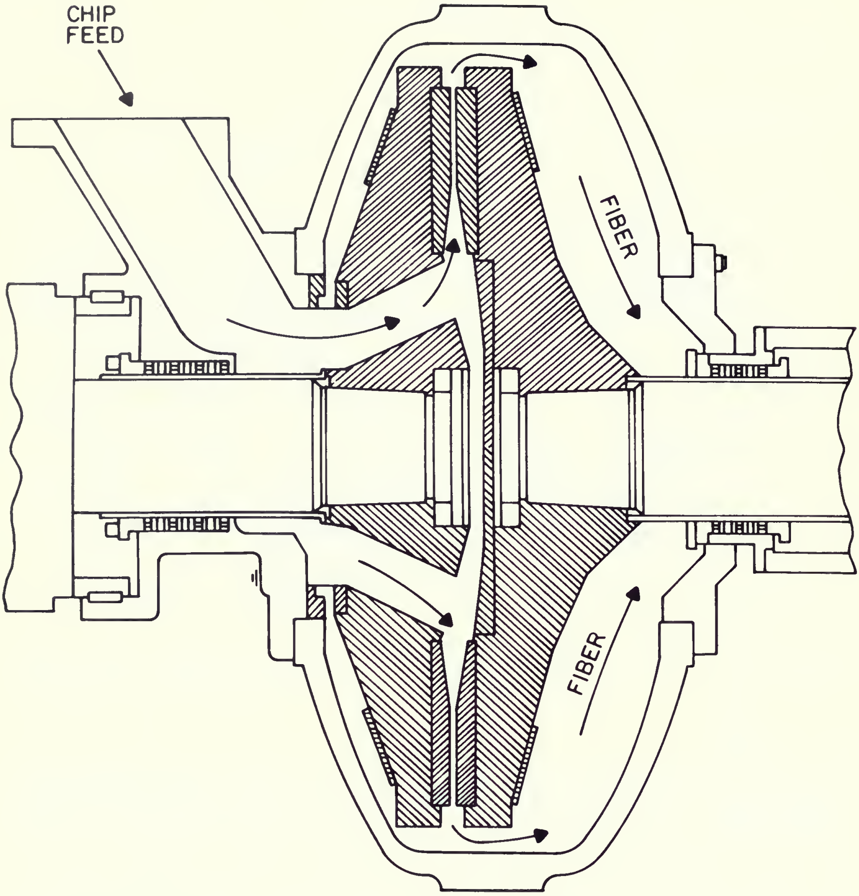


Figure 23-21.—Section through pressurized double-disk refiner showing stock flow. (Drawing courtesy The Bauer Bros. Co.)

charge) from 5 to 20 percent caused a slight increase in freeness, but as consistency was increased above 30 percent resulting pulp became slower (less free). Worn plates produce a much freer pulp at low consistencies, but at higher consistencies produce slower pulps than new plates. Thus pulp consistency can be varied to compensate for the effect of plate wear on pulp freeness (Mihelich et al. 1972).

In most wet process atmospheric refiners water is added to the chip feed to reduce consistency to about 12 to 14 percent dry wood content. More water is added to the refined fibers after they leave the refiner disks in order to make the furnish pumpable (1- to 2-percent consistency).

High consistency refining refers to refining without addition of water. Vacuum is applied to remove the furnish from the refiner case. The resulting pulp is finer and freer. This allows higher machine speeds, and, since the mat is fluffier, it allows more water to be squeezed out in the first phase of the press cycle. Forming machine consistency is, of course, the same as with conventional pulping, about 1 to 2 percent. The result is a shorter press cycle because the free pulp drains faster on the Fourdrinier and in the press section.

The reduced density of the mat is a disadvantage in the wet S2S process since it is more fragile, easier to break, and burns more easily. Here, high consistency refining may be applied to only part of the furnish to free up the stock and to speed up the machine.

Increasing the consistency in single disk refiners and opening the plate gap, causes a pad of pulp to be formed between the plates, which produces a highly satisfactory furnish at lower power consumption. Under these conditions, chips apparently are defiberized by wood-to-wood contact. If consistencies are too high, steam will develop and rupture the pad between the plates. This will allow chips and shives to leave the refiner which ruins the pulp and endangers personnel (O. B. Eustis[2]).

Pressurized refiners are essentially high-consistency refiners. Fiber for dry-process boards is always refined at high consistencies, with no water added; typical consistency for such pulp, measured at refiner outlet, is about 50 percent when chip moisture is about 100 percent (ovendry-weight basis).

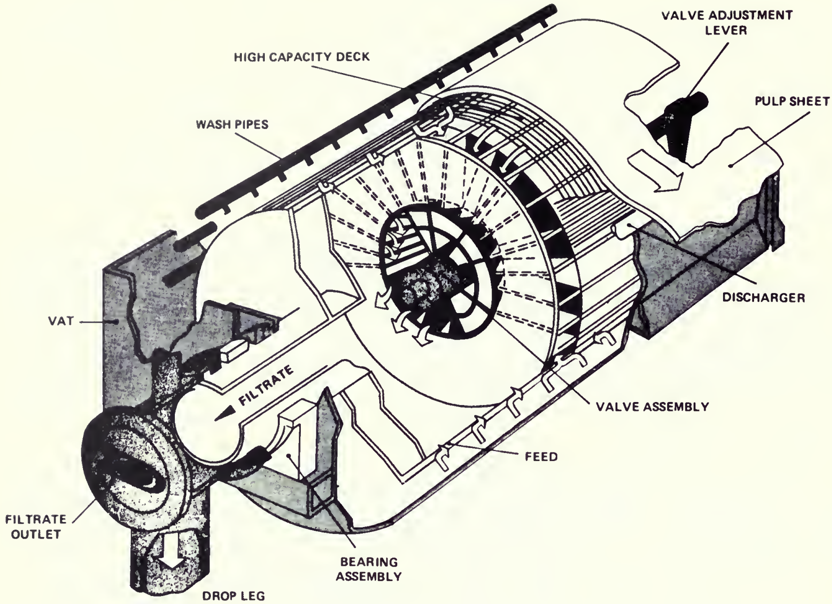
Plate design, accomplished empirically, affects pulp properties but the controlling mechanism is poorly understood. Readers interested in plate design and hydraulic action in refiners are referred to Tappi (1971) and Leider and Rihs (1977).

Selection of refiners for primary chip reduction is based on needed capacity. For example, a 100-ton-per-day insulation board plant would require atmospheric refining capacity of about 2,500 hp (100 tons/day x 25 hp days/ton). This could be handled by one 2,500 hp double-disk refiner (e.g., a Bauer 412) or by three 1,000 hp machines (e.g., Bauer 411's); the three smaller refiners might be a better choice, because plate changes or other maintenance would not interrupt all fiber production. Secondary refining in such a plant would require only 200 hp (1 or 2 hp days/ton), which could be handled by a 32-inch pump-through refiner (fig. 23-13). Some fiberboard plants operate without secondary refiners, doing the complete fiberizing job with primary refiners.

PULP WASHERS AND SCREW PRESSES

Pulp washers and screw presses, used only in wet-process plants, remove dissolved solids—primarily hemicelluloses, which, if retained can cause boards to stick to hot-press platens. To maintain processing consistency, the "contaminated" water is replaced with fresh water. Dissolved solids are the primary water pollutants from wet-process fiberboard plants, and their removal and treatment is costly. (See sect. 23-12.)

In **vacuum pulp washers** (fig. 23-22 top) a wire-mesh-covered cylinder revolves in a vat of diluted pulp. Vacuum applied to the interior of the cylinder causes water from the vat to flow through the wire mesh depositing thickened pulp on it. Fresh water supplied by shower pipes outside the pulp-covered revolving cylinder, drawn through it by the vacuum, completes the washing



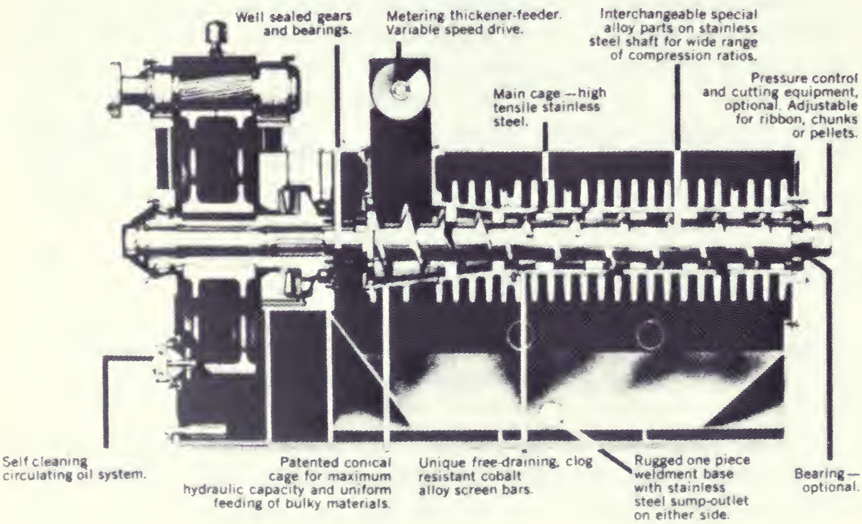


Figure 23-22.—(Top) Vacuum pulp washer; the water-drop leg applies vacuum to cylinder interior. Drawing courtesy Dorr-Oliver, Inc. (Bottom) Continuous rotary press, termed *pressafiner;* drawing courtesy The Bauer Bros. Co.

process. Elevated temperatures (but not above 140°F) and a pH of about 5 favor efficient washing. Vacuum washers may be arranged in series for **countercurrent washing;** in such arrangements the wash water runs in a direction opposite to the pulp so that the filtrate of the last stage is used as wash water and dilution water for the next to last stage, and so on, resulting in a concentrated filtrate discharge from the initial stage. Pulps are discharged from vacuum washers at consistencies of 12 to 14 percent.

Continuous rotary presses (fig. 23-22 bottom) remove more water from pulp than vacuum washers and discharge at consistencies up to 75 percent. They dewater pulp by forcing it into a conical cage with a tapered screw which applies pressure of several thousand psi. Water, forced through the screen cage into the machine housing, is then removed.

23-7 CHEMICAL ADDITIVES

Chemicals are added to fiberboard furnishes for seven reasons, the first four of which are common to most fiberboard processes, as follows:

- Control of pH
- Increased water resistance (sizing)
- Enhancement or establishment of fiber-to-fiber bonds
- Control of process (defoamers, release agents)
- Protection of fiber from decay and insect attack
- Fire protection
- Coloration

They are added in small quantities because they are costly and because their presence, while enhancing one desired property, may be detrimental to another. Chemicals that increase water resistance, for example, may interfere with fiber-to-fiber bonding.

SIZING OF FIBERBOARD

Sizing is the process by which individual fibers are coated with a hydrophobic chemical to reduce product water absorption, thereby diminishing its linear expansion, thickness swelling, surface deterioration, and strength loss caused by swelling of wood fibers. In dry-process fiberboards, the size is applied directly to either chips or fibers, generally together with the resin binder required in all such boards.

In the manufacture of all wet-process fiberboards, sizing is accomplished in two steps: first, the sizing chemical is mixed in the water-diluted pulp; then a precipitant is added which causes the size to floc and fix to fiber surfaces.

Rosin size.—Commonly used in paper manufacture, and to some extent in insulation board, most **rosin** is obtained from living southern pines (gum rosin), extracted from resin-rich stumpwood (wood rosin), or obtained by fractional distillation of tall oil, a by-product of southern pine kraft pulp mills (tall oil rosin). Rosin size, prepared by saponifying molten rosin through addition of sodium hydroxide or sodium carbonate, can be added directly to the pulp or emulsified (pH 9 or 10) before addition. Water resistance imparted increases uniformly with increasing content of rosin size up to about 2 percent; above 2 percent the effect lessens, and size content exceeding 3 percent (ovendry-weight basis) is of little benefit (Swanson et al. 1971).

The precipitant, **paper makers' alum** (aluminum sulphate $Al_2(SO_4)_3$) diluted to contain 1 or 2 pounds of dry alum per gallon of water, is added in a quantity sufficient to reduce the pH of the thoroughly mixed pulp and size to about 4.5.

Wax size.—Waxes, hydrocarbons of high molecular weights (300 to 700) derived from crude oil residuals or distillates, having melting points from 120 to 200°F, are insoluble in water, and are inert. Wax sizes are prepared by melting the wax and then emulsifying it in water to yield two types: acid-stable and non-acid-stable (table 23-4).

In the manufacture of fiberboard, wax sizes are used to improve water resistance. For wet-process boards, emulsified and homogenized wax sizes are added to the watery pulp at temperatures below the melting point of the wax, and precipitated with alum. Effectiveness of rosin and wax size increases with increasing drying temperatures applied to the fiber mat (fig. 23-23).

In dry-process fiberboards wax is added directly to chips or fibers, in molten or emulsion form—sometimes together with liquid resins. Wax sizes in both wet- and dry-process fiberboards lower strength properties more than rosin sizes, particularly when they exceed 0.5 percent of dry fiber weight; wax contents of 0.2 to 0.5 percent, however, have small effect on board strength.

Asphalt size.—Asphalt is a black to dark brown solid or semi-solid, predominantly bitumen material which gradually liquifies when heated. It occurs naturally or is obtained during petroleum refining. Asphalts used for sizing have a higher resin content, and lower oil content and molecular size than paving asphalts.

Asphalts are used in emulsion form, added to pulp not exceeding 135°F in temperature, and precipitated by addition of alum. Asphalt-sized pulps in headboxes of forming machines should be adjusted to a pH of 4.5 to 5.0 and temperatures not exceeding 135°F. Typical specifications for asphalt emulsion size are as follows (Lorenzini 1971):

Statistic	Value
Asphalt content, percent by weight	57-60
Emulsion pH	9-11
Particle size range, µm	1-5
Viscosity, Saybolt-Furol, seconds	20-100
Asphalt softening point (ASTM D 2308), °F	185-210
Asphalt penetration at 77°F (ASTM D5)	0-10

Asphalt sizes do not decrease bond strength; in insulation board, tensile and bending strength are increased by asphalt sizing due to smooth sheet formation and improved drainage. Because of the dark color imparted by asphalt sizing, its use is mostly limited to insulation board, where typical content of emulsified asphalt size is 10 to 15 percent of dry fiber weight.

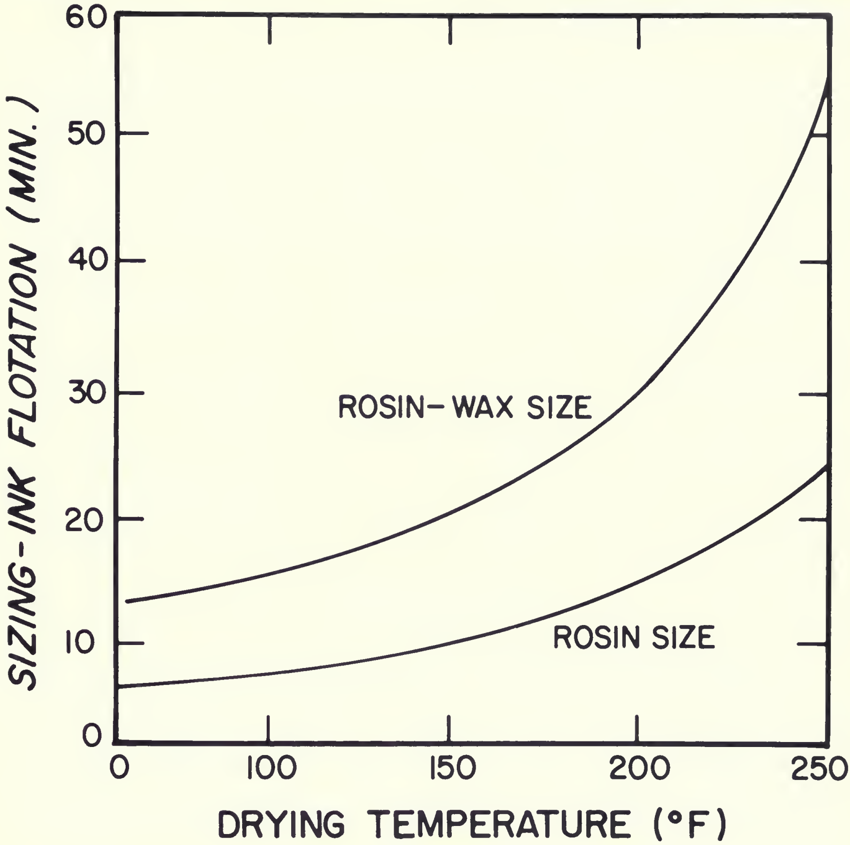


Figure 23-23.—Effect of drying temperature on the effectiveness of wax size, as measured by the ink flotation test. Longer time = better sizing. (Drawing after Cobb and Swanson 1971.)

TABLE 23-4.—*Physical and chemical properties of two types of wax sizes* (Porter 1971)

Property	Acid-stable	Non-acid-stable
Total solids, percent by weight	40 to 55	40 to 65
Density, pounds/gallon	7.6 to 8.1	7.6 to 8.1
pH	5 to 8	8 to 11
Particle size, average, microns	1	0.5
Color	White, off-white	White, off-white
Stability		
Alum	Stable	Unstable
Alkali	Stable	Moderately stable
Mechanical	Good	Good
Temperature		
Above 32°F	Stable	Stable
Below 32°F	Unstable	May be stable
Storage	3 to 6 months	3 to 6 months

FIBERBOARD BINDERS

Lignin is potentially the most important binder in fiberboard manufacture. If it is exposed by the pulping process and "activated" in the hot press, additional binders may not be necessary. Masonite, for example, makes wet-formed hardboards without additional binders. Most fiberboard manufacturers, however, use added binders to either enhance the lignin bond or establish artificial bonds in the absence of lignin bonding, as follows—listed in order from least to most binder content:

Process and product	Primary bond	Secondary bond
Wet process		
Insulation board	Hydrogen	Starch (corn, rye, or potato), asphalt
S1S Masonite	Lignin	—
S1S	Lignin	Phenolic thermosetting, thermoplastics
S2S	Lignin	Thermoplastics, drying oils
MDF	Lignin	Thermoplastics, drying oils
Dry process		
S2S	Thermosetting phenolics	—
MDF	Thermosetting ureas	—

Wet-formed S2S fiberboards cannot use thermosetting resins such as phenolics because in wet-forming the mat must be dried at high temperature before it is hot pressed, and thus would be precured before mat consolidation. Instead, thermoplastic resins such as Vinsol (derived from pine rosin) and Gilsonite (from naturally occurring asphalt) are employed. Drying oils such as linseed, tung, tall, and soybean oils are also used as binders in the wet S2S process—alone or in combination with thermoplastic resins.

In S1S wet-formed hardboard, water is first pressed from the mat without application of heat, and then the mat is consolidated in a hot press with a screen on one side of each board so steam can escape. For such boards a water-soluble, highly condensed thermosetting phenolic resin of high pH can be precipitated on fiber surfaces to form bonds during hot pressing.

Dry-formed hardboard and medium density fiberboards rely entirely on added resin binders, since their processes do not provide conditions under which the lignin bond can be utilized. These resins are cured during hot pressing.

Resin binders and drying oils not only bond fibers, but also size them. Drying oils size by surface modification; resins additionally impart stability by restraining swelling through improved bonding. Penetrating resins further enhance stability. Thickness swelling can be almost completely restrained by addition of sufficient resin (fig. 23-24), but only at levels uneconomic for standard hardboard manufacture. Normal phenolic resin levels are about 1 or 2 percent in wet-formed hardboard, and up to 5 or 6 percent in dry-formed hardboard. Most strength properties and soprtion characteristics improve little at resin content in excess of 3 percent (American Marietta Company n.d.). Urea-bonded medium-density fiberboard made by the dry process commonly requires 8 to 11 percent resin content.

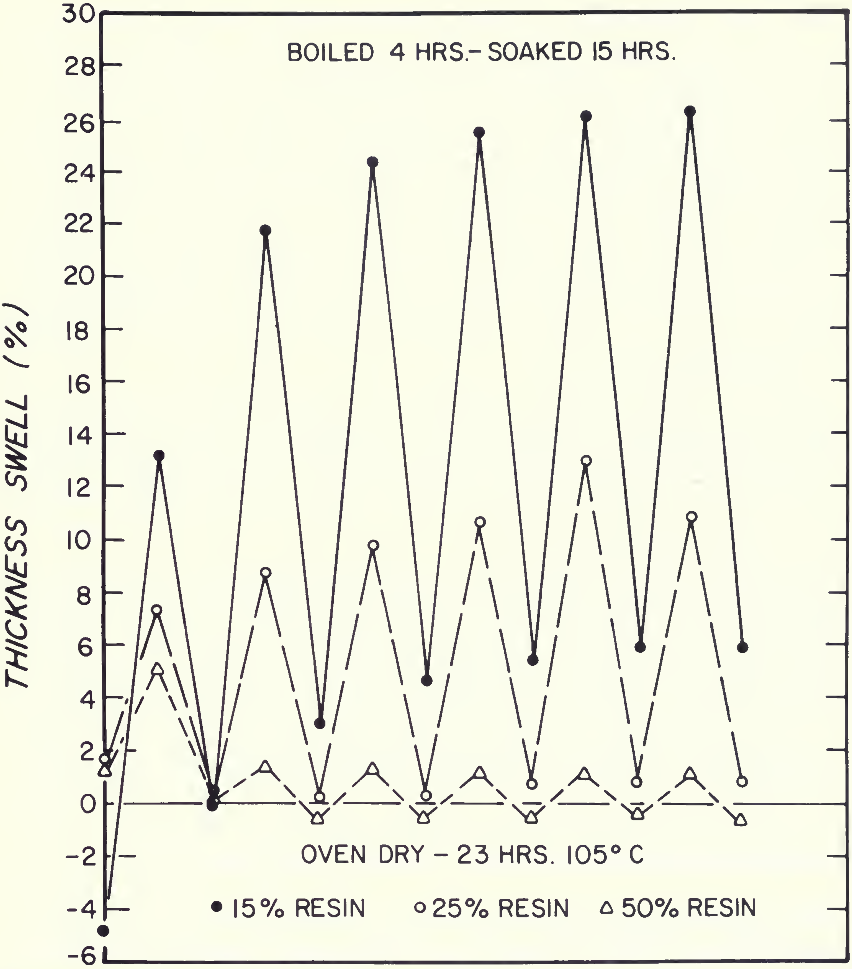


Figure 23-24.—Thickness swell of dry-formed hardboard at three contents of impregnating resin, during six cycles of exposure. (Drawing after Brown et al. 1966.)

FIRE RETARDANT AND PRESERVATIVE TREATMENTS

Fire retardants.—Fiberboard is combustible. At high temperatures it evolves combustible gas which increases fire destruction, and smoke which obscures vision and irritates the respiratory system. In panel materials such as fiberboard and plywood, flame spread rate, fuel contribution, and smoke development are the statistics of interest. Methods of measuring them, and the effectiveness of various chemicals, are summarized in Koch (1972, p. 1111-1128). In devices to measure flame-spread rate, untreated red oak has a rating of 100; lower numerical rating indicates slower flame spread. Class A materials suitable for exitways of unsprinklered assembly and institutional buildings must have a flame-spread rating of 0 to 25; class B (flame-spread rating of 26-75) is suitable for schools and hotels. Fiberboard, unless treatd with fire retardants, cannot be used where codes require class A or class B ratings.

Myers and Holmes (1975, 1977) have, on an experimental basis at the U.S. Forest Products Laboratory, achieved class B protection of dry-formed fiberboard with 20 percent retention of various chemicals, based on dry fiber weight.

In the United States, the only fire-retardant treatment of fiberboard in commercial use is one patented by the Masonite Corporation (Short and Rayfield 1978). The patent described the process, which achieved class A rating, as two-step. In the first step alumina trihydrate is added to the furnish to comprise 45 to 60 percent of panel weight. After forming and pressing several coats of borate ester resin, preheated to about 100°C, are applied to panel surfaces with flow and roller coaters, with time for penetration allowed between coats. Treated panels are then heated 1.5 to 2 hours at 150-160°C and finally humidified to about 5 percent moisture content.

Preservative treatments.[3]—Fiberboards, like other wood products, may be attacked by termites and may decay if wetted intermittently or placed in ground contact. A sodium salt of pentachlorophenol (e.g., Dowicide G), a common wood preservative soluble in water, can be added to fiberboard furnish to protect against termintes (chemical retention of 0.75 percent of ovendry fiber weight) or rot and mildew (0.5 percent).

When preservative is added, the furnish should have pH of about 8.5; it is precipitated and fixed on the fibers as insoluble sodium pentachlorophenate, together with size and other additives, by addition of alum or acid. Pentachlorophenol is a poisonous substance and requires special consideration during water treatment. It also interferes with sizing of fiberboard (U.S. Department of Agriculture, Forest Service 1974). Contamination of board to be used in products which may be handled by children or chewed by pets must be avoided.

PROCESS COMPARISONS AND INDUSTRIAL PRACTICE

Wet processes, general.—Figure 23-25 illustrates pH level, pulp consistency, and introduction of chemicals in a wet-process fiberboard plant from primary refiner to Fourdrinier sheet forming machine. This figure applies equally to the manufacture of insulation board, and S1S and S2S wet-formed hardboard and MDF. Following primary breakdown the stock is diluted to make it pumpable and less acid. Caustic soda is added to further raise its pH from below 4.0 to 5.0+, to reduce corrosion and make it easier to wash out dissolved sugars. Caustic soda addition does, however, reduce fibers' affinity for water. Much of the water added is removed in the washer, from whence it carries biodegradable materials which can be recirculated, but which must be removed before the water can be discharged.

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[3]This text reports research involving fungicides and pesticides. It does not contain recommendations for their use, nor does it imply that the uses discussed here have been registered. All uses of fungicides and pesticides must be registered by appropriate State and/or Federal agencies before they can be recommended. CAUTION: Fungicides and pesticides can be injurious to humans, domestic animals, desirable plants, and fish or other wildlife—if they are not handled or applied properly. Use all fungicides and pesticides selectively and carefully. Follow recommended practices for the disposal of surplus fungicides, pesticides, and their containers.

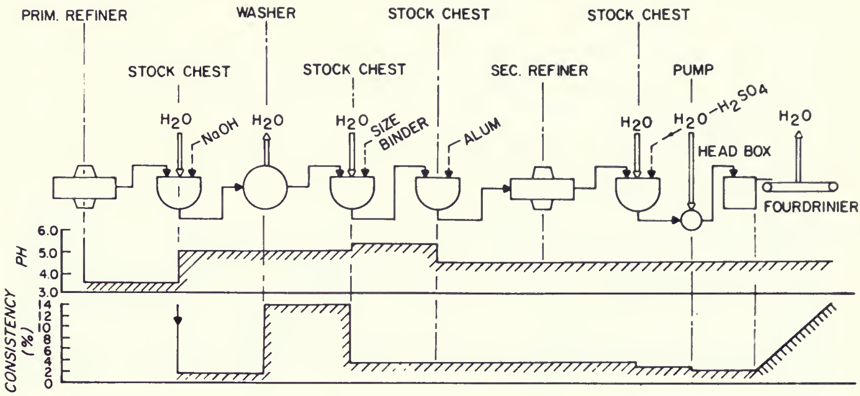

Figure 23-25.—Schematic of stock flow in a wet-process fiberboard plant, showing pH, stock consistency, and introduction of additives. (Drawing from Suchsland and Woodson 1985.)

In the next stock chest the consistency is reduced to about 3.5 percent. The diluting water can be fresh water, but generally is **machine white water** (water removed from the stock during sheet forming on the Fourdrinier machine). Recirculation of machine white water reduces water treatment requirements and recovers and reintroduces chemical additivies not retained in the mat. Size, binder, and other chemicals are added in this stock chest and mixed.

In the following stock chest the pH is reduced to about 4.5 by the addition of alum, to precipitate the chemical additivies. Secondary refining occurs next, followed by further dilution of the stock to forming machine consistency (2 percent). In the last stock chest prior to the forming machine, sulfuric acid may be added to finally adjust pH.

Application of extra resin (up to 5 percent of dry fiber weight) into mat edges during forming firms edges, reduces springback, and allows minimal press cycles (Eustis[2]). Steinmetz and Fahey (1968) found that addition of extra resin to wet mat surfaces improved dimensional stability in experimental boards, but resin levels required were very high.

Wax emulsion for improving water resistance is added to S1S furnish in very small quantities, from 1/10- to 1/2-percent based on dry fiber. Wax emulsion may also be added in diluted form by spraying it on the surface of the mat on the forming machine. The emulsion spray acts as a defoamer as it breaks surface bubbles and is then sucked into the mat by vacuum. In other cases, molten wax is added to very hot stock (180°F) or applied to the chips. However, this may cause the formation of wax drops which appear on the board surface as spots that interfere with finishing operations. Bark of some species, e.g., Douglas-fir (*Pseudotsuga menziesii* (Mirb) Franco) contains sufficient wax that its incorporation into S1S wet-process hardboard may preclude need for additional size.

Insulation board.—Insulation board is sized with wax in emulsified form (0.75 to 1.25 percent dry wax based on dry fiber weight), sometimes in combination with rosin, and with powdered asphalt (10 to 15 percent based on dry fiber weight). Rosin has a higher melting point than wax, and requires higher dryer temperatures to effectively coat fiber surfaces.

Starch (1 to 2 percent of dry fiber weight) is slurried in water and pumped into insulation board pulp just ahead of the forming machine; starch imparts strength to insulation board, but is attractive to rodents and insects.

S1S wet-process fiberboard.—Standard additives in S1S board manufacture are phenolic resins and wax. Resin is added in quantities of ½ to 1 percent, in some cases up to 2 percent, depending on length of press cycle. At minimum press cycles resin cure is incomplete. It can be completed during subsequent heat treatment, but the board will suffer substantial springback (immediate thickness expansion upon removal from press), particularly along the board edges, where temperatures in the press are lower than that at the board center. This can be compensated for by increasing the resin content. There is, therefore, a trade-off between resin content and press time, i.e., between resin cost and productive capacity. When resin costs are high, S1S boards will remain in the press longer to minimize springback due to lowered resin content.

Abitibi Corp., at their Alpena, Mich. plant, uses ferric sulphate as a precipitant in place of alum. Ferric sulphate is more corrosive than alum, but produces a dark grey color in the board which is a desirable background for printed paper overlays applied directly to the wet mat in their wall-panel manufacturing line (Eustis[2]).

Preparation of furnish for forming machines traps air and causes the stock to foam, particularly at higher temperatures. Tiny air bubbles, beaten into the stock in refiners and mixers, can reduce freeness by 10 to 15 percent, cause tanks to overflow, and interfere with the forming process. In insulation board and wet S2S plants, where efficient water removal on the forming machine is very critical because of the high energy cost of removing the remaining water in the dryers, this air is removed from the stock in **deculators,** which are vacuum tanks in which the air is boiled off and removed.

S1S lines do not normally use deculators because water remaining in the mat after forming can be squeezed out mechanically in the first part of the hot press cycle. Instead these plants add defoamers just ahead of the forming machine, to break up air bubbles in the stock. In the past kerosene was used. Currently, special defoamers are available, which reduce the surface tension of the water and cause the air bubbles to break. Too much defoamer, however, interferes with sizing of the sheet (Eustis[2]).

S2S wet-process fiberboard.—Wet-formed S2S boards cannot be bonded with phenolic resin binders, because they are thermosetting and would cure during drying of the mat prior to hot pressing. Binders in these boards are in-situ lignin, drying oils, or thermoplastic resins, depending on the final use of the product.

Masonite makes wet-formed S2S interior-application boards with the addition of wax size only. Masonite siding is made by the S1S process and uses phenolic resin. Other "interior" wet-S2S boards (Abitibi, U.S. Gypsum) are made with the addition of drying oils, linseed oil being the most common one. These oils are emulsified by stirring them with caustic soda; they are added to the stock at rates ranging from ½ to 1½ percent. The lower the board density, the more oil is added, as follows (Eustis[2]):

Board density	Oil addition
Pounds/cubic foot	*Percent of dry fiber weight*
65-70	¾
50-55	1.5-2

Both U.S. Gypsum Corp. and Abitibi Corp. use ferric sulphate, which is more corrosive than alum, to precipitate the oil emulsions, producing a characteristic grey pulp which turns to grey-brown in the hot press. It also results in bending strengths at least 10 percent higher than boards in which the oils are precipitated with alum. The fixation of the oils on the fiber seems to be purely mechanical. Losses are therefore great and closed water systems (recirculation of machine white water) become imperative (Eustis[2]). Much higher oil quantities are used in so-called slush ovelays—thin layers of highly refined pulp applied on top of the regular mat by means of a secondary headbox. Oil contents can be as much as 6 percent, but only about 1½ percent is retained. In closed white water systems the lost additives build to a constant level and circulate, only retained quantities being added.

Other mills vary considerably in their use of binders. Temple East-Tex produces wet S2S siding with only linseed oil and size. No resin is added. Boise Cascade at International Falls, Minn. produces wet S2S siding (Insulite) using 5 percent, based on dry fiber weight, of a high melting point thermoplastic resin derived from naturally occurring asphalt (Gilsonite); in this operation wax is used as size and alum as precipitant. Weyerhaeuser Co. at Craig, Okla. produces a wet-process S2S siding with a similar thermoplastic binder. The siding produced by Abitibi Corp. incorporates a thermoplastic resin made from pine rosin (Vinsol); it is an S1S product.

To prevent these thermoplastic resins from sticking to hot-press platens, release agents such as diesel fuel, kerosene, silicones, and urea are applied to the mat.

Dry-formed hardboard and medium-density fiberboard.—The standard binder for **dry-formed hardboard** is phenol-formaldehyde liquid resin, added in proportions greater than in wet-formed hardboard where phenolics and other binders play a secondary role. Wax is the usual sizing agent. As an example, Weyerhaeuser Co. at Klamath Falls, Oregon produces dry-formed siding with 6-percent phenolic resin content and ½-percent wax (based on dry fiber weight) applied before the dryer (fig. 23-26 top). In other mills, liquid phenolic resin is introduced through the disk refiner hallow shaft, so that it is applied to the chips as they are fiberized between the plates. Binder added to dry furnish must not have **tack** (stickiness) or the fiber will lump together causing uneven distribution so that deposition of the furnish in the forming machine is difficult or impossible.

The development of the **dry medium-density fiberboard** process in the 1960's was based in part on a so-called *in-situ* resin which was a combination melamine-urea formaldehyde resin of low molecular weight, low tackiness, and low viscosity which condensed after application to the furnish. Later, standard

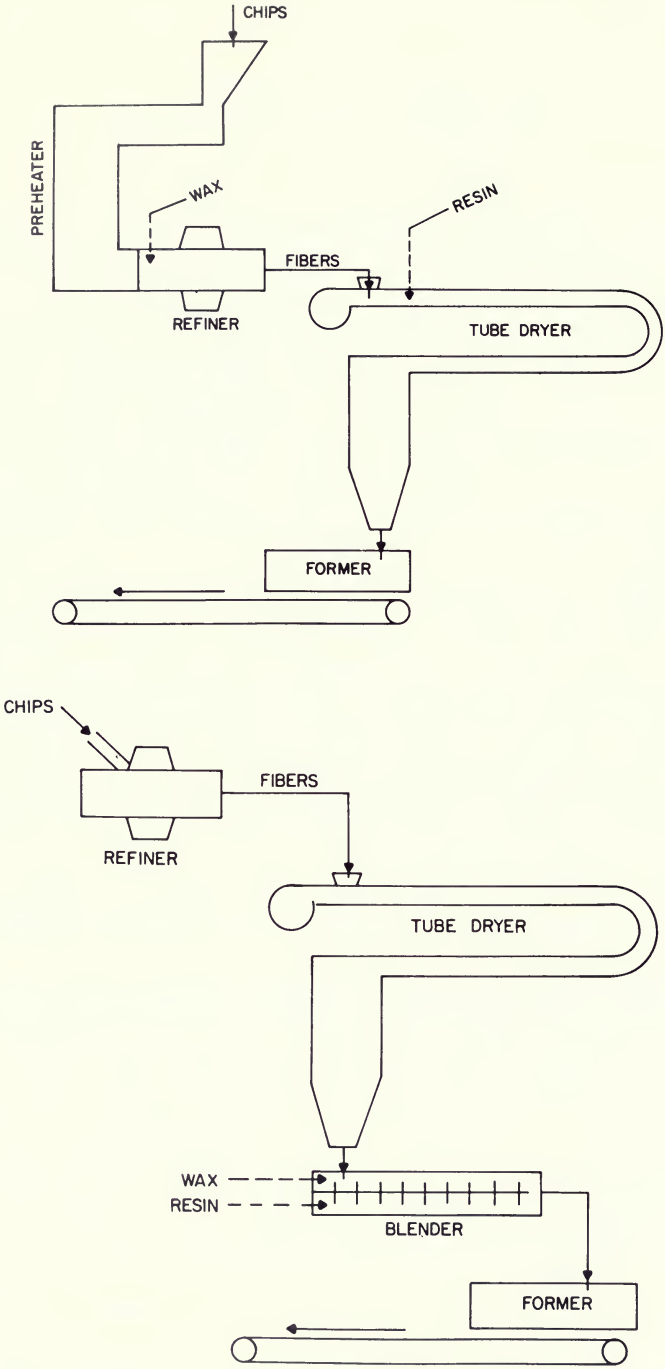

Figure 23-26.—Schematic of dry-process fiberboard plants. (Top) Hardboard plant showing addition of phenolic resin prior to admitting fiber to tube dryer. (Bottom) Medium-density fiberboard plant showing addition of resin in a short-retention blender after fibers exit tube dryer. (Drawing from Suchsland and Woodson 1985.)

urea resins with low tack were used as well. These binders, which must be introduced after the fibers are dried (fig. 23-26 bottom), are applied in short-retention continuous blenders (fig. 23-27). The retention time in such blenders is 1 to 3 seconds. The resin is injected into the fiber mass through radially arranged injection tubes. Typically, resin contents range from 8- to 10-percent resin solids, based on dry fiber weight.

The pH of the dry fiber furnish is generally not controlled. However, pH of the furnish is taken into consideration in binder formulation, since it affects curing rates. Meyers (1977) found that modification of the pH of dry fiber furnish by spraying it with either a 1- to 2-percent solution of sulfuric acid for downward adjustment or with a 5- to 10-percent solution of sodium bicarbonate for upward adjustment, had significant effects on mechanical and physical properties. He suggested that such treatments could counteract the refractory gluing properties of oaks and certain other species.

23-8 WET-PROCESS FIBERBOARD MANUFACTURE

Pulping procedures in fiberboard plants vary significantly according to board product selected for manufacture. Other manufacturing procedures also vary with product. Thus, a fiberboard plant is designed to produce either wet- or dry-formed board, and is generally limited to one or two classes of product. Wet and dry processing differ from forming through pressing. This section describes the

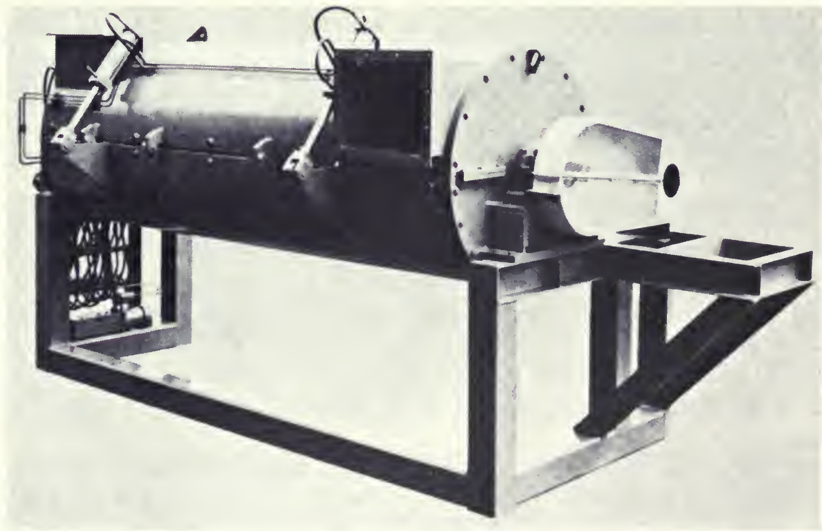

Figure 23-27.—Short-retention continuous blender.

wet process and section 23-9 the dry process. Subsequent steps of board humidification and fabrication after pressing are similar for boards made by both processes.

Until mats emerge from wet forming and pressing the technology of manufacture is almost identical in all wet lines. From that point on, however, processing of the wet mat is distinctively different for each of the three principal wet-formed products. The distinguishing feature in the insulation board line is the dryer and lack of a hot press, in the S1S hardboard line the hot press and lack of a dryer, and in the S2S line the dryer and hot press combination (fig. 23-28).

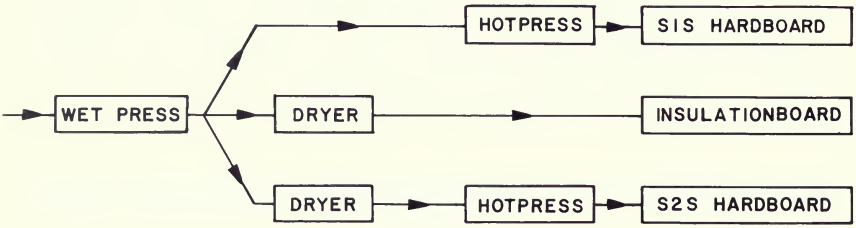

Figure 23-28.—Schematic description of processing wet fiberboard mats into the three principle wet-formed fiberboard products. (Drawing from Suchsland and Woodson 1985.)

CONSISTENCY AND WATER CONSUMPTION

Throughout initial stages of the wet process fibers are suspended in water, most of which is removed at the forming machine. The furnish consistency varies in these stages (fig. 23-25), and therefore water consumed or recirculated varies proportionately. Water quantities pumped can be very large; e.g., a reduction of consistency from 2 to 1 percent doubles the amount of water in the pulp stock.

Figure 23-29 schematically illustrates an S1S fiberboard process indicating both furnish consistency and actual quantities of water and fiber based on daily board production of 100 tons. The center part of the diagram shows the consistency variation in percent. The incoming raw material has an assumed moisture content of 100 percent (based on dry weight), which corresponds to a consistency of 50 percent. To produce 100 tons of board in 24 hours requires a constant rate of dry fiber flow from one end of the process to the other of 0.069 ton/minute.

At 100 percent moisture content (50 percent consistency) the raw material introduces into the process 18 gallons of water per minute. As water is being added and removed, the consistency of the furnish changes. The absolute quantity of dry wood fiber passing through each step of the operation, however, remains constant at 0.069 ton/minute.

To reduce consistency from 50 to 12 percent requires addition of only 116 gallons/minute. To further reduce the consistency from 12 to 1 percent, however, requires addition of 1,671 gallons of water every minute. All of this water is removed in the washer and partially replaced subsequently. Following the washer, the consistency is gradually reduced to the forming consistency of about 2 percent (fig. 23-25). On the forming machine the mat is formed by drawing the water from the slurry. Some more water is removed in the wet press, and the rest is squeezed out or evaporated in the hotpress.

Water consumption and water discharge problems can be greatly reduced by partial or total recirculation as indicated by the dotted lines in figure 23-29. Two water cycles are apparent. The primary water cycle recirculates the washer discharge, which is contaminated with sugars. The secondary cycle (machine white water) is kept separate from the first. It carries washed out chemical additives which will build up to a constant level so that chemicals have to be added only at the rate at which they are actually retained in the board. Similar diagrams could be drawn for the other two options of the wet process: insulation board and wet-formed S2S board. For insulation board the hot press would be replaced by the continuous dryer, and for wet-formed S2S board, a dryer would precede the hot press (fig. 23-30).

Although the amount of water removed in hot press or dryer is relatively small, these two steps impose important limitations on the wet process: only one smooth side in the S1S process, and considerable energy requirements for water evaporation in continuous dryers (insulation board and S2S board).

FORMING MACHINES

Sheets or mats are formed when the watery pulp suspension is flowed onto a wire screen which retains the fibers but allows the water to drain. Uniformity of fiber dispersion in the mat depends to a large extent on consistency, as pulp fibers have a tendency to form clumps at higher consistencies when their free movement is restricted. Lampert (1967) found that such floculation may occur if stock consistency in the **headbox** ahead of the former is greater than about 2.5 percent. At very low consistency, e.g., less than ¾-percent, fiber movement is unimpeded, but fibers may settle singly without the interweaving necessary for development of maximum sheet strength. Lampert (1967) found that maximum board strength resulted from a headbox consistency of about 1½ percent, just avoiding floculation. As dewatering proceeds, there occurs a **collective sedimentation** of fibers accompanied by physical interference at the moment of sedimentation resulting in a somewhat three-dimensional network. Optimal consistency in the headbox is influenced by fiber length, type, and cooking conditions.

Fast drainage enhances productivity and manufacturing economy. Freeness of pulp is the dominant factor, but water temperature also affects drainage rate because viscosity of water decreases as temperature increases. Adverse effects of higher water temperatures on additives limits stock temperatures in the headbox, however.

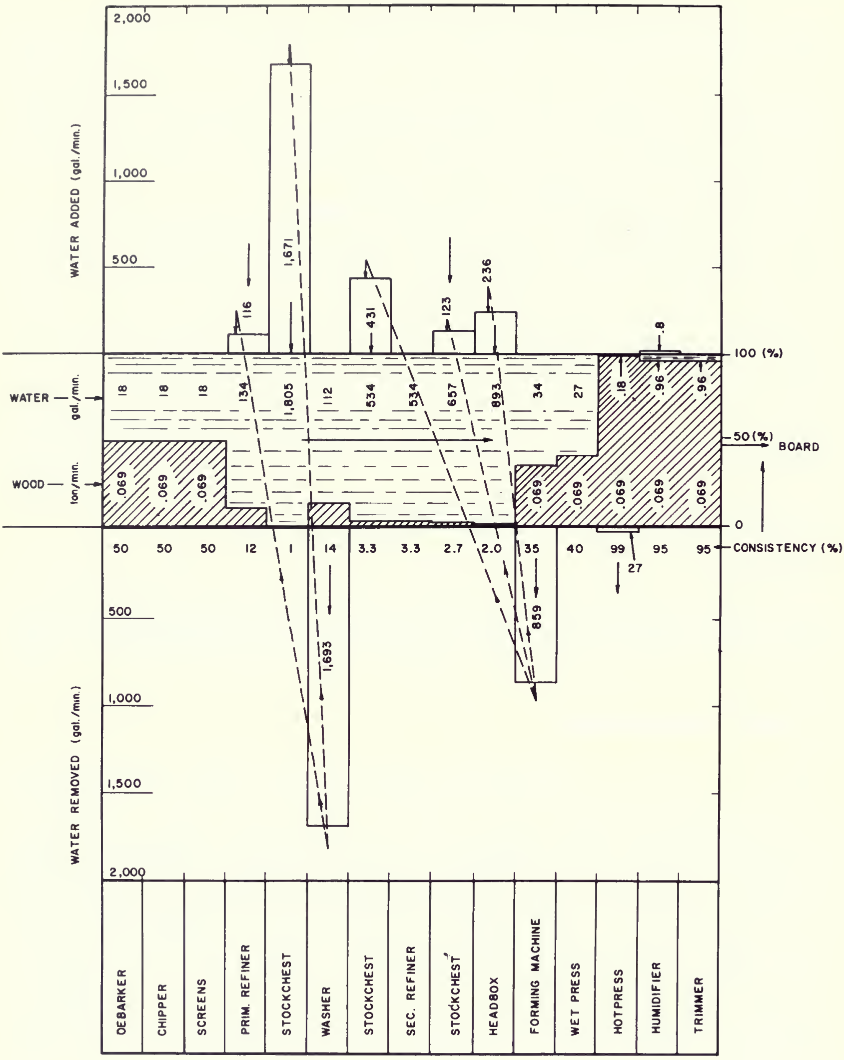

Figure 23-29.—Water balance of S1S fiberboard plant producing 100 tons of board per day, ovendry-weight basis. (Drawing from Suchsland and Woodson 1985.)

Three different wet forming machines are used in the industry:

- Batch-type sheet mold
- Continuous cylinder machine
- Fourdrinier machine

Of these, the Fourdrinier machine is most important, and is exclusively used in new installations.

Batch-type sheet mold.—The discontinuous or batch-type wet-forming process was developed by Ralph Chapman of Corvallis, Ore. in an effort to produce fiberboard economically on a small scale. Two plants in the United

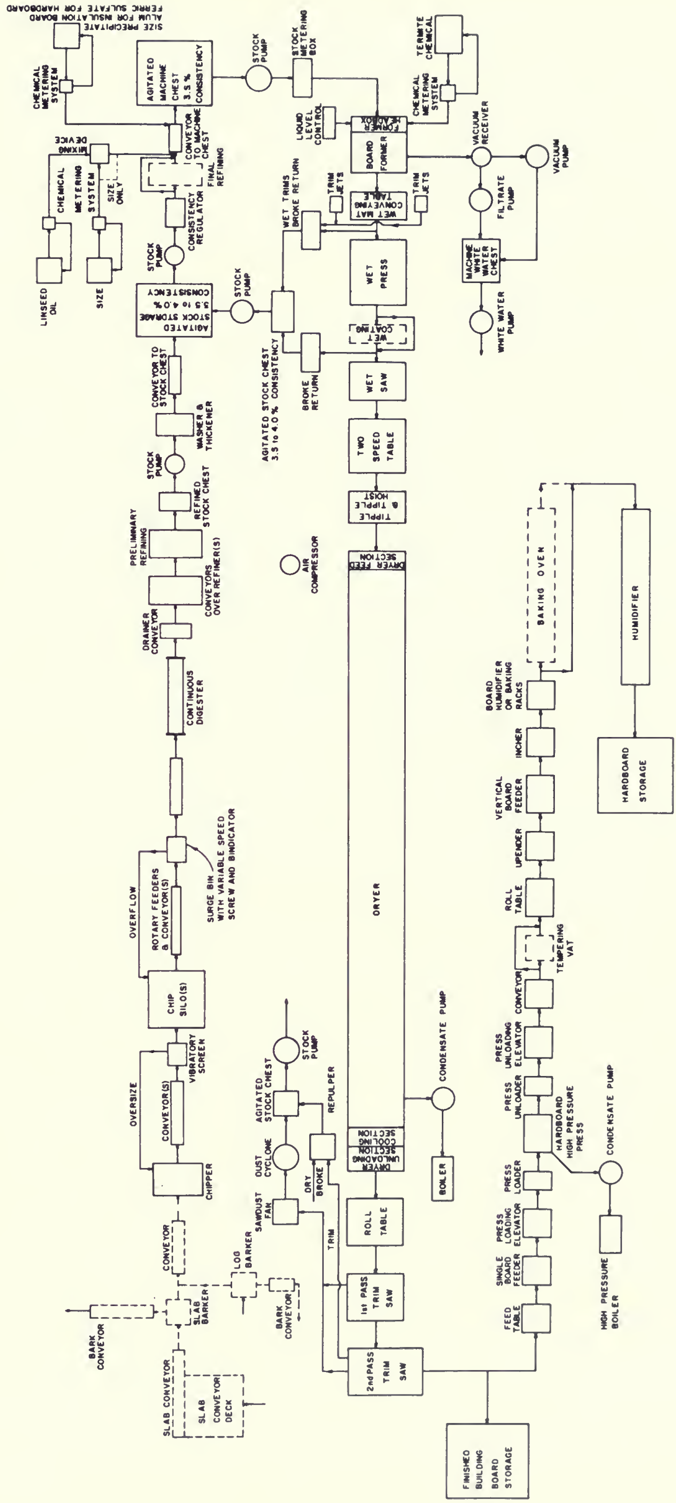

Figure 23-30.—Schematic diagram of wet-formed S2S hardboard process. (Drawing after Watts 1957.)

States and one in Canada use the process in which stock is pumped through swinging spouts into a 4- by 8-foot deckle-box positioned on top of an endless screen which also passes between platens of a cold press for dewatering the resultant mat. After the mat is formed on the screen and water drained with vacuum assist, the **deckle-box** is lifted and the endless screen moves the mat between platens of the dewatering press where mat consistency is increased to 33 to 37 percent. On discharge from the dewatering press, mats are delivered by tipple to a multi-opening rack to await charging into a hot press to yield S1S panels.

Cylinder forming machines.—Cylinder machines are continuous formers, similar in design to the vacuum pulp washer described by figure 23-22 (top). They are simple, relatively inexpensive, rugged, and work well with both hardwoods and softwoods. **Single-cylinder machines** (fig. 23-31 top) are built in diameters from 8 to 14 feet and are 9 to 15 feet long. The screen-covered cylinder revolves partially submerged in a constant-level vat of continuously agitated stock, where an internal vacuum sucks water through the screen and deposits fibers on it. Forming is complete where the cylinder emerges from the stock vat, and the mat is compressed by press rolls covered with wire or felt to force more water through the mat into the interior of the cylinder. No water is removed from the top (outside) of the mat. A vacuum of 15 to 24 inches of mercury is maintained on the interior portions of the cylinder up to the location where the mat is lifted off the screen by a **doctor** bar and delivered to a wet press by roller conveyor. A 14-foot-diameter single-cylinder machine can form mats for ½-insulation board at 50 to 60 feet per minute while rotating 1.1 to 1.4 rpm. Mats for 1-inch insulation board are formed more slowly—about 20 to 24 feet per minute while rotating at 0.45 to 0.55 rpm. Capacity for production of ½-inch insulation board varies from 70 to 250 tons per day depending on cylinder diameter and length (table 23-5).

TABLE 23-5.—*Production capacities of single-cylinder forming machines producing ½-inch insulation board* (Lyall 1969)

Cylinder diameter and length (feet)	Cylinder area	Daily (24 hours) production[1]	Tons per day
	Square feet		*Tons*
8.0 x 9.0	225	200,000	70
11.5 x 10.0	350	300,000	100
14.0 x 9.0	396	350,000	120
14.0 x 13.3	572	600,000	200
14.0 x 15.0	660	700,000	250

[1]These values are minimums; greater production is possible.

In a **double-cylinder** forming machine (fig. 23-31 bottom), the two cylinders are geared to run at the same speed but in opposite directions. Each cylinder forms one-half the total mat thickness, the two halves being merged and laminated in the nip between the cylinders, where hydraulic pressure forces them together and helps dewater the mat. Doubling of drainage area contributes to the higher productivity of this machine. Also, cylinder construction is simplified because the pressure differential needed to form the mat is created by a **water-drop leg** (see fig. 23-22 top for illustration of drop leg) rather than a vacuum system. Resulting positive water pressure requires sealing of the vat where the two cylinders enter the pulp, and around the ends of the cylinders. Air blown into the nip keeps water in the vat away from the outgoing mat.

The double cylinder machine has an important advantage over all other forming machines because it produces a mat of symmetrical fiber structure. All single-cylinder wet-forming machines tend to deposit coarser fractions of stock first and finest fractions last. The two surfaces of the board will therefore have different appearance and properties, a condition only partially alleviated by agitating the stock in the vat during forming. Laminating the two halves of the mat mates top surfaces from each cylinder and presents identical bottom surfaces outside. Bond quality depends on the fiber characteristics; if the surface fibers are too fine or too coarse, the sheet may delaminate during or after drying.

The caliper of the laminated mat, besides being a function of the thickness of the two halves, is controlled by the force applied to the mat in the nip. A force of 400 pounds per lineal inch of nip is not uncommon. Double cylinder machines produce boards with exceptional uniformity of caliper and density.

Cylinder machines produce a mat of relatively low water content (less than 80 percent), and are capable of handling slower stock than Fourdrinier forming machines at the same forming speed and on the same forming surface area, but they are not suitable for very free draining stock.

Cylinder machines have a tendency to orient fibers in the machine direction (direction of rotation). Eustis[2] estimates this bias as 60/40 which means that properties of the finished board measured in the two principal directions will have a ratio 60/40. Bending strength would be greatest in the machine direction, and the linear expansion coefficient would be largest perpendicular to the machine direction.

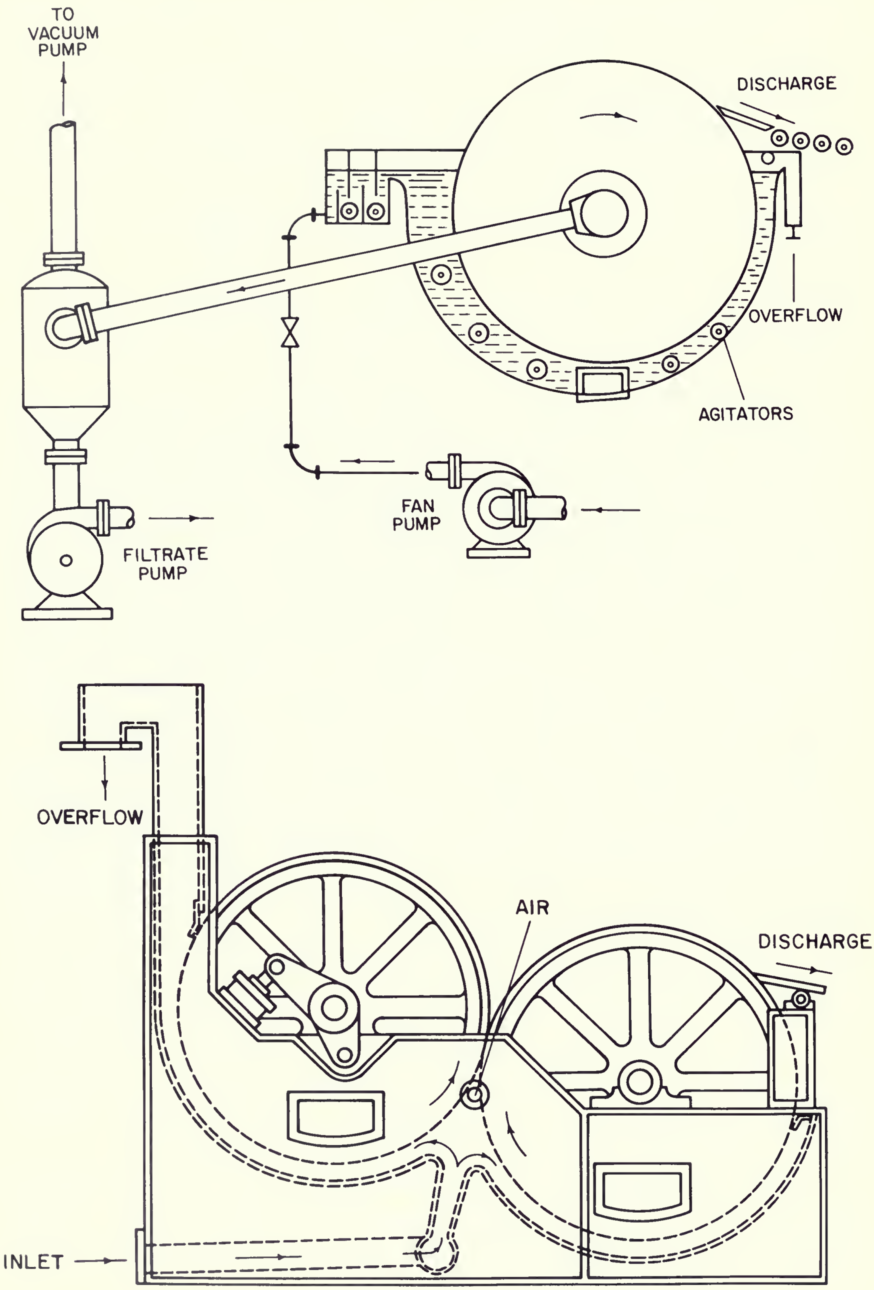

Figure 23-31.—Cylinder forming machines. (Top) Single-cylinder vacuum-forming machine. (Bottom) Double-cylinder gravity-forming machine. (Drawing after Lyall 1969.)

Production rates of cylinder forming machines depend mainly on stock freeness and on the required thickness and density of the mat. For a given pulp the build-up of the mat is determined by the cylinders' peripheral speed. The slower the speed, the thicker will be the mat on the screen. The relationship between mat thickness and forming speed is not linear, however, because as the mat builds up, the vacuum or the pressure differential becomes less effective in forcing water through the screens. The forming speed for very thick mats is, thus, greatly reduced.

Forming speeds of mat for ½-inch-thick insulation board on double cylinder machines are about as follows (Lyall 1969):

Cylinder diameter	Cylinder speed	Forming speed
Feet	*Rpm*	*Feet/minute*
4	0.5 to 2.0	6 to 25
8	to 1.6	to 40
12	1.6+	60+

Fourdrinier forming machines.—The Fourdrinier fiberboard forming machine (fig. 23-32), modified from the paper forming machine invented by Henry Fourdrinier in England, forms the sheet continuously on a wire screen travelling in a horizontal plane. Water is removed initially by gravity and vacuum, and in the press section of the machine by hydraulic pressure. Fourdriniers can accommodate a wide range of pulp freeness and are used to manufacture S1S and S2S hardboards as well as insulation board.

The main element in a Fourdrinier forming machine (fig. 23-32) is an endless wire screen, or simply the **wire.** It is driven by the **couch roll,** the last bottom roll of the machine, and serves as both the forming surface and conveyor which carries the mat through the continuous wet press, the final section of the machine. The wire has a weave of 14 to 32 mesh using phosphor bronze for the warp wires (running along the machine direction) and brass for the shute wires (running across the machine direction). Newer machines use plastic wires.[4]

The wire is joined to form a loop, either by a seam produced at the factory, or by a pin seam secured on the machine. The seamed wire requires a cantilever frame for installation so that the loop can be slipped over the rolls from one side of the machine. The pin seam can be used on any machine but does leave an impression on the backside of the board. Pin seams on plastic wires, however, leave virtually no marks and have made the cantilever design unnecessary.[4]

The pulp is supplied at the appropriate consistency (1 to 2 percent) to the **headbox** which is preceded by a manifold which assures uniform distribution of the pulp over the width of the machine. The headbox releases the pulp onto an apron, a piece of plastic-covered cloth attached to the lip of the headbox and extending out over the forming surface, from which it flows onto the forming table. A fence (**deckle**) on both sides of the wire prevents the stock from flowing over the sides of the screen and establishes the board edges.

The forming table consists of supportive frame work, screen supports, and dewatering devices. On it the sheet is formed, transforming the dilute pulp slurry

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[4]Private communication (1981) from Edge Wallboard Machinery Company, Downington, Penn.

in which each fiber is freely movable to a sheet in which all fibers are fixed in positions relative to one another that they will maintain through the rest of the process. Since many of the qualities of the finished board are established here, subsequent steps must not disturb this structure.

The forming table slopes upward from the headbox towards the wet press. This slope is adjustable and helps match the speed of the outflowing stock to the speed of the wire. Any speed differential will cause drag on the fibers and biased fiber orientation affecting directional mechanical and physical properties. A double adjustable tilt permits a steeper slope at the exit from the headbox, then a more gentle slope to the press section.[4]

On the machine shown in figure 23-32 the screen is supported by a series of closely spaced idling steel table rolls 4 to 5 inches in diameter. These rolls are designed to carry the considerable load of the stock and also contribute to dewatering. Figure 23-33 graphs development of the considerable vacuum caused by surface tension in the outgoing nip of a table roll running at peripheral speeds of 2,000 to 2,500 feet/minute. Only paper machines run at such speeds. A fiberboard machine operates at speeds less than 100 feet/minute and the vacuum created will be much smaller.

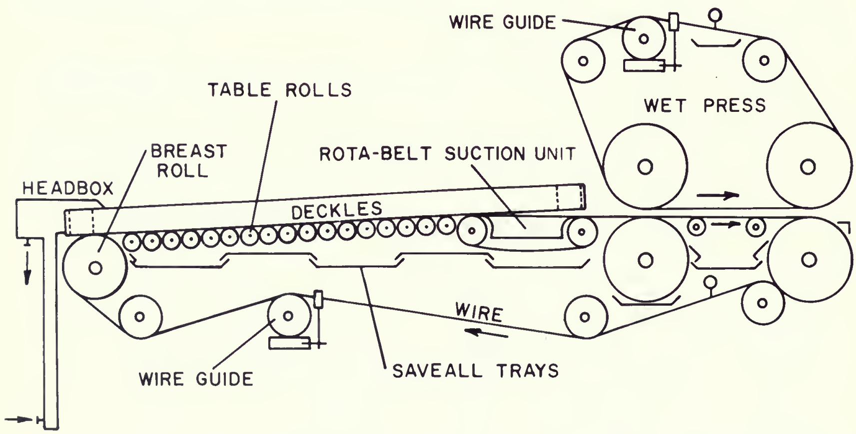


Figure 23-32.—Fourdrinier board forming machine with wet press. (Drawing after Lyall 1969.)

At some point on the forming table, the stock will change from a watery suspension of fibers to a fiber mat. Past this point, the **wet line** (fig. 23-34) where light reflected from the liquid water surface disappears, the mat surface appears dull. In the arrangement depicted in figue 23-32, a **rota-belt suction unit** is located past the wet line. It carries a slotted rubber belt which travels with the screen to reduce friction and wear; pumps apply a vacuum of up to 10 inches Hg to boxes below the belt, further dewatering the mat.

Vacuum should be applied gradually along the length of the wire. Too rapid drainage in the beginning of the forming process may tighten the sheet, slowing subsequent drainage. Springy stock resists compaction better and can tolerate more suction. Past the wet line the vacuum can be increased, but if increased too abruptly, may suck the sheet down so forcefully that the surface may crack.

One of the biggest changes made to Fourdrinier machines in recent years is elimination of table rolls and acceptance of polyethylene-topped suction drainage boxes. Because these boxes of ultra-high-molecular-weight material are structually more rigid than table rolls, they provide a flat surface for formation. Under some conditions a normal table roll may deflect as much as 0.200 inch, while the suction box will deflect less than 0.040 inch.[4]

A modern Fourdrinier without table rolls normally has 10 suction boxes, each box 3 feet long (in direction of screen travel). The first three boxes after the headbox are operated through a drop leg to a seal box, 6 or 7 feet below the wire.

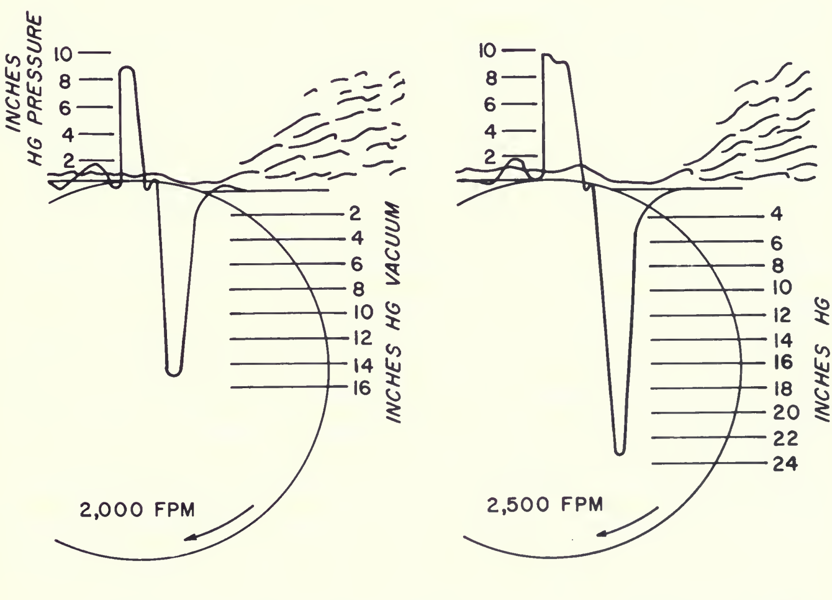


Figure 23-33.—Dewatering action of a Fourdrinier table roll on a paper machine is attributable to the vacuum developed at the outgoing nip below the mat. Action on a fiberboard former is similar, but due to lower speeds (100 feet/min.) vacuum is smaller. (Drawing after Strauss 1970.)

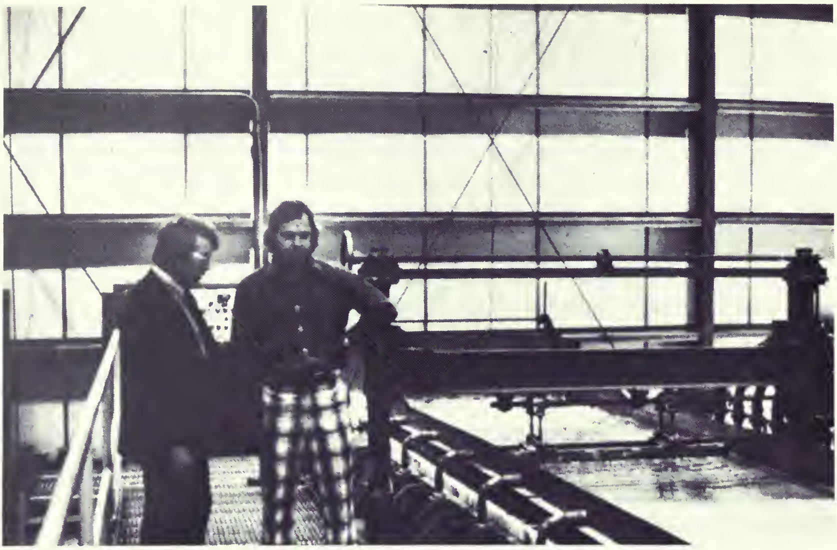


Figure 23-34.—Wet-line on Fourdrinier forming machine; *puddler* board is located above the mat just ahead of the wet line. (Photo courtesy of Edge Wallboard Machinery Company.)

The next four boxes are piped to a deeper seal pit and a low-vacuum manifold (3 to 5 inches Hg). Then by valving, the vacuum level on these boxes is graduated to control the rate of dewatering. The eighth box is piped to a high vacuum manifold (15 inches Hg). The last two boxes are piped to individual separators and the high vacuum manifold. The polyethylene topped suction box has also replaced the rota-belt on modern machines.[4]

The amount of water that can be extracted from an uncompressed mat is limited. At some point (about 80 percent water content) the vacuum will suck air and very little water. To extract any more water requires compressing the mat to saturation. This takes place in the wet press.

Board surface modification on a Fourdrinier.—All modern Fourdrinier machines are equipped with a **puddler** (fig. 23-34). This flat board, spanning the wire and located ahead of the wet line, oscillates up and down to just dip into the top layer of stock. This puddling action brings water and fines to the surface and develops a superior surface finish.

Most S1S hardboard siding machines and some S2S hardboard machines are equipped with a secondary headbox, which applies a surface layer of fine pulp on top of the main sheet. The overlay is generally a much slower stock, applied to upgrade the surface quality of an otherwise fast and relatively coarse stock. Secondary headboxes apply up to 10 percent overlay based on the weight of the substrate. The drainage time of the overlay may be twice as long as that of the substrate. For instance, an 18- to 20-second stock (TAPPI Standard SFMC) may receive an overlay of 50-second stock. If the overlay stock is too slow, not enough water can be removed from it before it reaches the wet press, where it may be “crushed”.[2]

Secondary headboxes are located past the wet line. The overlay stock flows over a dragging apron onto the substrate. Normally, insulation board is not overlaid.

Fourdriniers for S1S hardboard compared to those for insulation board and S2S hardboard.—An S1S hardboard or medium-density board forming line is normally coupled directly to the hot press, i.e., a forming line feeds one hot press; press cycle and forming speed are synchronized for continuous operation. The width of the hot press and former is either 4 or 5 feet. Wider presses require very substantial strengthing to resist bending stresses and would be less cost efficient.

In the manufacture of insulation board and S2S wet formed hardboard, the forming line is coupled to a dryer rather than to a press. Drying a 12-foot-wide mat is much more efficient than drying three 4-foot-wide mats, and increased panel width does not call for extraordinary design measures. Widths of insulation board and S2S hardboard forming machines are therefore equal to a multiple of one standard panel module: 8, 12, or 15 feet. The dried mat, much more easily handled than the wet mat, is cut to a standard width before fabrication or pressing.

Wet press.—A **wet press** further reduces water content of a mat after extraction by vacuum and gravity in the uncompressed mat has reached a practical limit. This limit is about 80 percent water content (20 percent dry fiber) for Fourdrinier forming machines and somewhat less water content for cylinder forming machines. Most wet presses are continuous roller presses—independent units in the case of cylinder forming, and an integral part of Fourdrinier forming machines (fig. 23-32). The discontinuous Chapman process described earlier in this section uses a cold platen press as wet press. The following discussion pertains to the wet press as it is found on Fourdrinier machines; those for cylinder forming are similar but simpler because cylinder-formed mats reach the wet-press at lower water content.

S1S hardboard differs from insulation board or S2S hardboard in requiring less complete dewatering in the wet press. In both cases the final product is practically dry, i.e., all of the water must be removed, and some of the water is removed at low cost in the wet press (fig. 23-35). Water remaining in the insulation board and S2S mats must be converted into steam in the dryer at very high energy cost. The cost of manufacturing insulation board and S2S hardboard is, therefore, very sensitive to the moisture content of the mat at the dryer. At $2.50/million Btu’s, and 65 percent dryer efficiency, a reduction of **tipple** moisture of 3 percent in a 350-ton/day machine would save annually more than $165,000.

In the manufacture of S1S, a very high pressure applied at the beginning of hot pressing squeezes out most liquid water before heat from the platens converts it to steam. As in the wet press, this uses little energy and the little water remaining is essentially independent of the water content of the mat leaving the wet press.

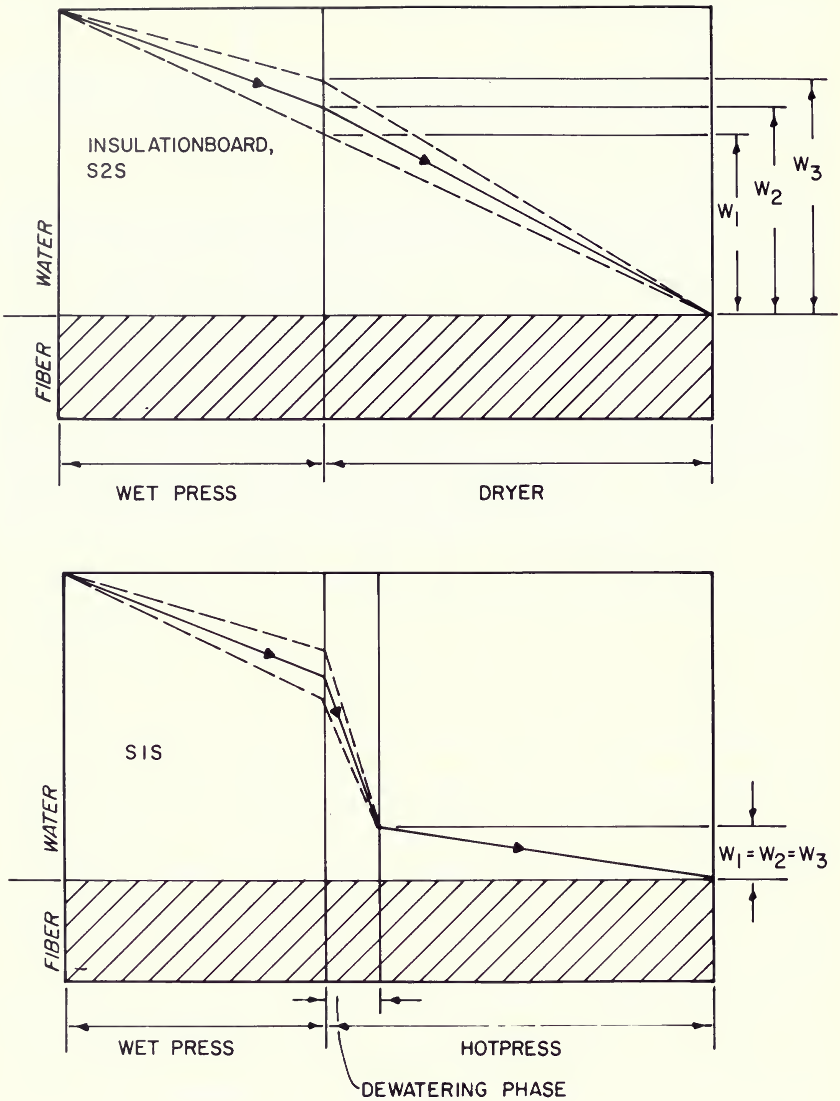


Figure 23-35.—In manufacture of insulation board and S2S hardboard, dryer costs are greatly affected by efficiency of the wet press (top). In S1S manufacture, however, dewatering during hot pressing is little affected by efficiency of the wet press (bottom). (Drawing from Suchsland and Woodson 1985.)

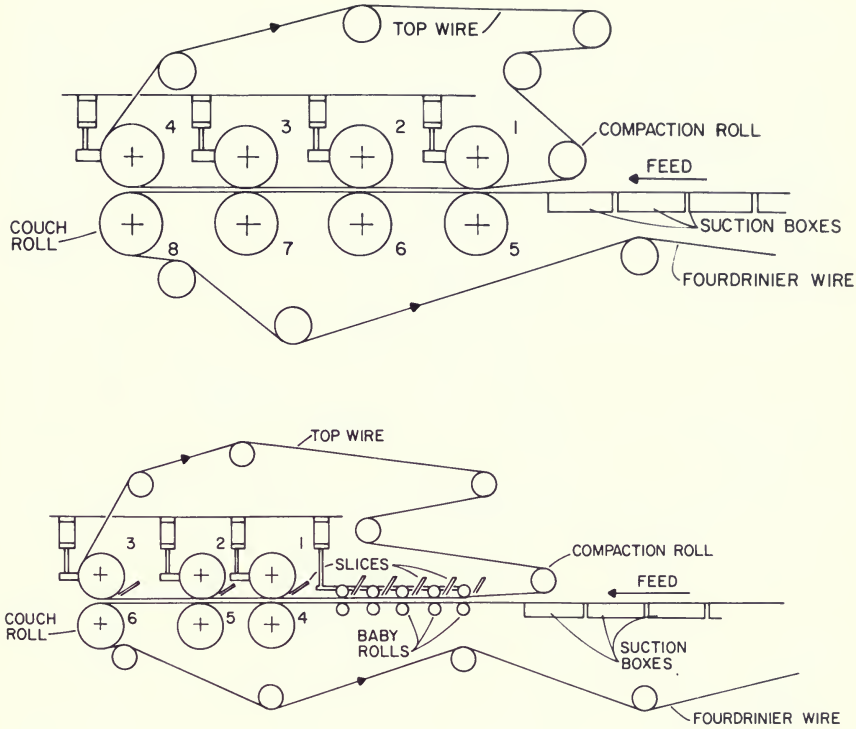


Figure 23-36.—Wet-press sections of Fourdrinier machines. (Top) Insulation board machine. All rolls are 30 inches in diameter; rolls 1, 2, 3, and 4 are suction rolls; rolls 5, 6, and 7 are perforated shell rolls; roll 8 is rubber covered with no perforations. (Bottom) Hardboard machine. Rolls 1, 2, 3, and 6 are 24 inches in diameter, rubber covered, and not perforated; rolls 4 and 5 are also 24 inches in diameter, but are perforated. (Drawings from Suchsland and Woodson 1985.)

Figure 23-36 diagrams wet-press sections of insulation board and hardboard machines. The numbered rolls are the press rolls, the main elements in such wet presses. Between each pair of press rolls starting from the infeed end, the gap between the Fourdrinier wire and the top wire is reduced by forcing the top rolls down against adjustable stops by means of hydraulic cylinders. This reduces the air volume in the mat until the mat is saturated with water at a density of 62.5 pounds/cu ft. At this point hydraulic pressure inside of the mat builds and forces water to flow from the mat. The water flow can be approximated by the following equation:

$$\text{Water removal} = \frac{\text{Press loading x temperature}}{\text{Feed rate x weight per 1,000 sq ft of dry sheet}} \text{ x K} \qquad (23\text{-}1)$$

K is a constant reflecting permeability of the pulp. Total press loading (nip pressure) is the sum of internal hydraulic pressure and resistive pressure of the mat (fig. 23-37 top). According to equation 23-1, water flow could be increased

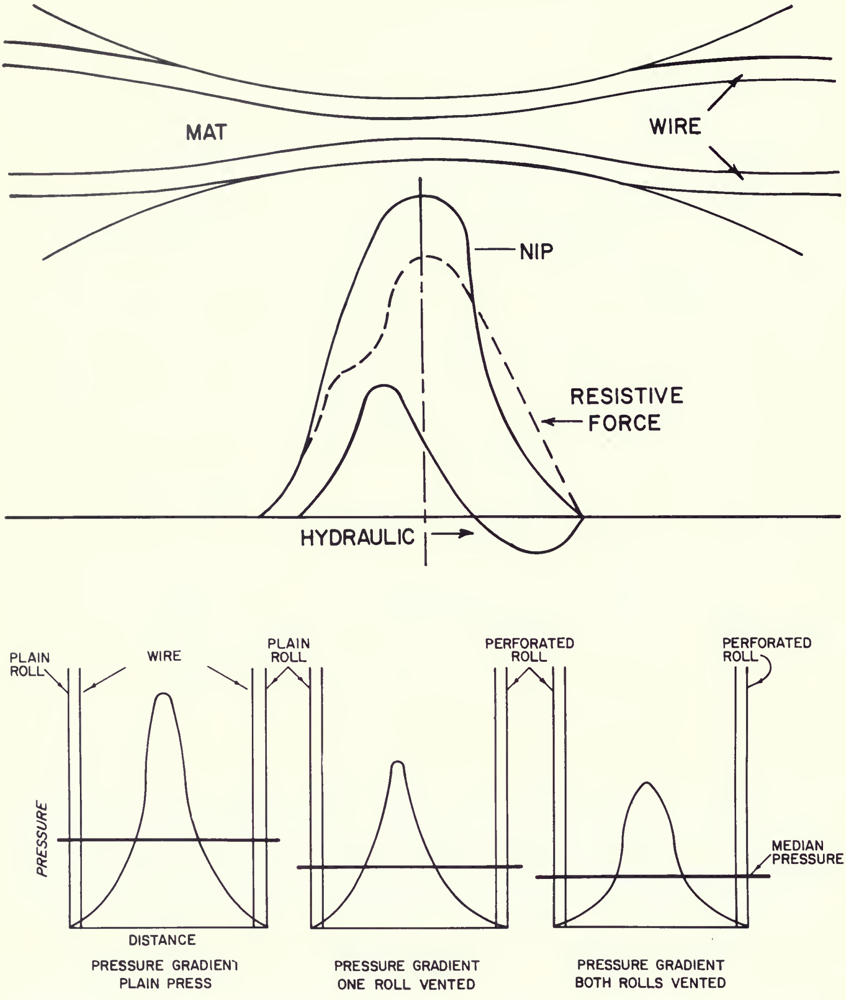


Figure 23-37.—Internal mat pressure in wet-press nip rolls. (Top) Components. (Bottom) Mat pressure distribution between press rolls of various designs. (Drawings after Strauss 1970.)

by increasing the press loading. However, excessive nip pressures will cause the hydraulic pressure to exceed the resistive pressure of the mat, at which point fibers will be dislocated and the mat structure destroyed. This condition is known as **crush** and is evidenced by the appearance of wrinkles in the sheet. Modern machines are run "crush limited", i.e., pressure is increased until crush occurs and then the rolls are backed off. Even then, fiber dislocation can occur in the center of the sheet, because there the hydraulic pressure is higher than in the outside layers (fig. 23-37 bottom).

Edge Wallboard Machinery Company (n.d.) found that perforated rolls or suction rolls reduce the pressure gradient, allow higher press loading, and produce stronger boards. Higher stock temperatures, because of their effect on water viscosity and thus on stock drainage, increase the water flow according to equation 23-1. However, depending on stock consistency, some or all of the energy saved in the dryer must be expended to heat the stock going into the headbox. Thus, higher consistencies favor net energy savings. All these considerations are much more important in the manufacture of insulation board and S2S hardboard than in S1S manufacture. The wet press illustrated in figure 23-36 (top) uses four suction rolls on top and three perforated rolls on the bottom. The fourth bottom roll is the main wire drive roll and is rubber covered to increase traction. Perforated bottom rolls have proven as effective as suction rolls, yet do not require the maintenance and the vacuum and separation system demanded by suction rolls. Insulation board may be dewatered to 45 to 65 percent water content in such a wet press.

The insulation board wet press not only dewaters but also presses the mat to a thickness equal to the final board thickness plus an allowance for shrinkage in the tunnel dryer. Deflection of press rolls sometimes causes difficulties in thickness and moisture content control, moisture content along mat edges being lower than in the center. Increasing stiffness of the rolls by using stainless steel shells, or by use of crowned rolls are two measures to combat roll deflection. Crowned rolls, however, can cause distortion of the wire from small peripheral speed differences.

In the hardboard machine (fig. 23-36 bottom) solid rolls are used instead of the expensive suction rolls. The squeezed-out water is removed from the nip by **suction slices,** which are vacuum devices with narrow slots extending across the width of the machine and located as close to the nip as possible. Initial compaction is accomplished by a series of so-called "baby rolls", also equipped with slices. Dewatering is not as efficient as in the insulation board machines, output water content ranging from 65 to 75 percent.

Modern board machines are driven by sophisticated DC or variable-frequency AC drive systems, with individual motors for each press roll and various auxiliary drive points. They run at speeds of 20 to 100 feet/minute, 60 feet/minute being average. Both hardboard and insulation board machines are about 60 feet long including the forming section (27 to 30 feet) and wet press. S1S machines are generally 5 feet wide; insulation board and S2S machines are 165 inches wide (nominal width, 12 feet).

Trimming of wet fiber mat.—All forming machines with the exception of the Chapman former produce a continuous mat, which has to be subdivided into individual sheets that conform to press size or multiple final board sizes.

End trimming is accomplished by rotating steel disks while the mat is traveling on roller conveyors (fig. 23-38). Simultaneously mat edges are trimmed by steel disks or water jets. The trim waste from the edges as well as entire defective mats can be detoured and returned to the process via a repulper in which the waste is broken down and diluted.

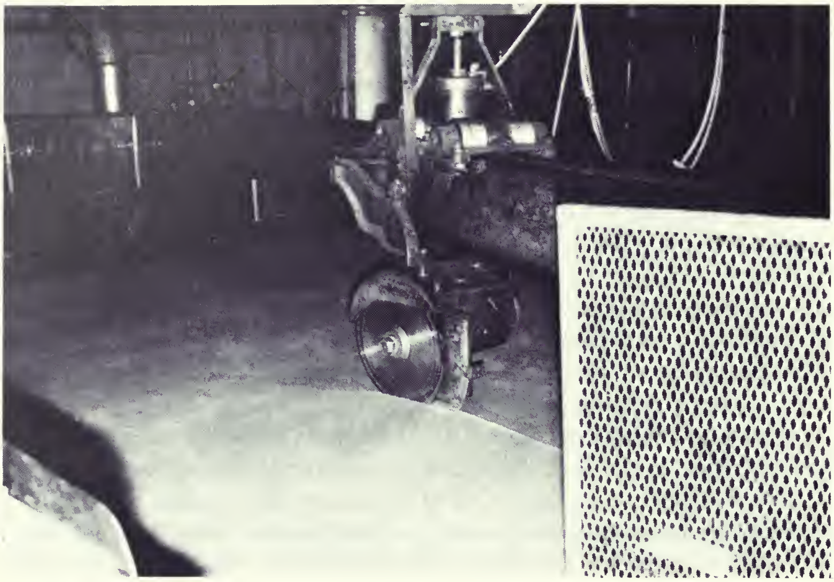


Figure 23-38.—Disk trimmer cutting traveling mat to length after its emergence from a wet press. (Photo from Suchsland and Woodson 1985.)

DRYING MATS FOR INSULATION AND S2S BOARDS

Insulation-board plants have mat dryers but no hot press. S2S wet-process fiberboard plants have dryers followed by a hot press. In both types of plant the dryer must reduce water content of the mat from about 70 percent of wet mat weight to almost ovendry, i.e., about 2 tons of water must be evaporated per ton of dry board. The technological benefit of this costly effort is the development of hydrogen bonding in the case of insulation board and the possibility of making high-density S2S hardboard without screens.

Fiberboard dryers are continuous machines. While it is possible to couple a single-deck dryer directly to the wet press of a Fourdrinier forming machine, space required for such an arrangement is excessive. Modern dryers are typically enclosed multi-tiered roller-conveyor decks, perhaps 525 feet long if forming-line speed is 35 feet/minute and drying time is 2 hours (fig. 23-39).

Dryer construction.—Drying of fiberboard can be accelerated without scorching the board if temperatures in initial zones of the dryer are very hot and those of succeeding sections progressively cooler. Figure 23-40 shows theoretical air temperatures which afford most rapid drying without harming the board, and actual temperatures commonly achieved. Dryer temperature increases to about 825°F in the first zone, gradually decreasing in following zones to about 225°F; zones 2, 3, and 4 circulate air across the dryer, but air in zone 1 flows counter to board flow to minimize heat leakage through the dryer entrance. After

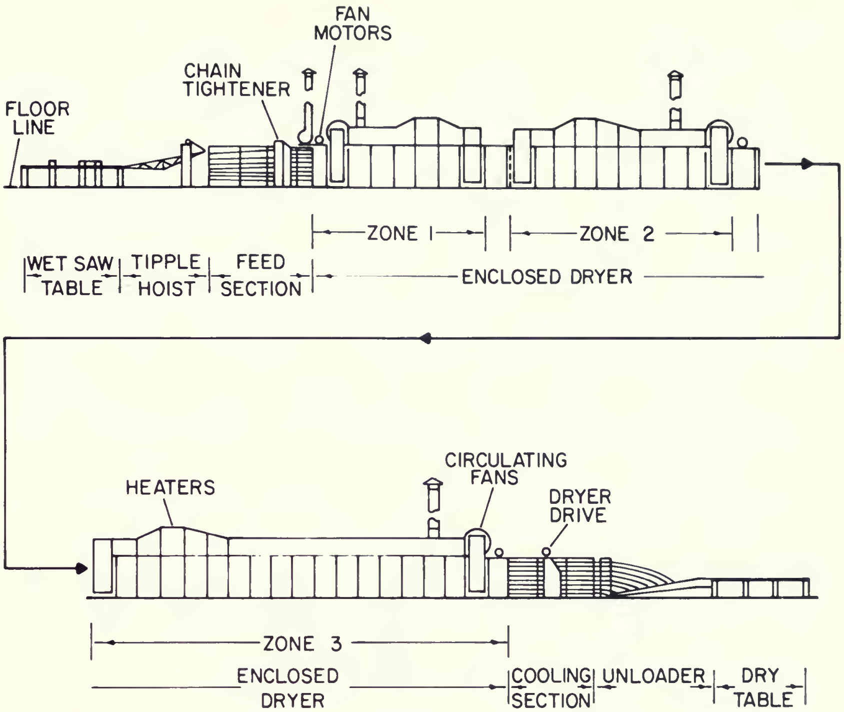


Figure 23-39.—Gas-fired fiberboard dryer. (Drawing after Lyall 1969.)

leaving the last zone the board passes through a cooling section. Dryer entrance and exit are protected from leakage by seal sections in which unheated air is circulated and a negative air pressure maintained equal to the slightly negative dryer pressure.

Heating and circulation.—The drying medium, air at temperatures above the boiling point of water, can be heated by gas, oil, or steam, but is typically gas heated. Gas- and oil-heated dryers operate at higher air temperatures, and cost less to install, than steam-heated dryers. Maintenance costs and fire hazard for dryers direct-fired with gas and oil may be higher than for steam dryers, however. Typically, gas burners capable of delivering 26 million Btu/hour are installed in each zone, requiring about 4,000 cu ft of combustion air per minute. Heated air and spent combustion gases are circulated in each zone by two fans located above the dryer, driven on a common shaft by a 125-hp motor capable of circulating about 165,000 cu ft of air per minute (Lyall 1969).

Feeding and transporting.—The drying mats are transported by closely spaced chain driven-rollers on eight separate decks. The speed of the rollers is adjustable and is matched to the line speed so that there are no unnecessary gaps between boards. Standard roller diameter is 3 inches with a roller spacing of 4 inches at the wet end and up to 2 feet at the dry end. A 250-foot, eight-deck dryer contains approximately 8,100 rolls and 16,200 bearings. In order to keep all eight decks completely loaded with a continuous supply of cut-to-length mats, a

tipple is provided at the infeed. This belt conveyor is hinged at one end of the line conveyor level while the other end can be raised or lowered to match up with any of the eight dryer decks, each of which is provided with speed-up sections at the infeed end so mats being delivered by the tipple can quickly catch up to those loaded in the previous sequence. Tipple speed matches line speed (about 40 feet/minute); therefore dryer speed is ⅛th this value or about 5 feet/minute.

Dryer performance.—Three phases of drying can be distinguished. In the first phase water evaporates from the wet surface of the mat and is resupplied by capillary action from the interior. Under constant conditions drying during this phase proceeds at a high but constant rate. The second phase begins when the surface of the mat starts to dry because water from the interior does not rise to the surface as fast as it is being removed. The temperature of the mat rises during this second phase and the rate of drying decreases. In the third stage, during which drying further slows, water from the interior moves to the surface as water vapor, by diffusion.

Drying must be controlled to prevent too-rapid initial surface drying, which would create an insulating barrier, severely retarding moisture removal from interior board portions during later drying phases. Excessively high surface temperatures must also be avoided to prevent discoloration of surfaces and to reduce fire hazard. Heat energy required per hour is a function of entering and leaving mat moisture content and temperature, and hourly production of dry fiber. Typically roller dryers are 50 to 75 percent efficient.

Safety.—Danger of explosion and fire is inherent in high temperature drying of combustible material, particularly when the recirculating drying air is in direct contact with open flames. Protective devices such as automatic burner shut-off and water deluge systems triggered by sensors responding to sudden temperature rises within the dryer, are mandatory.

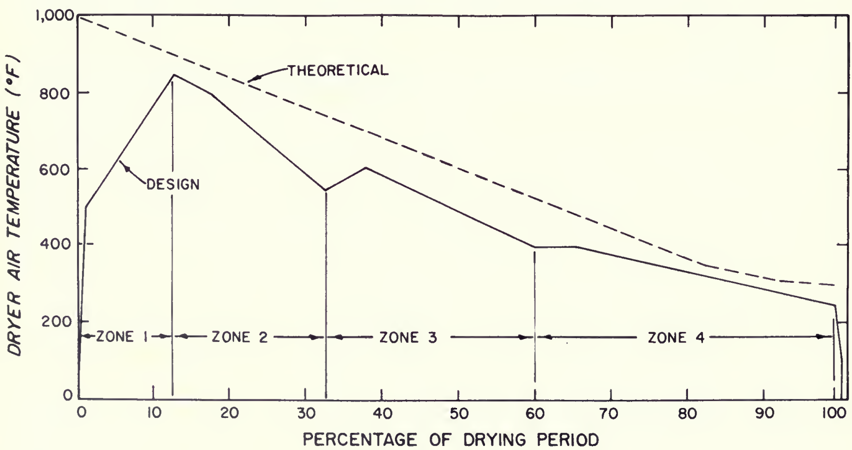


Figure 23-40.—Theoretically ideal and actual temperature distribution for entry zone 1 to discharge zone 4 in a four-zone fiberboard dryer. (Drawing after McMahon n.d.)

Fires in board dryers are almost always caused by overdrying, which lets board temperatures rise to danger levels. Overdrying also causes thermal breakdown of wood substance and formation of pyrophoric carbon at board surfaces. This carbon is very reactive, oxidizes exothermically, and can cause fire or charring in stacks of overdried insulation board.

HOT PRESSES, TYPES AND CONSTRUCTION

Because of the large forces involved, the difficult problems associated with the rapid transfer to the mat of large quantities of heat, and because of the need to precisely adjust and modify press cycles, continuous hot presses are not practical.

The hot press is thus a batch operation in an otherwise continuous process. Since pressing time is generally constant for a given board type and thickness, the press capacity and the capacity of the entire production line is a function of platen size and number of press openings. The multi-opening press used universally in the fiberboard industry has the advantage, that, by virtue of the series combination of mats and press platens, any number of boards can be compressed with the same total force (fig. 23-41). The important relationship between forming line speed, press time, and press size is illustrated in figure 23-42. An 18-foot-long, 20-opening hot press, for example, with a total press time including loading and unloading, of 6 minutes, could accommodate a forming line speed of 60 feet/minute. If this same line were used for the manufacture of a thicker board, requiring a press time of 8 minutes, the line speed would have to be reduced to 45 feet/minute. Given data on width of forming line, number of press openings, platen dimensions, and press time, the line capacity in square feet per minute can be readily determined.

Almost every part of a press is subjected to very large forces, which are generated by the action of hydraulic rams compressing the boards between platens. Given a specific pressure on a fiberboard mat of 1,000 psi, for example, the total force on a 5- by 18-foot press platen is almost 13 million pounds. This total force is resisted by the structural members of the press, causing stresses and bending moments. No reaction forces other than the press weight are transmitted to the foundation (fig. 23-43).

Frame members of the press may consist of press crown and base bolted together on each side by a series of cylindrical columns to form a **column press** (fig. 23-41). In a **frame press** the structural members consist of solid steel frames, each cut from a single piece of steel plate; crown and base are mounted inside of the frames. Both types are found in the fiberboard industry. Newer presses seem to favor the frame design.

Platens provide the plane, smooth surfaces against which the fiberboard surfaces are pressed and molded, and they are carrier of the heating medium, either saturated steam or hot water. A system of interior channels provides passage and distribution within the platens of sufficient heating medium to assure quick and uniform heating of the mat over its entire area. Most fiberboard presses in the United States are heated by saturated steam. The European industry has turned to hot water systems. Greater uniformity, lower accumulator

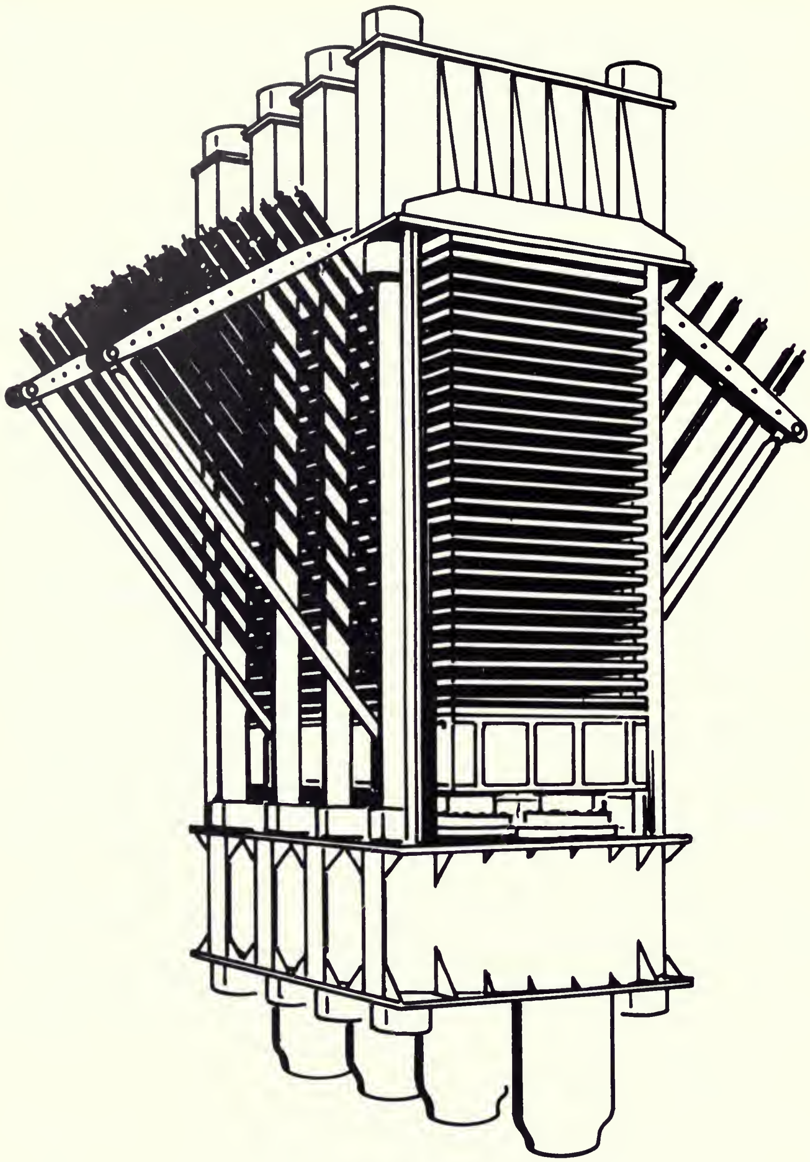


Figure 23-41.—Column-type board press with four rams, equipped for simultaneous closing of the 24 openings. (Drawing after Morse 1967.)

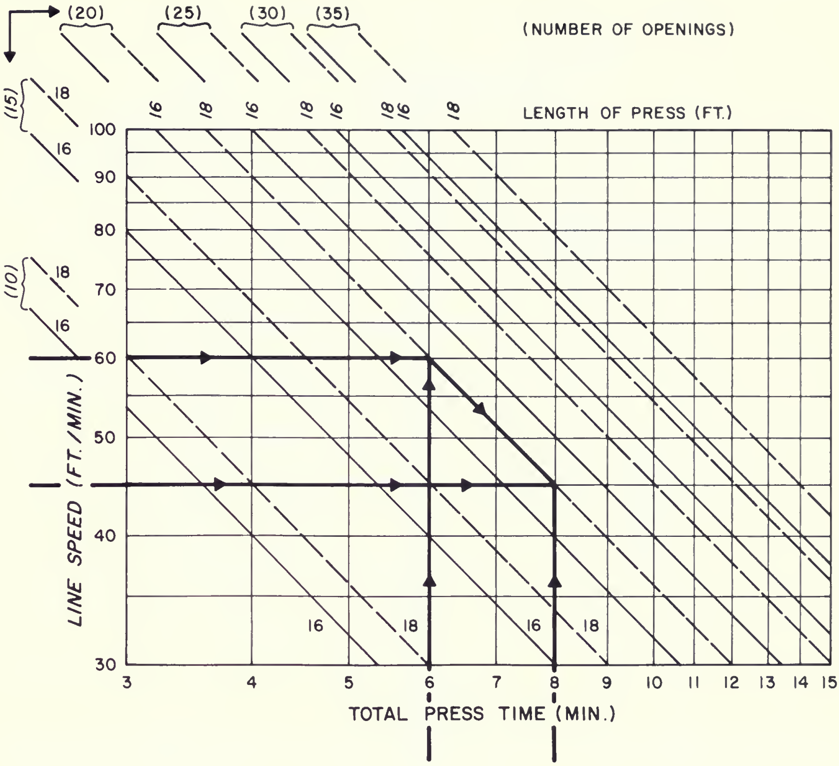


Figure 23-42.—Relationship between line speed, press time, press length, and number of openings. See text for explanation of examples indicated. (Drawing from Suchsland and Woodson 1985.)

pressure, less heating medium leakage, and possibly pH control are cited as advantages of the high pressure hot water system. On the other hand, hot water requires forced circulation; and in most mills steam is already available because it is required for the operation of digesters, pressurized refiners, and dryers.

Press temperatures vary, but average about 400°F. One cycle of a 4- by 8-foot, 20-opening press may expend up to 1.5 million Btu, so both steam- and water-heated presses use accumulators to provide such capacity. Since the water accumulators operate at constant pressure, boiler pressure is less than for steam systems, where accumulators operate between 25 and 20 atmospheres. Press platens are about 2½ inches thick with heating channels 1⅛ inches in diameter. Platens must be plane and their surfaces parallel within tolerances of 0.005 inch.

Pressure is applied to the press platens by a series of cylinders and rams, so dimensioned that they will be able to provide the required specific pressure on the fiberboard mat with a reasonable hydraulic working pressure. Larger and fewer cylinders are the trend, because they reduce maintenance costs. Hydraulic working pressures are between 3,000 and 5,000 psi. To provide a specific pressure of 1,000 psi requires a ratio of platen area to total ram area of from 3 to 1 to 5 to 1.

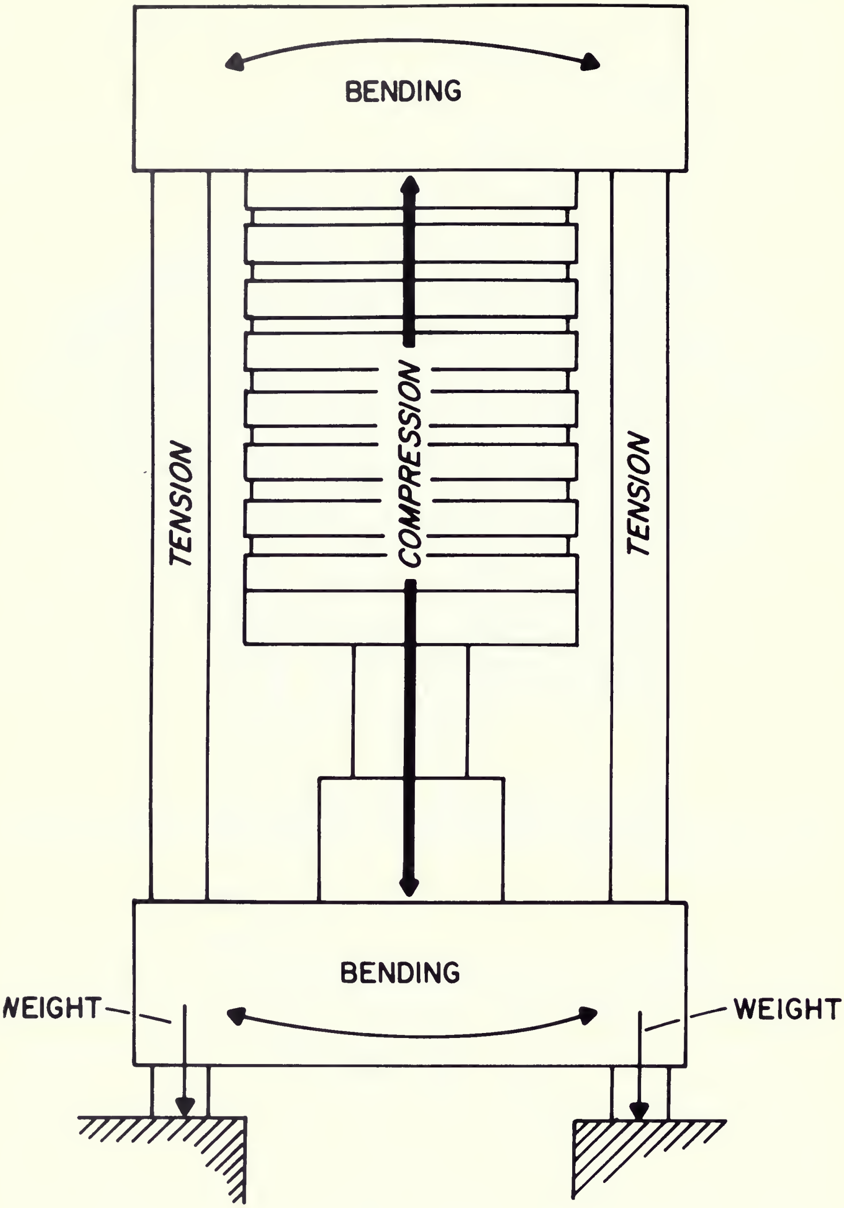


Figure 23-43.—Forces and bending moments in a board press. (Drawing from Suchsland and Woodson 1985.)

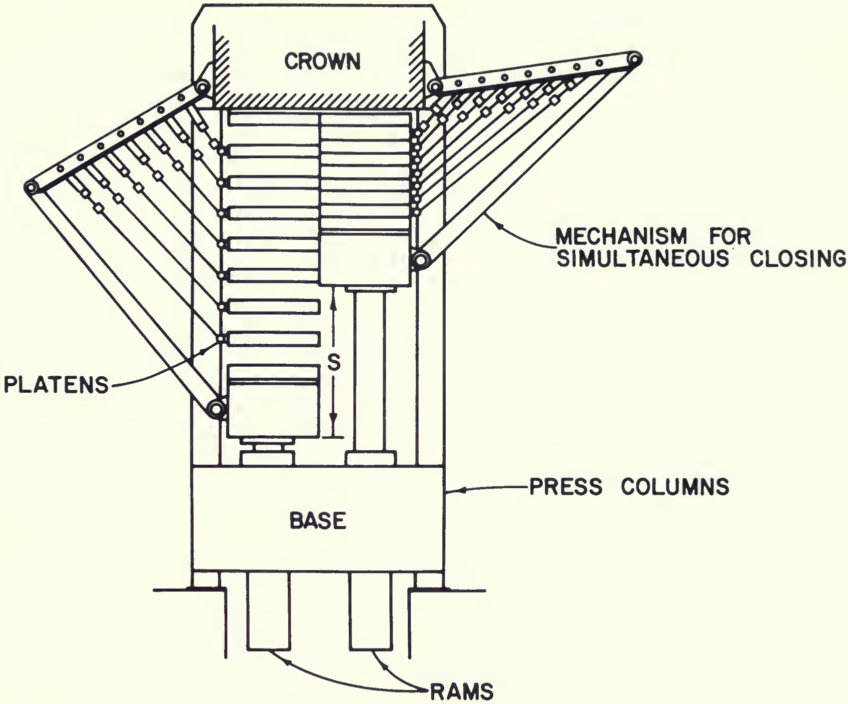


Figure 23-44.—Eight-opening press with simultaneous closing arrangement. (Drawing after van Hullen 1966.)

The hydraulic medium in fiberboard presses is generally water, to which lubricants and other additives have been introduced. Pure oil reduces wear and is less costly to pump, but can easily be contaminated by water squeezed from wet mats during initial phases of press cycles. For this reason water is preferred.

Demand for fast closing and pressure build-up makes it necessary to provide hydraulic fluid at very high flow rates which may exceed pump capacity. Either jack rams or low pressure accumulators are used to overcome this difficulty. **Jack rams** have small diameter and can close the press quickly with a small quantity of hydraulic fluid. The larger main cylinders are filled by gravity without pumping. An **accumulator** is a low pressure storage device, which can deliver large quantities of hydraulic fluid in a very short time. During periods of low fluid demand (after press has closed) the pumps recharge the accumulator against a cushion of air or nitrogen.

It is advantageous to close all openings simultaneously rather than successively as the rising rams push the platens upwards. Simultaneous closing provides more uniform heat transfer on both surfaces of each board and assures that the boards in all openings are subjected to identical pressing and heating conditions. However, the closing speed of the individual openings is then only a fraction of the ram speed. Simultaneous closing therefore requires high ram speeds. Figure 23-44 illustrates the principle; as the press table moves upward at speed V_r, the tie rods lift all platens simultaneously at speed $V_o = V_r$ /number of platens.

PRESSING S2S HARDBOARD

The original patent for S2S hardboard (Mason 1938) reads in the first claim, as follows:

> "The process of making a hardboard product having high dry and wet strength from a light porous sheet of lignocellulose fiber containing the natural fiber incrustations including the steps of drying the sheet to a bone-dry condition, and then applying pressure to the bone-dry sheet at a temperature of about 400 to 500°F sufficient to materially consolidate and densify and impart high dry strength and high wet strength to the sheet by activation of the bonding properties of the incrusting substances."

This claim presents the critical requirements for the successful manufacture of wet formed S2S hardboard, i.e., drying the mat to bone-dry condition and then applying press temperatures in excess of 400°F. The low moisture content (zero percent) is necessary to allow short press cycles without the danger of entrapping steam in the board. The high temperatures are required to soften the lignin and to generate small amounts of water—apparently necessary in the bonding process—via destructive distillation of the wood fibers.

Mat handling.—One of the important characteristics of the S2S process is its extremely short press cycle. It is possible to press 30 press loads/hour. In the case of a 4- by 16-foot, 20-opening press, such speed requires 600 mats/hour or 10 mats/minute, and effective press line speed of 160 feet/minute. Considering that mats must be spaced, accelerated, and decelerated, maximum mat speeds can easily reach 300 feet/minute.

The S2S mat coming out of the dryer is a rigid but low density product and does not tolerate rough handling. Any fractures or other injuries of the S2S mat will result in unsatisfactory S2S hardboard. The speed at which mats can be handled without damage probably defines the upper limit of productivity in S2S hardboard plants.[2]

Mats for S2S hardboard are generally 12 feet wide and 16 feet long as they come from the dryer, with allowance for edge trim and kerf from saws cutting mats to hot-press size. Efficiency of the line could be increased somewhat by cutting double-length mats (32 feet) on the forming machine, which would reduce spacing losses in the dryer and trim allowances. It would, however, require longer speed-up sections in the dryer and larger size double trimmers.[2] Since it is very difficult to exactly synchronize forming machine and hot press, and an S2S press generally can handle ¼-inch board faster than it can be formed, but not ⅛-inch board, intermediate storage is provided, following the double trimmer. Most systems also are designed to permit mat removal between dryer and trimmer to allow for sawblade changes and other down times.

Pre-drying.—Prior to entering the hot press, the trimmed S2S mats at 1- to 5-percent moisture content pass on edge through a short, **picket-type** pre-dryer where moisture content is reduced to practically zero, and mat temperature elevated to as close to 300°F as possible. The low mat moisture content and high temperature allow fast application of full hot-press pressure without breathing phases in the press cycle, thereby shortening pressure time. However, if press times are increased to accommodate breathing cycles for steam escape, S2S boards can be made without pre-drying the mats.

Press loading.—S2S mats, rigid enough to be handled without supports, are charged into the press loader, where they are supported along the edges only. As the press opens, a hydraulically operated charging ram pushes the mats into the press simultaneously by means of a series of lugs, which engage the end of the mats, accelerate them, push them into the press opening, slow them down, and retract, leaving the mat exactly positioned on the press platen. Edges of all mats in the press must be in exactly the same position relative to the edge of press platens to assure maximum control of thickness tolerances.

As the mats enter the press openings, they encounter and push forward the pressed boards into pinch rolls, which remove them into the unloading cage. These boards are emitting gas and thus are not actually resting on the platens, but are supported by a layer of gas, which practically eliminates the friction between board and platen surfaces, allowing boards to slide out of position at the slightest touch. If the press is not leveled properly, the force of gravity may dislocate the boards. Positioning devices are often used to align the pressed boards just before discharge and the mats on the platens before press closure.

S2S presses may or may not use caul plates. When plates are used wear of the press platens is reduced but the **press daylight,** i.e., the maximum clearance between platens when the press is fully opened, must be increased because the cauls don't stay flat. The upper caul will have considerable center deflection and both cauls will show distortions due to thermal stresses.

When embossed boards are made, the embossing plate—made of mild steel—is the top caul. For embossed board, proper alignment of the mat in the press is particularly important, because the final trimming must match witness marks left by the embossed plate. Removal and replacement of caul plates is made easier by quick release fasteners.

Press cycle.—Press cycles vary depending on species, board thickness, board density and press temperature. Hardwoods require less press time than softwoods. Thin boards, low board densities, and high press temperatures also favor short press cycles.

Figure 23-45 shows S2S press cycles for ⅛-inch and ¼-inch boards made from hardwood fibers at press temperatures of 450°F. In both cases the pressure is built up as fast as the press will allow, held for the required time—60 seconds for the ⅛-inch board and 75 seconds for the ¼-inch board—then released as fast as the escaping gas will allow without causing blisters. Kept under pressure too long, excessive gas may develop from destructive distillation and blow the board out of the press. As closed white water systems retain more dissolved solids in the board, these difficulties increase because the pollutants are volatilized in the hot press and discharged into the air.

These dissolved solids (hemicelluloses) also increase the danger of boards sticking or clinging to the top caul or the top press platen. The boards don't adhere strongly, but require release by compressed air. Release agents applied to the board before pressing eliminate this problem.

Volatiles escaping from the press are vented outside. Substantial quantities, however, condense in the vent stacks as their temperature drops below 300°F, where they pose a fire hazard unless burned off periodically.

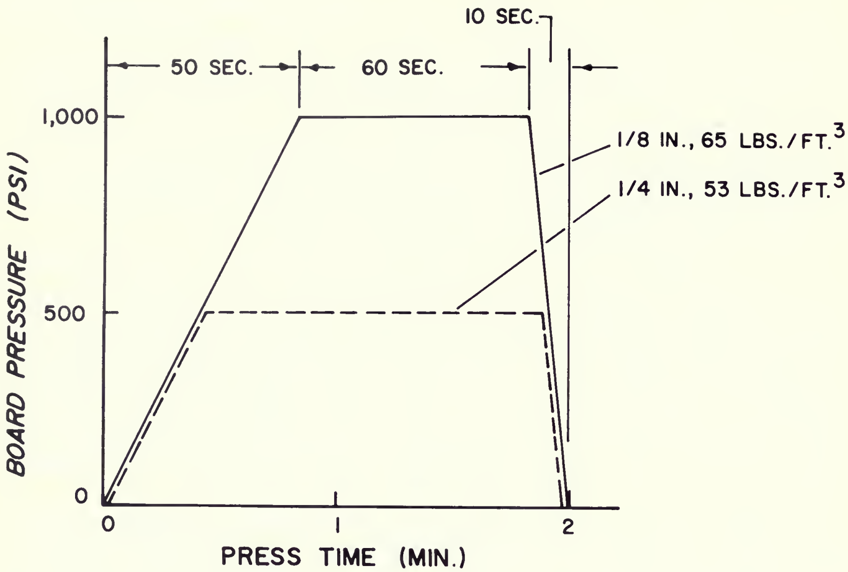


Figure 23-45.—Press cycles for ⅛- and ¼-inch-thick S2S hardboard from hardwood fibers; press temperature 450°F. (Drawing from Suchsland and Woodson 1985.)

Figure 23-46 shows two types of press cycles used when mats are not predried. The board is then either "toasted", i.e., dried under very low pressure and then densified during a second high pressure phase, or the water vapor is vented by "breathing" the press once or several times.

When S2S board leaves the press it is right at the threshold of combustion. If not immediately cooled, it will ignite spontaneously. It is cooled by rapidly moving air immediately after discharge from the press and before it is lowered to a conveyor line by the unloading elevator. The boards must be kept moving to prevent condensation of fumes from blemishing board surfaces. Such fumes will also condense on any steel members of the cooling racks that are allowed to cool below 300°F.

Thickness tolerances.—S2S hardboard is often used as a substrate for high quality finishes involving precision printers, which require close thickness tolerances. Thickness variations of the finished board can be caused by the mechanical limitations of the press and associated equipment, such as thickness variations in the caul plates. They can also be caused by a non-uniform distribution of furnish in the mat, or by non-uniform mat thickness, resulting from roll deflection in the forming machine and wet press. Such mats coming out of the dryer could be 1/16-inch thicker in the middle than at the edges. The trimmer would therefore produce one thick mat from the center and two wedge-shaped mats from the outside. These mats are not easily pressed to uniform board thickness, particularly when they are used for the manufacture of low density boards.

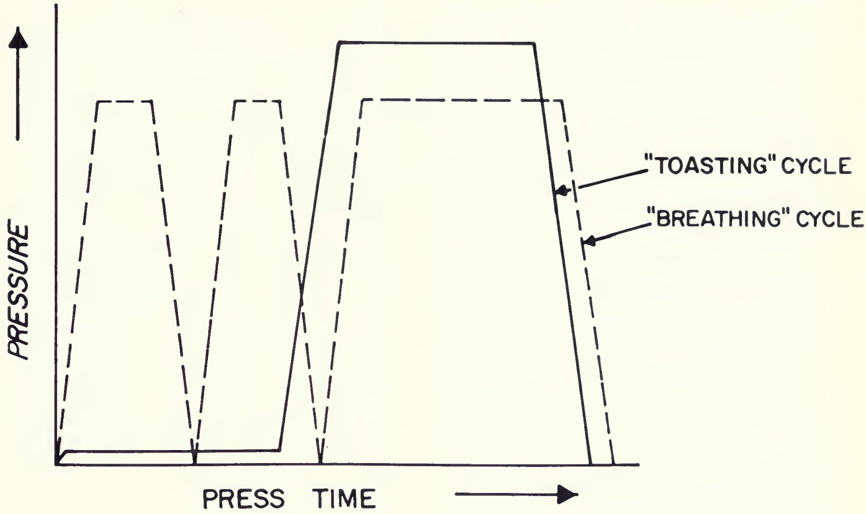


Figure 23-46.—Press cycles for S2S hardboard mats that have not been pre-dried. (Drawing from Suchsland and Woodson 1985.)

Some thickness variation develops in the finished board after the press opens. Some pressed boards expand (springback) as the pressure is released. Generally, the higher the press temperature, the less springback. Higher press temperature tends to plasticize fibers and relax internal stresses. Temperature variations within or between press platens can cause board thickness variations. The center of the board is generally thinner than the edges, and the top and bottom boards in a multi-opening press are often thinner because the heat losses are smaller at these locations.

Typical thickness variation in a ⅛-inch-thick, 4-foot-wide board pressed in a 20-opening press to a density of 65 pounds/cu ft could be 0.015 to 0.020 inch within boards and 0.025 to 0.030 inch between boards. Within-board variations can be greatly reduced by pressing 4-foot-wide boards in a 5-foot press.[2]

Another phenomenon in S2S hardboard associated with springback is so-called **chip pop,** a very localized thickness variation due to springback of a highly compressed sliver of wood or fiber bundle. In this state, the compression deformation is apparently not as plastic as it is in completely defiberized material, or is not sufficiently arrested by fiber bonds. The closer the "chip" is to the surface, the more severe the distortion. Slush overlays will obscure these chip pops to some extent. Chip pops are not as common in S1S boards, because the presence of water apparently contributes substantially to plasticizing wood under pressure.

Density distribution.—Surface layers of S2S hardboard are typically more dense than interior portions (fig. 23-47). The symmetry of this density accounts for the bending stiffness of S2S hardboard.

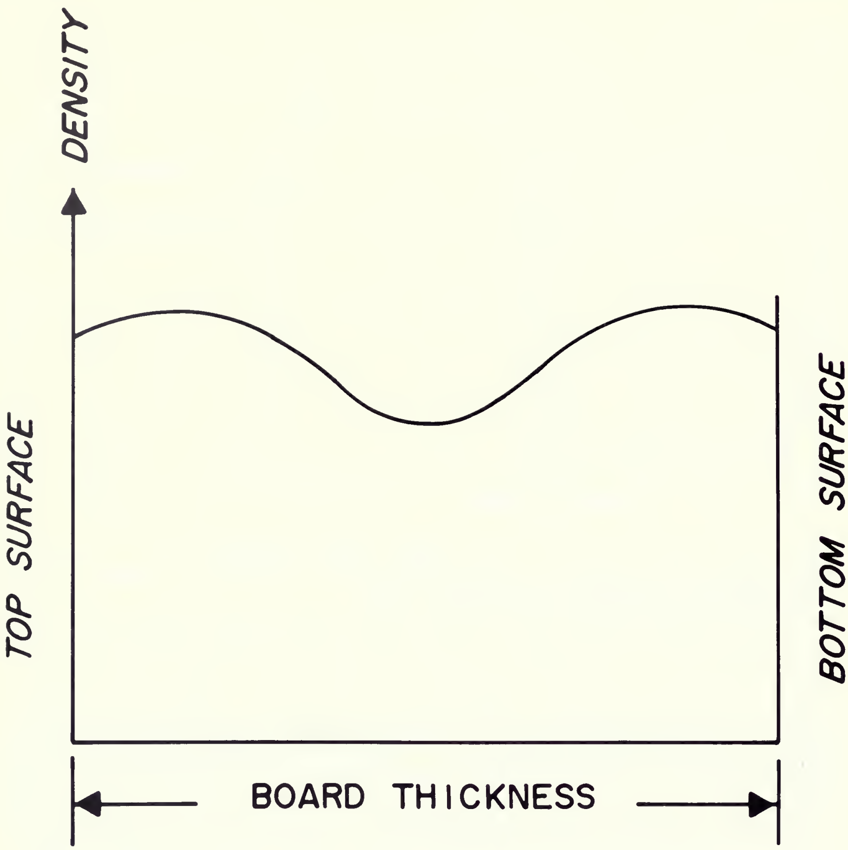


Figure 23-47.—Density profile of S2S hardboard. (Drawing after Spalt 1977.)

PRESSING S1S HARDBOARD

In the manufacture of S1S hardboad (fig. 23-48 top) mats move from wet-press on the forming line to hot press with no intermediate drying stage (fig. 23-28).

Press lines.—Since pressing is a batch process, provision must be made in the press line to match the continuous output of the wet press to the cyclic nature of hot press operation. Coupling of line to press can be accomplished simply by loading a number of mats into a series of movable press loaders which when full are removed to one of a number of available hot presses. Each press loader holds a number of mats equal to the number of openings per press. This is the procedure of the Masonite Corporation in their Laurel, Miss. plant.

Most other wet-process S1S hardboard plants have a direct coupling between wet press on the forming line and hot press. The system provided by Siempel-

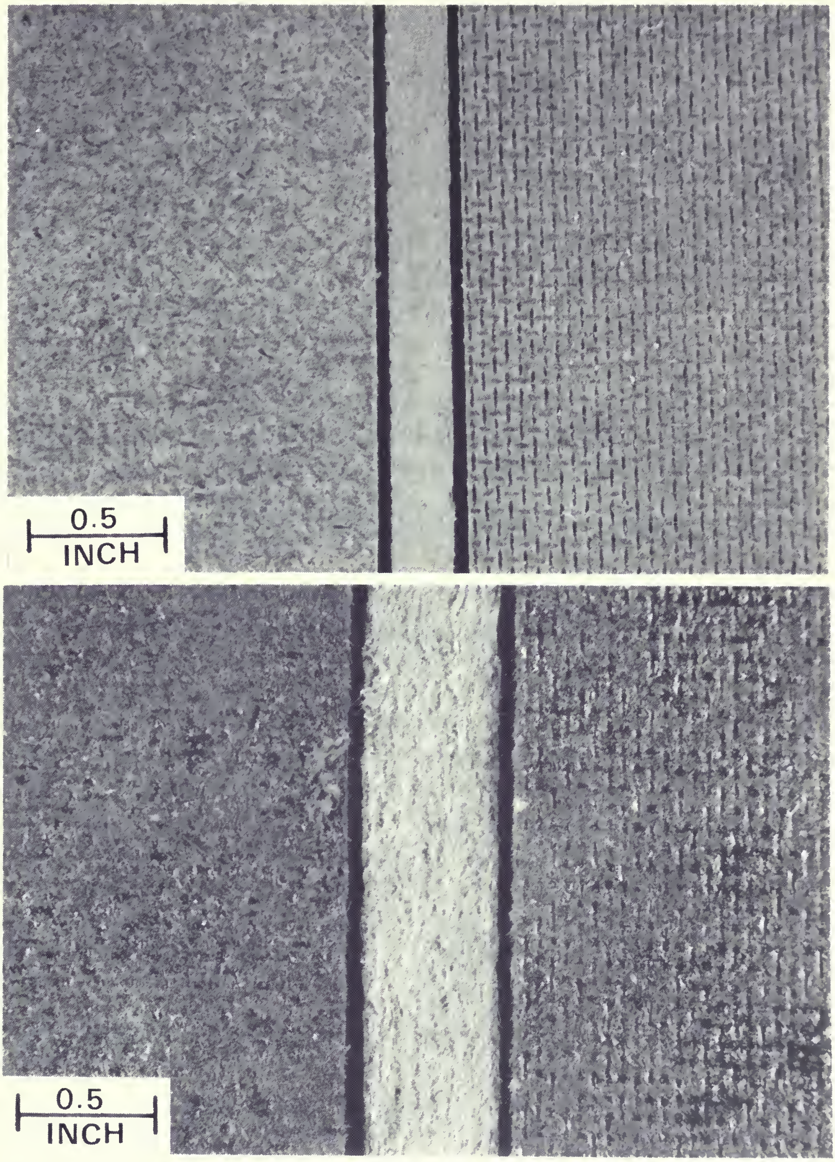


Figure 23-48.—Wet-formed fiberboards. (Top) Hardboard ¼-inch-thick, smooth on one side with a screened back. (Bottom) Insulation board ¾-inch thick.

kamp Corporation in a number of plants in the United States, can be used to illustrate typical procedures. The main features of this system are a simultaneously-closing, 24-opening, 4- by 16-foot press, and a vertical wire-screen orbit which returns the carrier screens under the press to the mat conveyor. Here, each mat, cut to press size, is placed on a wire screen, which in the hot press will allow water and steam to escape from the densified mat and which gives one side of the board the characteristic screened appearance (fig. 23-48 top). The screens are not continuous, but are sized to accommodate one mat which has been previously cut to hot press size. In the hot press the top board surface is made smooth by a smooth top platen, and the bottom board surface shows a screen pattern. See Suchsland and Woodson (1985) for a more complete illustrated description of this system.

Other press lines use steel cauls (rigid steel sheets) as screen and mat support. These cauls carry screen and mat, and the entire assembly proceeds through the press. Cauls and screens are returned on a horizontal conveyor system.

In time, carbon deposits appear on caul plates and wire screens, which if not removed (by cleaning in sodium hydroxide solution), will cause carbon particles to appear on board surfaces.

Press cycle.—Water content of mats entering the hot press is typically 65 to 75 percent, yielding a ratio of water to dry fiber of about 2 to 1. Press cycles are designed to remove the water from the mat at minimal cost, while developing optimal physical and mechanical properties in the board. While press cycles vary, most manufacturers of S1S hardboard approximate the pressure-time pattern shown in figure 23-49. The platen temperature is constant. Pressure-time functions clearly divide the press cycle into three phases:

1. High pressure squeeze phase.
2. Low pressure drying phase or dwell phase.
3. Consolidation phase.

The first phase is designed to remove as much water as possible from the mat as quickly as possible without transferring unnecessary heat to the water. The high pressure level, normally between 800 and 1,000 psi, is therefore established as rapidly as the hydraulic system of the press allows. Some lower density boards may be squeezed at pressures as low as 400 psi. Pressures in excess of 1,000 psi do not result in appreciable improvements.

On application of this pressure the water is forced downward through the mat and then escapes laterally through voids in the wire screen. The process is aided by reduced viscosity as water temperature rises.

The large temperature differential between mat and press platen and the great heat capacity of the wet mat cause large quantities of heat to be transferred from the platen to the mat, placing a heavy burden on the boiler. Steam demand of a 20-opening press may jump to 20,000 to 30,000 pounds/hour for a short time when the press is first closed. Steam accumulators are used to ease this burden.

Ideally, the first phase ends when all the squeezable water has been removed and the remaining water has reached a temperature of 212°F. Phase one takes about 1.5 minutes of which 40 to 45 seconds are required for the initial pressure

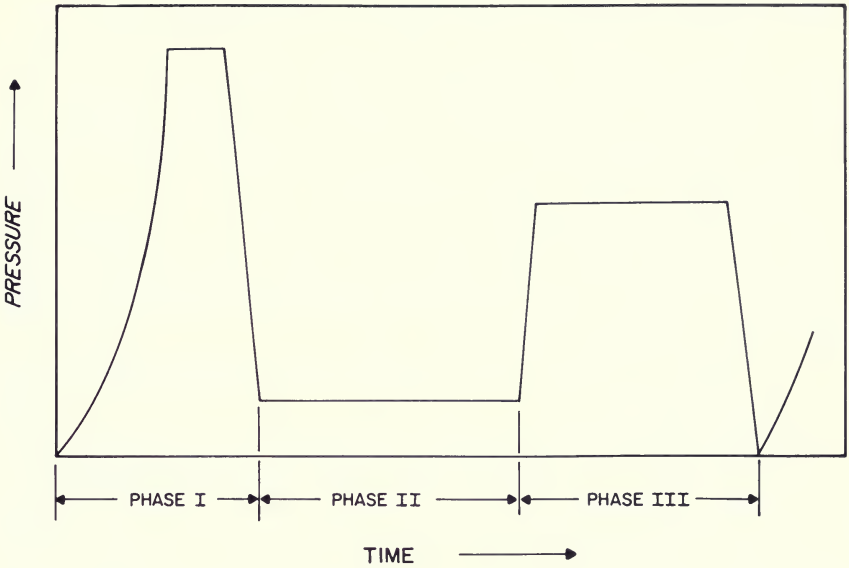


Figure 23-49.—Typical press cycle for wet-process S1S hardboard. (Drawing from Suchsland and Woodson 1985.)

build-up. About 50 percent of the water present in the wet mat is removed, bringing the ratio of water to fiber to about 1:1.

In the second (drying) phase, most of the remaining water is removed as steam. Practical pressure levels are between 80 to 100 psi, or about 1/10 of the initial high pressure. If pressures during this phase are too low, steep steam pressure gradients may structually damage the mat. The second phase ends in 3 or 4 minutes when steam ceases to exit visibly but before the board has dried to a moisture content of less than 8 percent.

In phase three, pressure is increased again (to 400 to 500 psi), densifying the board to desired thickness and developing fiber bonds. Plasticity of the mat, afforded by high mat temperature in combination with sufficient fiber moisture content, favors board consolidation. Compression deformation under these conditions is essentially permanent. If the third phase is initiated too late, i.e., when the moisture content has fallen below 8 percent, then compression of the mat is much more elastic and it swells to a much larger degree upon pressure release. If phase three is started too early, higher moisture contents cause staining of board surfaces.

Phase three, requiring 2 or 3 minutes, ends with opening of the press when the moisture content has been reduced to about 0.5 to 1.0 percent. Terminating the press cycle at higher moisture content risks incomplete fiber bonding, splits along the center plane of the board, and boards sticking to the top caul plates. Final moisture in excess of 3 percent may cause permanent distortions (sagging) during subsequent handling and transportation, and lead to misalignment of saw cuts relative to embossed plant scores.[2]

When pressing low density boards (less than 55 pounds/cu ft), phase three may be eliminated; phase two would simply be extended to assure adequate drying. At board densities of 60 pounds/cu ft and up, however, the consolidation phase is necessary for final thickness adjustment. The total press cycle as described above requires about 6 to 8 minutes for a ⅛-inch-thick hardboard. A 6-minute cycle would allow the pressing of eight press loads per hour, assuming 1½ minutes per cycle for loading and unloading.

Although figure 23-50 applies to dry formed hardboard, it clearly demonstrates the important effect of press temperature on press time and therefore on productivity. However, there are several practical limits to increasing the press temperature in fiberboard manufacture:

- Too rapid steam generation and subsequent blow-out danger, particularly in high density board.
- Beginning deterioration of wood at temperatures in excess of 420°F.
- Limited heat resistance of printing ink on overlay papers applied to the mat prior to hot pressing. This method is used by Abitibi Corp. and limits platen temperature to 380°F (fig. 23-51).

Pressing to stops.—Most fiberboards are pressed without stops. Final board thickness is determined by the total accumulative response of the mat to the press cycle. The pressure varies during the cycle according to the requirements of efficient water removal, while the compressibility of the mat varies with changing mat temperature and moisture content. A given press cycle will compress identical mats to identical final thickness. Uniform mats are therefore essential to small thickness tolerances.

Thickness control by gage bar or **pressing to stops** is used in the manufacture of some relatively thick, low density siding products. This method is also standard procedure in the manufacture of particleboard and medium-density fiberboard. Metal strips of a thickness equal to the final board thickness are inserted between press platens alongside the mat and limit the compression of the mat. The pressure on the mat is determinate only until the spacers are reached, when they carry part—and eventually most—of the total load (fig. 23-52).

In practice the press load is reduced constantly to the level required to just keep the press closed. In such an operation the boards may be removed when the mat pressure approaches zero, regardless of the moisture content; beyond this point, the press is simply used as a dryer. Final moisture reduction could be accomplished in heat treating ovens, if available. Gage bars are often replaced by electronic control devices.

Thickness tolerances.—Final board thickness is affected by **springback,** an instantaneous recovery upon pressure release of the preceeding compression deformation. Springback is greater along board edges than in the center, due to lower edge temperatures there from heat losses as water flows out of the mat. Prior injection of additional resin into board edges reduces this springback and shortens the press cycle (U.S. Patent No. 4,168,200).

Density profile.—Mat densification, in response to applied pressure, is affected by its temperature, moisture content, and other factors which vary with

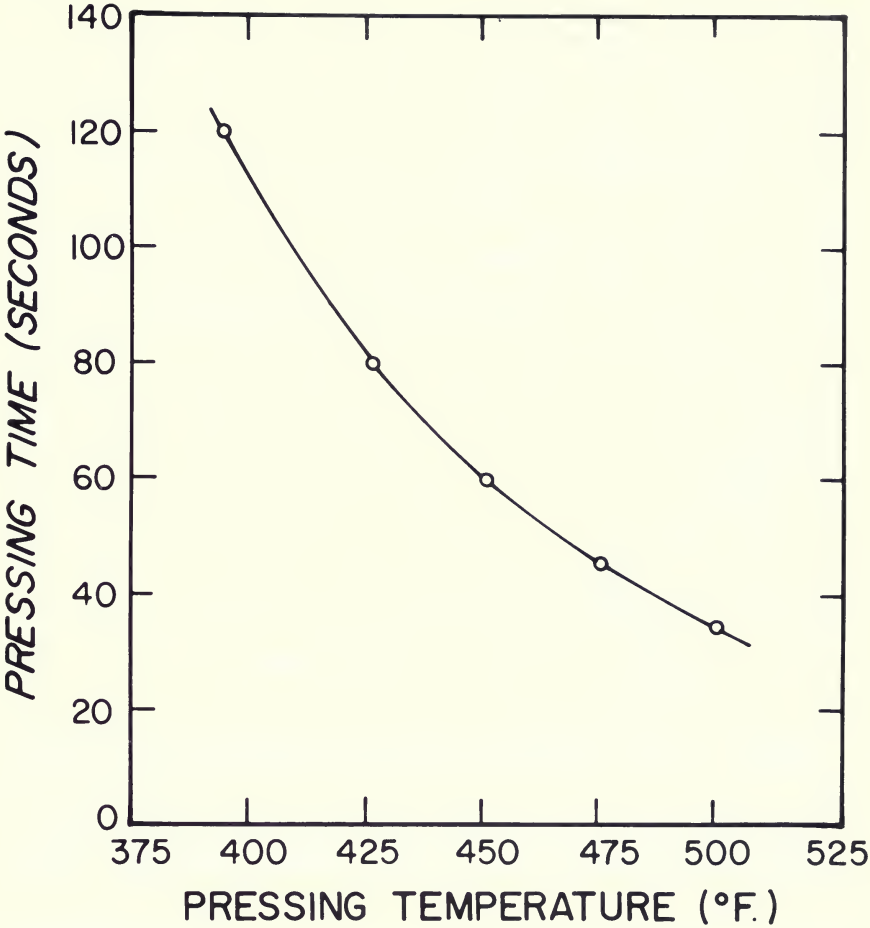


Figure 23-50.—Effect of press temperature on press time for dry-formed hardboard. (Drawing after Norberg and Back 1968.)

distance from the press platen. This gives rise to density variation over the board cross section. Some board properties such as surface hardness, bending stiffness, and **internal bond** (tensile strength perpendicular to board plane) are very sensitive to such density variation. In thicker medium density fiberboard and particleboard this density variation can be controlled to some extent by changes in the press cycle. In S1S hardboards density is near maximum at the smooth top surface, and minimum at the screened back (fig. 23-53). This unsymmetrical distribution results from water flow toward the screen.

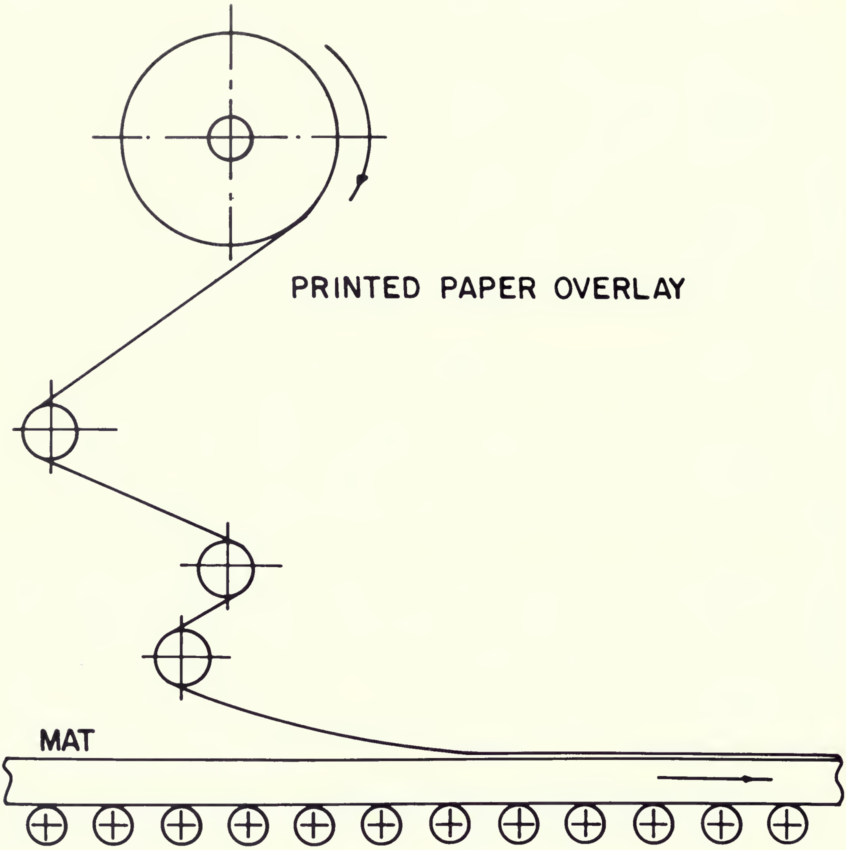


Figure 23-51.—Application of printed overlay to wet mat prior to hot pressing. (Drawing from Suchsland and Woodson 1985.)

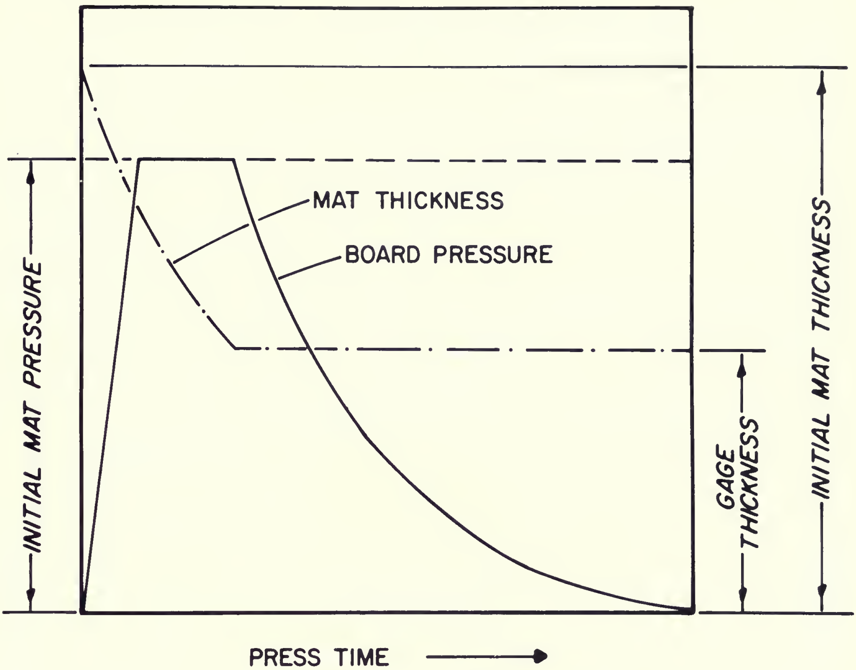


Figure 23-52.—Pressing to stops. Press time and mat thickness related to platen pressure on the board. (Drawing from Suchsland and Woodson 1985.)

23-9 DRY-PROCESS FIBERBOARD MANUFACTURING

OVERVIEW

Dry-process boards (see fig. 23-1 for classification) are defined as those formed by using air as a distributing medium, regardless of the moisture content of the furnish. Any board process using a fiber furnish and air forming is thus a dry fiberboard process. The **semi-dry process** differs from all other dry processes in that its mat moisture content is too high to allow the pressing of S2S board. The high moisture content may be due to using green or cooked chips without drying after refining (some drying always occurs as a result of the temperature increase of the furnish during the pulping process), or it may be due to addition of water to the board surface prior to pressing for improving surface quality. In either case, screens are required and the boards have the same screenback characteristics as wet-formed S1S boards. The process is "dry" however, by our definition, because air is used for transporting the fibers and for forming the mat. The first dry-process board plant in the United States was a semi-dry plant (Anacortes, Wash.). It is today the only semi-dry plant in operation in the United States.

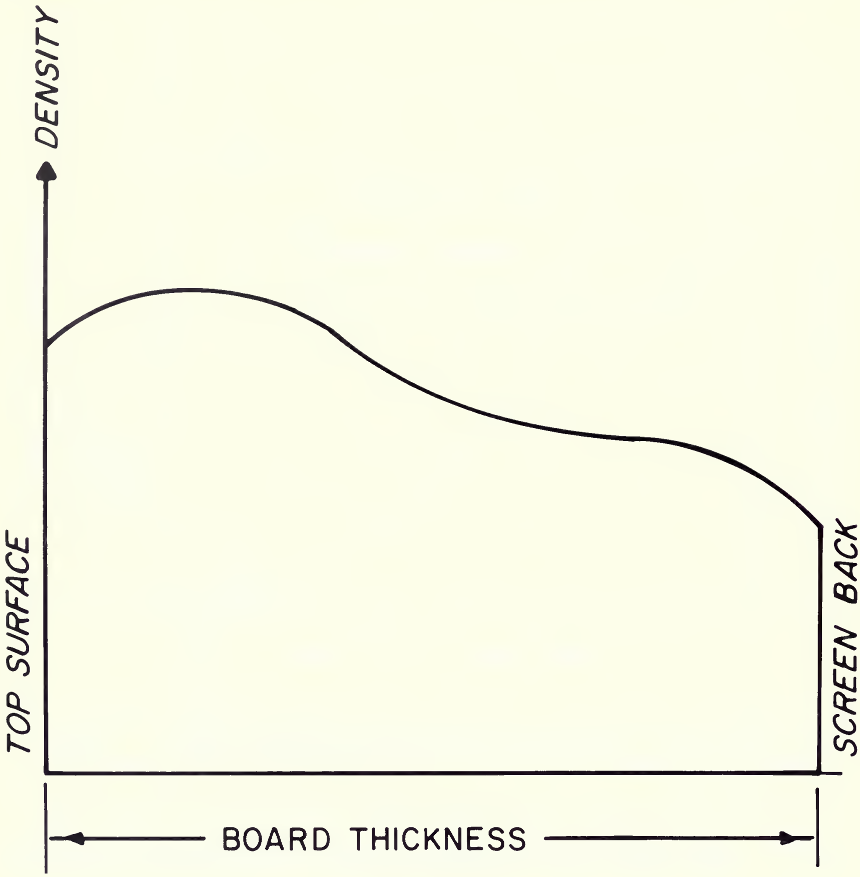


Figure 23-53.—Typical density profile of S1S hardboard. (Drawing after Spalt 1977.)

The obvious major advantage of dry process fiberboards, very large reduction in process water, is increasingly important in light of stringent regulation of effluent quality.

Another important advantage of the dry fiberboard process is its ability to make medium-density boards thicker than ½-inch, the upper limit for wet-processing. This allows dry-process fiberboard to compete in a market previously dominated by particleboard. This medium-density, thick, dry-formed fiberboard, normally called MDF, combines dry-process hardboard and particleboard technologies to make a very versatile board product.

Dry process fiberboards may be classified as thin boards (<⅜-inch) and thick boards (>⅜-inch). The thin boards are similar to wet-process fiberboard in appearance and applications, and are sold under the same commercial standards. They are made in both medium-density (40 to 50 pounds/cu ft) and in the high-density range (over 55 pounds/cu ft). Thick boards are made only in the medium-density range by a process almost identical to that for medium-density thin boards, but are governed by a different commercial standard and are sold in entirely different markets.

Any comparison of wet- and dry-process fiberboard manufacturing must therefore be limited to thin boards. Besides the two important attributes mentioned above, the dry process has the following technological limitations and advantages:

Limitations of dry-process thin boards.—

- elimination of hydrogen bonds
- elimination or substantial reduction of lignin bonds
- absolute necessity of resin binder addition
- difficult control of uniform fiber deposition
- furnish handling and storage difficulties due to low bulk density
- greater fire danger
- air pollution problems
- inferior board surface
- greater linear expansion

Advantages of dry-process thin boards.—

- S2S surfce
- higher yield
- possibility of making multi-layer board
- reduced sensitivity to species characteristics
- possibility of using automatic thickness and density control devices
- absence of bias (difference in properties in the two principal directions)
- high internal bond strength

None of these limitations and advantages are decisive enough to cause a shift from wet process to dry process or vice versa, since most can be compensated for, where necessary, by adjusting process variables and by improved processing equipment.

Once expected to dominate future fiberboard manufacture in North America, the dry process has encountered growing costs and power needs for air-pollution abatement. Also, increases in oil prices have substantially increased costs of fiber drying and resin. At the same time, the wet-process manufacturers have reduced their effluent disposal problem by better white water circulation systems. These developments have kept the wet-process competitive (FAO 1976).

A direct comparison of capital and manufacturing costs of wet- and dry-process plants, manufacturing ⅛-inch hardboard and 7/16-inch medium density siding is given in tables 23-6 and 23-7. An analysis of the manufacturing cost estimates indicates the following:

- Chemical costs are signifcantly higher for the dry process than for the wet process.
- The wet process has slightly higher power costs but lower fuel requirements.

- The higher production capacity (short press cycle) of the dry process for the 7/16-inch siding significantly lowers the unit labor, supplies, administration and depreciation costs.
- The total unit manufacturing cost is slightly lower for the wet process than for the dry process.

These estimates are based on cost levels in the United States in 1975. Further increases in oil costs since 1975 may have shifted the picture even more towards the wet process. For these reasons most dry process plants currently produce medium density siding—high quality products that are cost competitive. For additional data on the economics of a wet-process S1S siding plant, see section 28-30.

TABLE 23-6.—*Estimated capital costs for wet- and dry-process hardboard plants in 1975* (FAO 1976; Vajda 1976)

Item	Wet process[1]	Dry process[2]
	Thousand dollars	
Equipment (including design engineering)		
Woodyard	800	800
Fiber preparation	1,730	2,400
Forming and pressing	4,570	4,780
Heat treatment and humidification	2,880	1,560
Finishing	650	650
Auxiliary equipment	2,050	1,620
Electrical	1,410	1,330
Installation and construction management	4,200	3,260
Subtotal	18,290	16,400
Site preparation and buildings		
Site preparation and services including effluent treatment	2,000	750
Building structures	3,850	2,950
Subtotal	5,850	3,700
Mobile equipment	250	250
Freight, duty, and taxes (allowance)	1,100	1,100
Contingency and escalation allowance (10 percent)	2,500	2,100
Siding priming and finishing line, including buildings, installation and engineering	2,700	2,700
Total capital costs	30,690	26,200

[1]26-opening press, 2,438 x 5,486 mm platen size; daily production of 200 metric tons of 3-mm board or 222 metric tons of 11-mm board.

[2]24-opening press; 1,524 x 5,486 mm platen size; daily production of 185 metric tons of 3-mm board or 277 metric tons of 11-mm board.

TABLE 23-7.—*Estimated manufacturing costs for two thicknesses of wet- and dry-process hardboard*[1] (FAO 1976; Vajda 1976)

Item	Wet process		Dry process	
	3.2-mm board[2]	11-mm siding[3]	3.2-mm board[4]	11-mm siding[5]
	Dollars/metric ton			
Manufacturing costs				
Wood at $25/ovendry ton	29.40	29.20	29.15	28.52
Resin	2.10	7.70	15.40	33.60
Wax	3.30	3.30	3.30	3.15
Alum	1.17	1.17	—	—
Power	5.75	5.75	5.25	5.25
Fuel	8.08	8.08	8.72	8.51
Labor	18.46	16.67	18.00	12.00
Operating and maintenance supplies	11.73	11.74	11.08	8.57
Administration and overhead	7.04	6.21	7.65	5.14
Taxes and insurance	5.46	5.30	5.00	3.74
Cutting, priming, and packaging costs	—	26.23	—	26.23
Total manufacturing cost excluding interest and depreciation	92.49	121.35	103.55	134.71
Depreciation (15-year straight line)	28.72	28.43	26.11	19.41
Total cost	121.21	149.78	129.66	154.12

[1]Based on 325 operating days annually.
[2]65,000 tons annual production.
[3]72,000 tons annual production.
[4]60,000 tons annual production.
[5]90,000 tons annual production.

Efforts to produce dry-formed fiberboard without addition of resin binder have generally been unsuccessful. Only one binderless dry fiberboard process exists. The plant, which is in Czechoslovakia, uses defibrator pulp further processed in atmospheric Bauer refiners. The boards are pressed with sealing frames to control release of water and gas, which appears to be critical to the process (Swiderski 1963; Nagy 1964; Pecina 1980).

In addition to conventional platen-pressed thick and thin, medium- and high-density dry-process fiberboards, a unique continuous board process, the **Mende process,** applicable to the manufacture of both particleboard and fiberboard was developed in Germany and is being used to some extent in the United States. Since board thickness is limited to about ¼-inch, it competes directly with conventional dry- and wet-process hardboard. One of the attractive features of the Mende process is its capability to produce hardboard on a small scale economically, as described later. Alignment of fibers in the fiber mat to enhance certain board properties in one of the principal directions of the board is a fairly recent development, and will be discussed briefly at the end of this section.

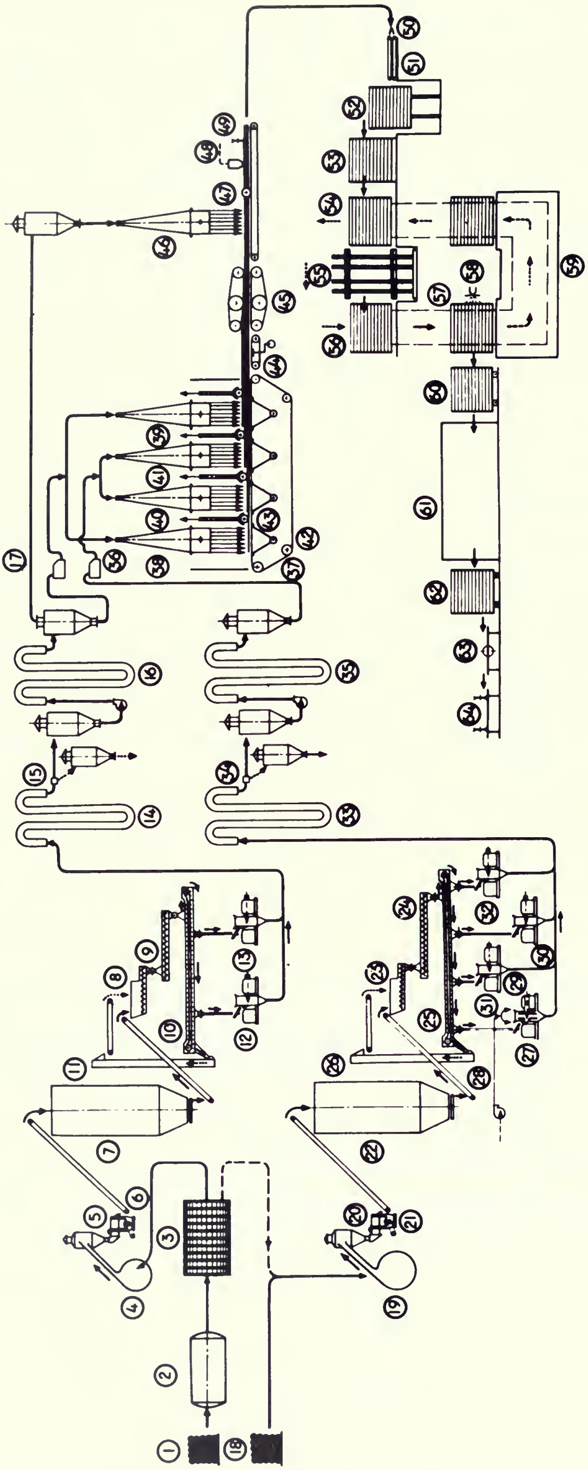


Figure 23-54.—See facing page for caption and legend.

Figure 23-54.—Schematic process chart of dry-process hardboard manufacturing plant in the United States. (Drawing after Swiderski 1963.)

1. Raw material for surface layers
2. Steaming drum
3. Drum debarker
4, 19. Chippers
5, 20. Screens
6, 21. Secondary mills
7, 22. Chip silos
8, 23. Metering devices
9, 24. Digesters
10, 25. Conveyors
11, 26. Conveyors for return of excess material
12, 13, 27, 30, 31, 32. Bauer double disk refiners
14, 33. Predryers
15, 34. Separators
16, 35. Main dryers
17, 36. Buffer storage
18. Raw material for core layer
28. Air supply
29. Adhesive addition
37. Forming screen
38. 39. Formers (vacuum) for surface layers
40. 41. Formers (vacuum) for core
42. Vacuum supply
43. Shave-off roll
44. Automatic mat scale
45. Prepress
46. Former for fine top layer
47. 49. Saws
48. Automatic mass sensor
50. Tipple
51. 52, 53, 54. Press loading
55. 20-opening hotpress
56, 57. Press unloading
58. Compressed air
59. Caul return and cooler
60, 62. Buggies
61. Humidifier
63, 64. Saws

HIGH- AND MEDIUM-DENSITY HARDBOARDS

Figure 23-54 illustrates a typical dry-process hardboard plant in the United States. It shows the combination of three important elements: atmospheric Bauer disk refiners, tube suspension dryers, and vacuum formers. This is by no means the only practical or possible configuration, but it does represent common industrial practice. The largest dry process hardboard plant in the country (Masonite at Towanda, Penn.), for instance, uses an Asplund Defibrator and a secondary refiner in a combination pulping unit. Weyerhaeuser Company at Klamath Falls, Ore., uses Asplund type D and L defibrators. The illustrated plant uses roundwood as raw material. Today's mill would supplement or replace the roundwood supply with purchased debarked pulp chips, whole-tree chips, or mill residue.

Drying.—To press hardboard without a screen, the moisture content of the mat going into the press must be below specific threshold values which depend on board density and other variables. Excessive moisture will be trapped as steam in the board, resulting in steam blisters (**blows**) as the press is opened. High temperatures and pressures generally require lower moisture content but the drying schedule must not be severe enough to condense the resin adhesive, which is generally applied prior to drying. The drying must, therefore, terminate before the resin cures; at temperatures high enough to assure efficient water removal, this limits drying time to a few seconds.

Moisture content of furnish entering the dryer is around 50 percent. Target moisture content of the dry furnish entering the forming machine is between 8 and 12 percent.

The dryer most commonly used is a **tube dryer,** in which fibers are suspended and transported by the drying medium—hot air or combustion gases. The ratio of air to fiber is about 50 cu ft/pound and air speed about 3,000 feet/minute (Rausendorf 1963). Air or gas temperatures at the wet end range between 500 and 650°F. Exit temperatures are about 150 to 190°F. At 650°F the curing time for a phenol-formaldehyde resin is about 8 seconds. To prevent precure of the resin, drying time should be limited to about 5 seconds which, at 3,000 feet/minute air velocity, would require a dryer length of 250 feet (Rausendorf 1963).

Single- and double-stage tube dryers are diagramed in figure 23-55. Two stages are advantageous when the moisture of the incoming furnish fluctuates widely. The first stage is then used as a pre-dryer to equalize the moisture content, and main drying occurs in the second stage. The final moisture content, adjusted by control of dryer outlet temperature, must be kept within small tolerances to provide proper venting in the press and to allow accurate control of board density or board thickness.

Two problems are inherent in high temperature drying of wood fibers: danger of fire and explosions, and emission from the dryer of fibers, fiber fractions, solid particles resulting from the combustion process, and small particles which are condensation products of volatile materials evaporated from the furnish. The installation of sensitive fire detection and control devices is therefore imperative. The emission of larger particles such as fibers and fiber fractions can be

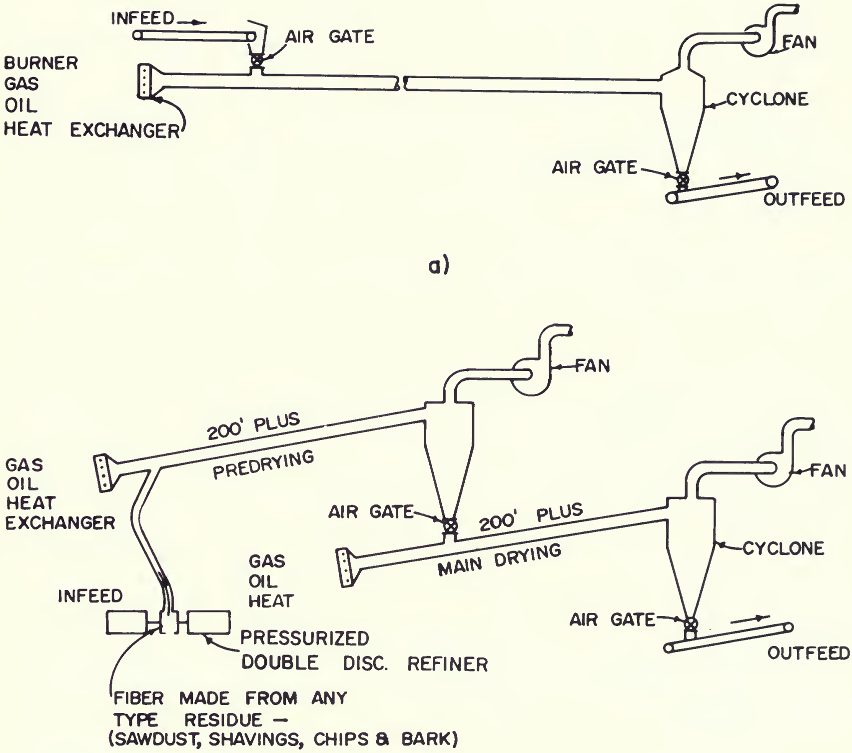


Figure 23-55.—Tube dryers. (Top) Single-stage. (Bottom) Double-stage. (Drawing after Buikat 1971.)

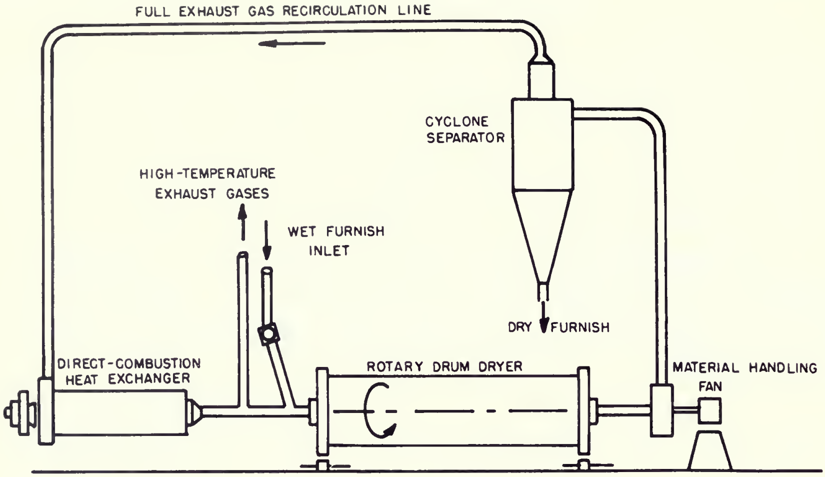


Figure 23-56.—Drum dryer with full recirculation of exhaust gas. (Drawing after Junge 1977.)

controlled relatively easily by installation of cyclones, filters, and scrubbers. Control of the **blue haze** caused by evaporation of volatiles is more difficult. This evaporation could be greatly reduced by lowering drying temperatures, but this severely reduces dryer productivity and efficiency. The only other alternative is complete recirculation of exhaust gases to the dryer combustion chamber. The disadvantage of this system is the higher energy input required because of the high temperature of the exhaust gases vented from the combustion chamber (fig. 23-56).

Forming.—The basic difference between wet forming in water and dry forming in air is the much lower density of air. Some of the typical difficulties of dry forming arise from the difference; e.g.:

- Fibers remain in supsension in air only at considerable air velocities and will promptly settle out when the air flow slows down.
- A fiber-air suspension does not flow laterally on a horizontal support.

Another important characteristic of dry fiber furnish is its tendency to congregate and form lumps as soon as the concentration of the fiber-in-air suspension exceeds certain limit values.

The technical and patent literature offers many approaches to achieving a mat of uniform density from air-suspended fibers (Swiderski 1963; Sandermann and Kunnemeyer 1957). These devices either deposit the furnish by gravity or filter the fibers out of the fiber-air suspension. There are also examples of combinations of these principles.

The first dry process (actually semi-dry) fiberboard plant in the United States at Anacortes, Wash. employs a gravity forming machine which was developed and patented by the Plywood Research Foundation. This lines does not use a dryer, and the forming machine is a **felting box** above the forming belt. The furnish enters the box through a swing spout which distributes the fibers across the width of the box and on top of a high speed rotor, which agitates the fibers and creates a "snowstorm effect" in the felting chamber (Evans 1957; Robinson 1959). The fibers then gently settle down on the moving belt and build up a mat of a density of about 2 pounds/cu ft, and 4 to 12 inches thick, depending on the final thickness of the board. An equalizer or **shaving** roll reduces the mat to uniform thickness, i.e., it controls the uniformity of the mat by controlling its thickness. This volumetric metering results in uniform board density or uniform board thickness only if the bulk density of the furnish does not fluctuate. Close control of all process characteristics that affect bulk density, such as air velocity, pulping conditions, and moisture content is therefore critical.

Another gravity type forming machine is used by Champion International at Lebanon, Ore. (Uschmann 1956). A volumetric metering device supplies the furnish to a vertical chute within which it is distributed laterally across the width of the forming machine by means of a number of horizontal screw conveyors. A series of closely-spaced sawblade-like disks project partially into slots at the bottom of the chute and transfer the furnish from the chute and through the slots to moving cauls carried through the machine by a conveyor belt. The action of the rotating "sawblades" prevents congregation of the furnish and deposits a loose uniform mat. As the furnish falls to the cauls, a suction device creates an air current which deflects the final material, depositing half of it ahead of the main stream, as the bottom surface layer, while the other half is carried forward and placed on top of the mat. An equalizer roll controls mat thickness before application of the top surface layer. Figuire 23-57 shows a schematic of the entire operation.

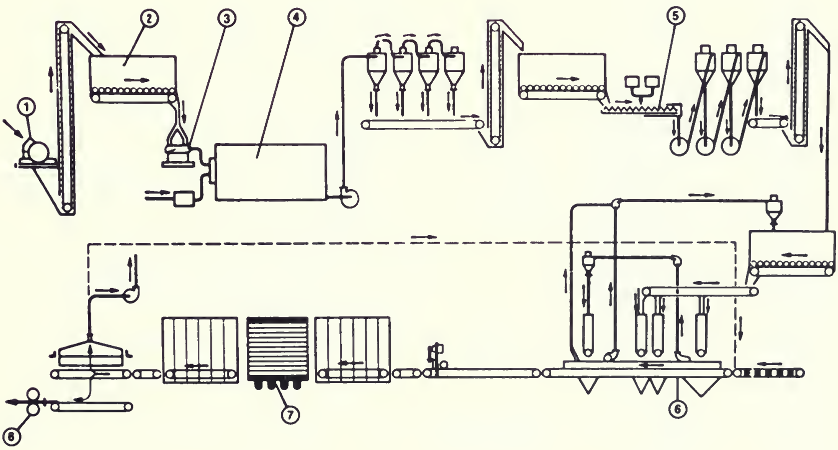


Figure 23-57.—Schematic diagram of dry-process hardboard plant of Champion International Corp., Lebanon, Ore. (Drawing after Sandermann and Kunnemeyer 1957).

1. Chipper
2. Silo
3. Bauer mill
4. Dryer
5. Addition of resin
6. Former
7. Hot press
8. Humidification

A forming machine which filters the furnish from the fiber-air-suspension is illustrated in figure 23-58. The metered furnish is supplied to one or more positively pressured vertical chutes (felting heads) suspended above a moving screen. Rotating brushes inside the head agitate the furnish and discharge an air-furnish stream through its perforated bottom. The stream is drawn by vacuum through the traveling screen, which filters out the furnish and builds up the mat. This vacuum-type forming machine is used by the Weyerhaeuser Company in the dry-process siding plant at Klamath Falls, Ore. (Fig. 23-59).

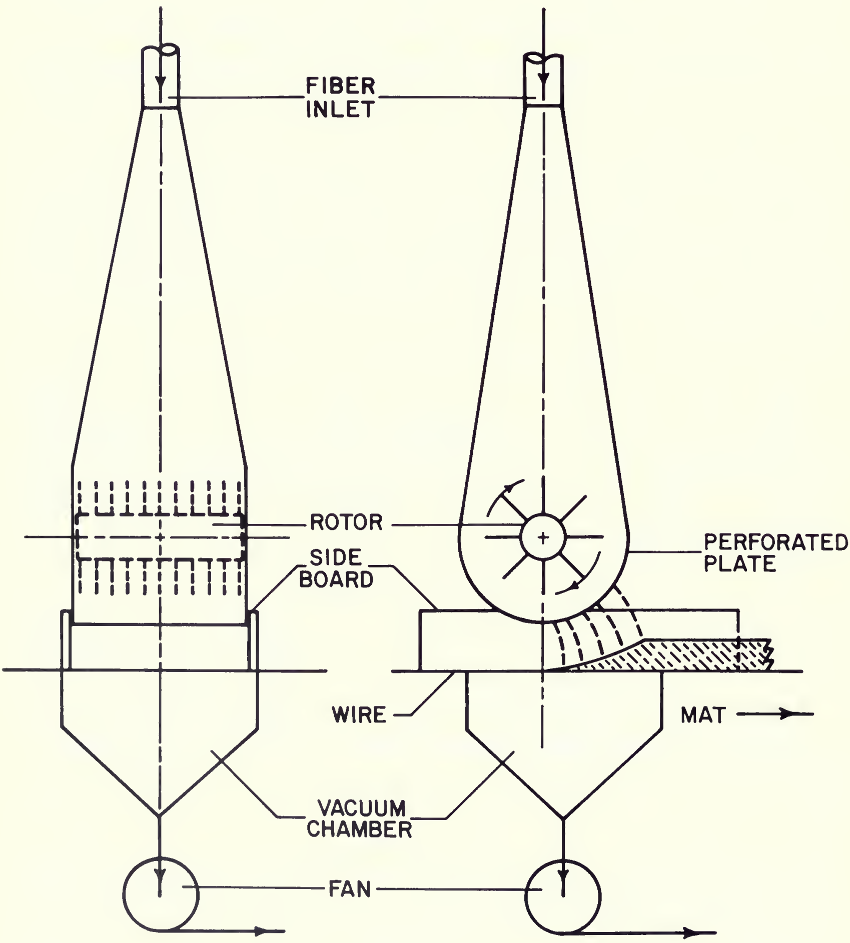
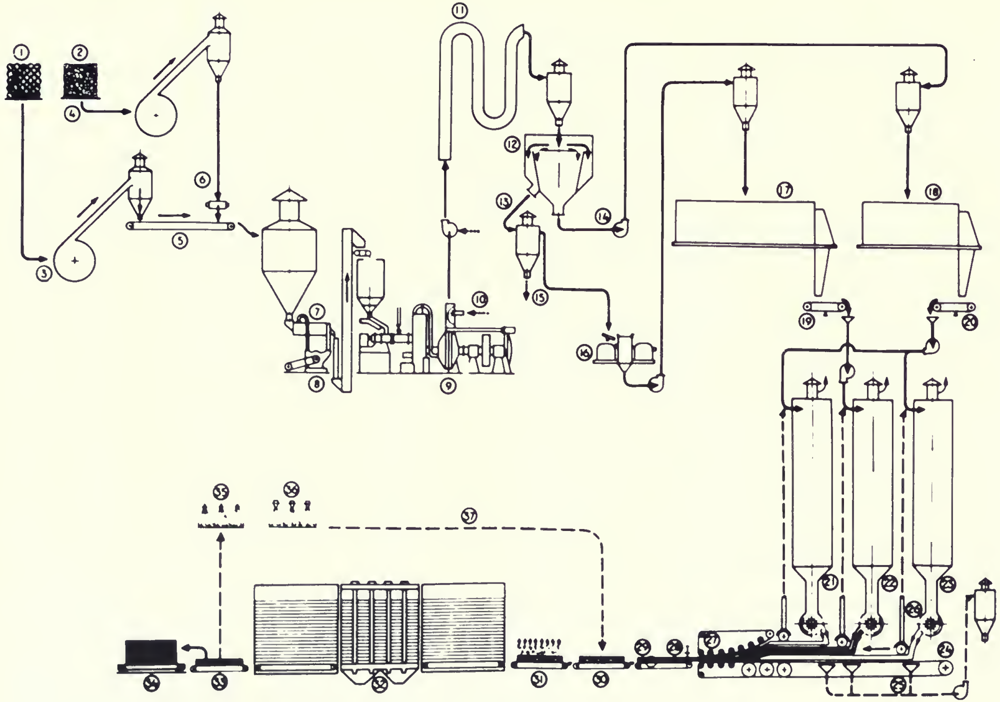


Figure 23-58.—Vacuum forming machine. (Drawing after Robinson 1959.)



1. Roundwood
2. Mill waste
3, 4. Chippers
5, 6. Chip conveyors
7. Screen
8. Mill
9. Defibrator
10. Addition of resin
11. Suspension dryer
12. Separator
13. Coarse fibers
14. Fine fibers
15. Separation of fiber bundles
16. Bauer refiner
17. Buffer storage
18. Buffer storage
19, 20. Scales
21, 22, 23. Formers
24. Forming screen
25. Vacuum supply
26. Nylon brush roller
27. Prepress
28, 29. Saws
30. Placement of mat on screen
31. Water spray
32. Hot press
33. Separation of cauls and boards
34. Humidification of boards
35. Washing of cauls and screens
36. Drying of cauls and screens
37. Caul and screen return
38, 39. Saws

Figure 23-59.—Schematic chart of the Weyerhaeuser semi-dry plant in Klamath Falls, Ore. This plant now produces siding by the dry process (no screens). (Drawing after Sanderman and Kunnemeyer 1957.)

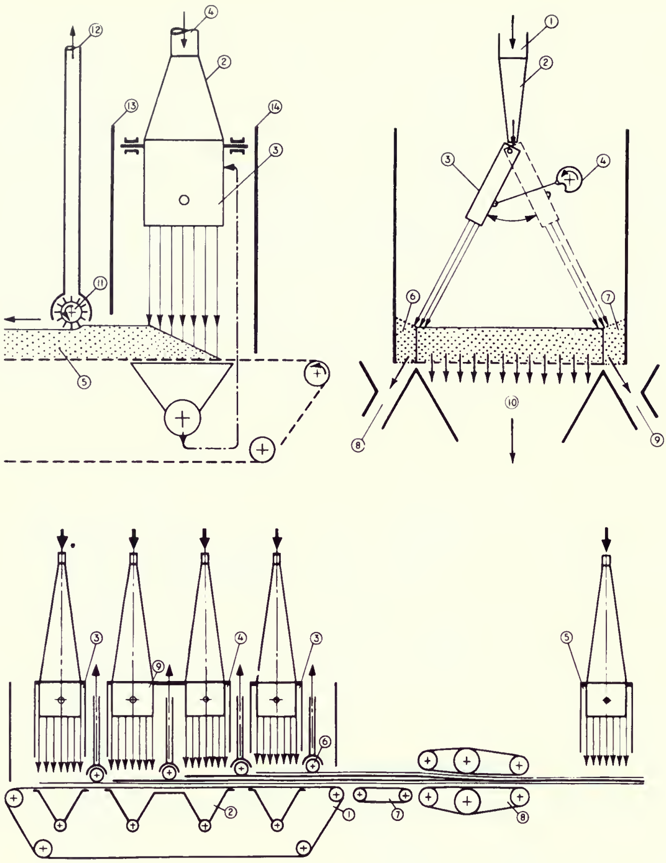


Figure 23-60.—Vacuum former with swing spouts.

(Top) Schematic of swing spout former element
1. Fiber supply
2. Inlet funnel
3. Swing spout
4. Drive
5. Forming screen
6. Fiber excess along edges of mat (also 7)
8, 9. Vacuum ducts
10. Vaccum
11. Shave-off roll
12. Furnish return
13, 14. Walls of forming chamber

(Bottom) Four-stage vacuum former with element for forming fine surface layer.
1. Forming screen
2. Vacuum
3. Formers for surface layers
4. Formers for core
5. Former for fine surface layer
6. Shave-off rolls
7. Automatic mat scale
8. Prepress

(Drawing after Lampert 1967.)

Such vacuum felters yield more uniform mats than gravity felters, and are the standard dry-process forming devices, despite their considerable electric power requirement. In a more recent four-stage vacuum former (fig. 23-60), the furnish is distributed across the machine width by means of swing spouts oscillating at about 120 cycles per minute. The furnish is metered to the spouts at air speeds of 3,600 to 5,400 feet/minute. To improve mat uniformity, furnish is applied in excess thickness and then reduced to required mat thickness by equalizer rolls and vacuum devices.

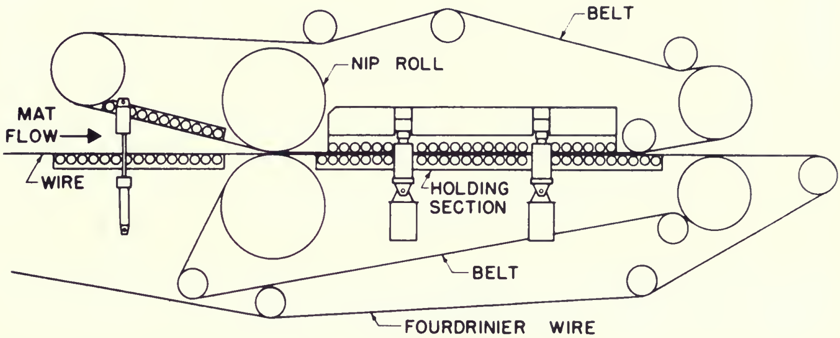


Figure 23-61.—Roll pre-press. (Drawing after Peters 1968.)

Pressing.—The dry-formed mat has very low density, and for ¼-inch board could be 8 inches thick. To reduce daylight requirements and closing times in the hot press, and to improve handling quality of the mat and surface quality of the finished board, the mat is prepressed in a continuous band press (fig. 23-61). Roll pressures are about 1,000 pounds/inch. Mat density is thereby doubled or tripled (Peters 1968). In some cases a surface layer of fine fiber material is applied to the precompressed mat.

The travelling densified mat is then trimmed by disk cutters and transferred to caul plates which carry the mat through the pressing operation. Dry formed board is hot-pressed in multi-opening presses very similar to those for wet-formed S2S board. Presses allow rapid, simultaneous closing. Platen temperatures are high (400°F +) and press cycles are short.

At low mat moisture contents (5 percent) single-phase press cycles are used (fig. 23-62). Higher moisture contents require 2 or 3 phases (fig. 23-63). Two phase press cycles work particularly well with hardwood furnish. Three phase cycles require precise control; the total pressure release after phase one can reduce surface quality.

Quick drying of surface layers of the loose mat during closing of the press increases their compressive strength and leads to a densified core layer (fig. 23-64). Surface densification, at least in the top surfaces can be increased by adding water spray to the mat surface prior to hot pressing. At the Weyerhaeuser plant in

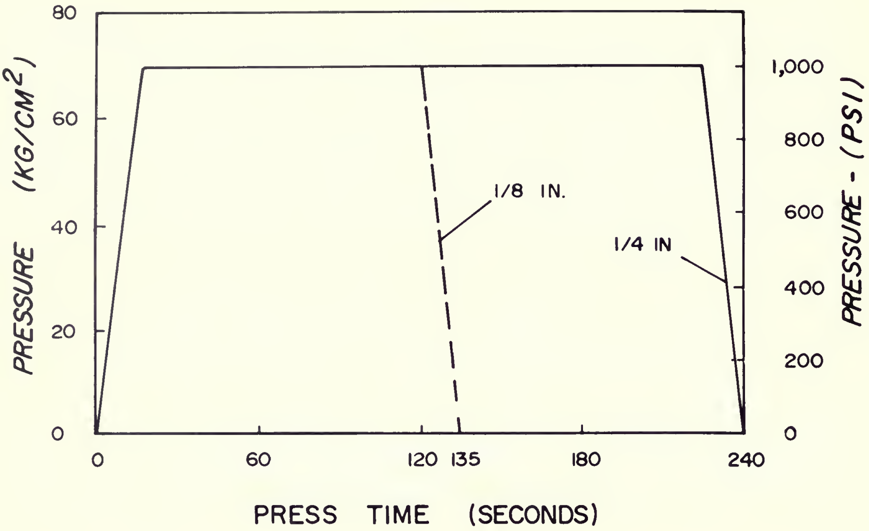


Figure 23-62.—Single-phase press cycles for ⅛- and ¼-inch-thick, dry-formed hardboard of three-layer construction. Press temperature, 455°F. (Drawing after Lampert 1967.)

Klamath Falls, 60 grams of water per square foot is applied to the surface of the siding mat, increasing the total moisture content of the mat considerably. The press cycle starts with a low pressure phase (1½ minutes at 150 psi) followed by a high pressure phase to stops. The paintability of this particular siding product is very good.

Process (density) control.—Board density is a basic property of hardboard often used as a quality indicator. It affects most of the physical and mechanical properties such as bending strength, modulus of elasticity, hardness, and thickness swelling. It also affects cost since higher board density requires more wood, additives, process water, and energy.

Figure 23-65 (top) shows the basic relationship between board density and bending strength as reported by Kumar (1958). The curve below is the derivative of this relationship; it shows that for each 1-percent change from an average board density of 58 pounds/cu ft, the bending strength will change about 3 percent. A density variation of ±7 percent, either within or between boards, would be reflected in bending strength variation of ±21 percent.

Efforts to control board properties should concentrate on board density, or, more precisely, on mat weight. The economic advantage of such process control efforts is illustrated in figure 23-66. The hypothetical distributions of bending strength show how closer board density tolerances would reduce the variation of the bending strength about the average. Since the board now exceeds the required bending strength, the board density or the resin content—or both—can be reduced. Other important board properties would be similarly affected.

Controlling board density requires accurate measurement of the mat density or mat weight. A density control system must include accurate moisture content

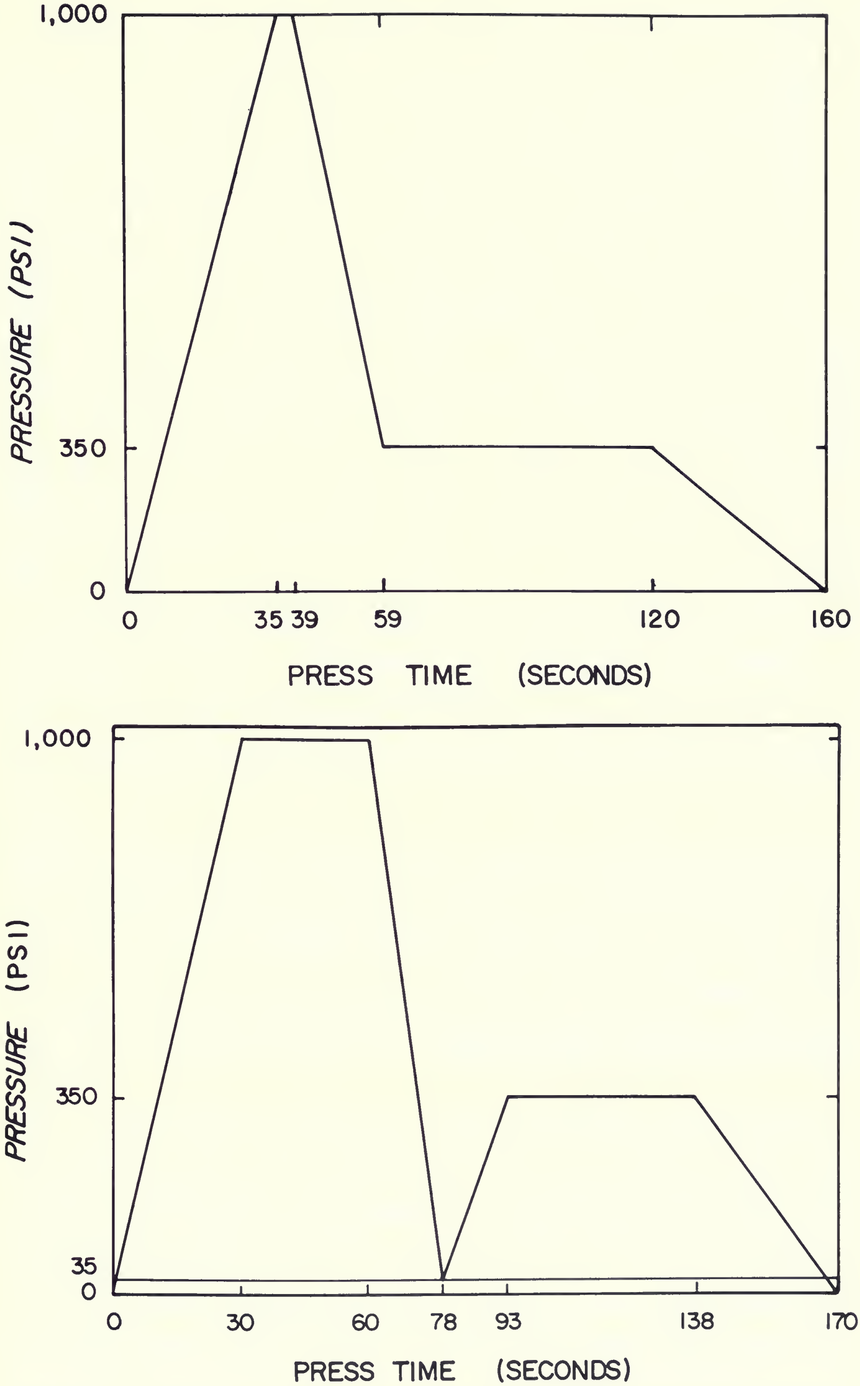


Figure 23-63.—Press cycles for ⅛-inch-thick, dry-formed hardboard at press temperature of 428-466°F. (Top) Two-phase. (Bottom) Three-phase. (Drawing after Swiderski 1963.)

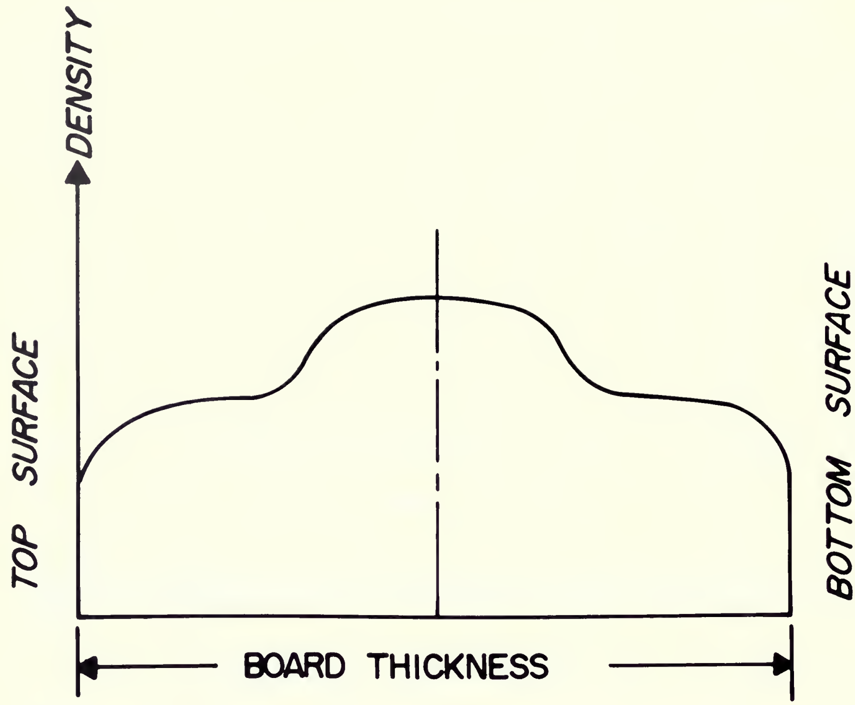


Figure 23-64.—Density profile of S2S dry-formed hardboard. (Drawing after Spalt 1977.)

measurement and moisture content control. Such a system developed by the Measurex Corporation has been applied to the dry-process hardboard siding plant in Paris, Tenn., operated by the Celotex Corporation. Readers needing an illustrated description of this system are referred to Betzner and Wallace (1980) or to Suchsland and Woodson (1985).

MEDIUM-DENSITY FIBERBOARD

Medium-density fiberboard (MDF), according to common usage of the term, refers to thick (3/8- to 1-inch plus) fiberboard sold in the industrial core stock market in direct competition with particleboard. The manufacturing process is therefore controlled to produce a product with bending strength, modulus of elasticity, internal bond, machinability, and screw-holding power sufficient for these applications. These requirements have not been determined precisely; the commercial standard simply identifies those materials that are being successfully used in these applications in terms of certain properties which can readily be evaluated by the manufacturer, and which can be maintained within certain tolerances.

The medium-density fiberboard process has been developed for uses which are different from all other fiberboard applications. Experience and research

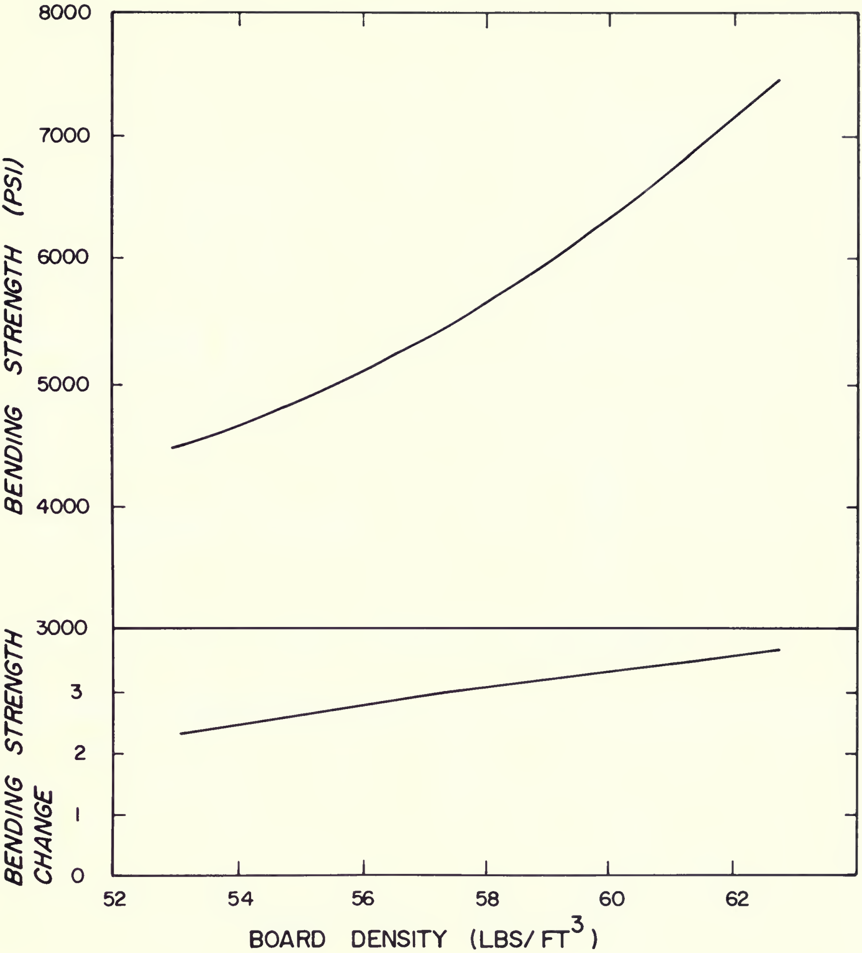


Figure 23-65.—(Top curve) Relationship between bending strength and density of hardboard. Drawing after Kumar 1958. (Bottom curve) Percent change in bending strength per 1-percent change in hardboard density. (Drawing from Suchsland and Woodson 1985.)

may further improve controls on resin content to meet internal bond requirements and develop press cycle designs for density profiles to improve edge machinability; such considerations are of less than secondary importance in other dry fiberboards.

A typical process flow diagram for a medium-density fiberboard plant is shown in figure 23-67. This schematic differs little from the dry-process hardboard flow diagram in figure 23-54 but has three unique elements, described by Raddin and Brooks (1965).

First, a pulp of very low bulk density (2 pounds/cu ft or less) is required to develop good fiber bonds during compression to normal board density (45 to 50

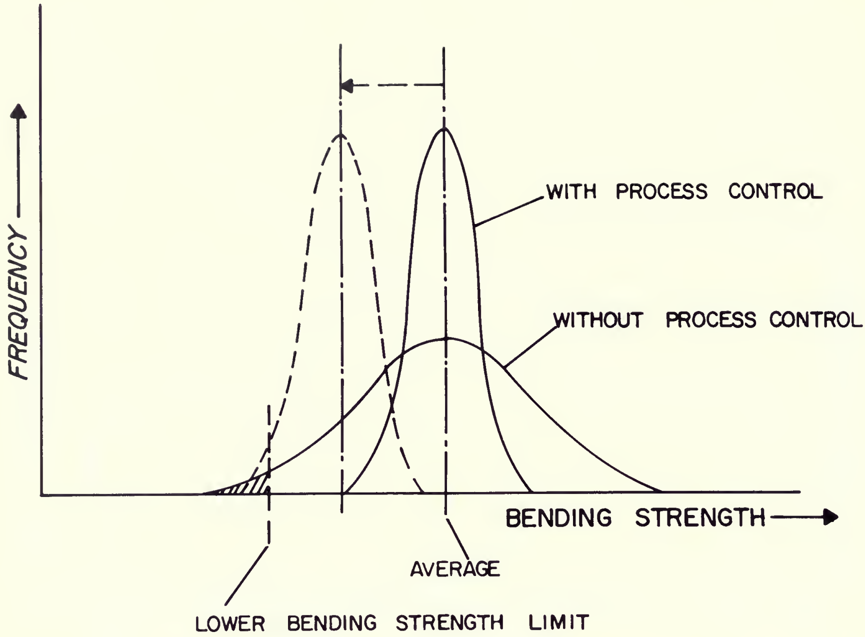


Figure 23-66.—Benefits of mat density control. (Drawing from Suchsland and Woodson 1985.)

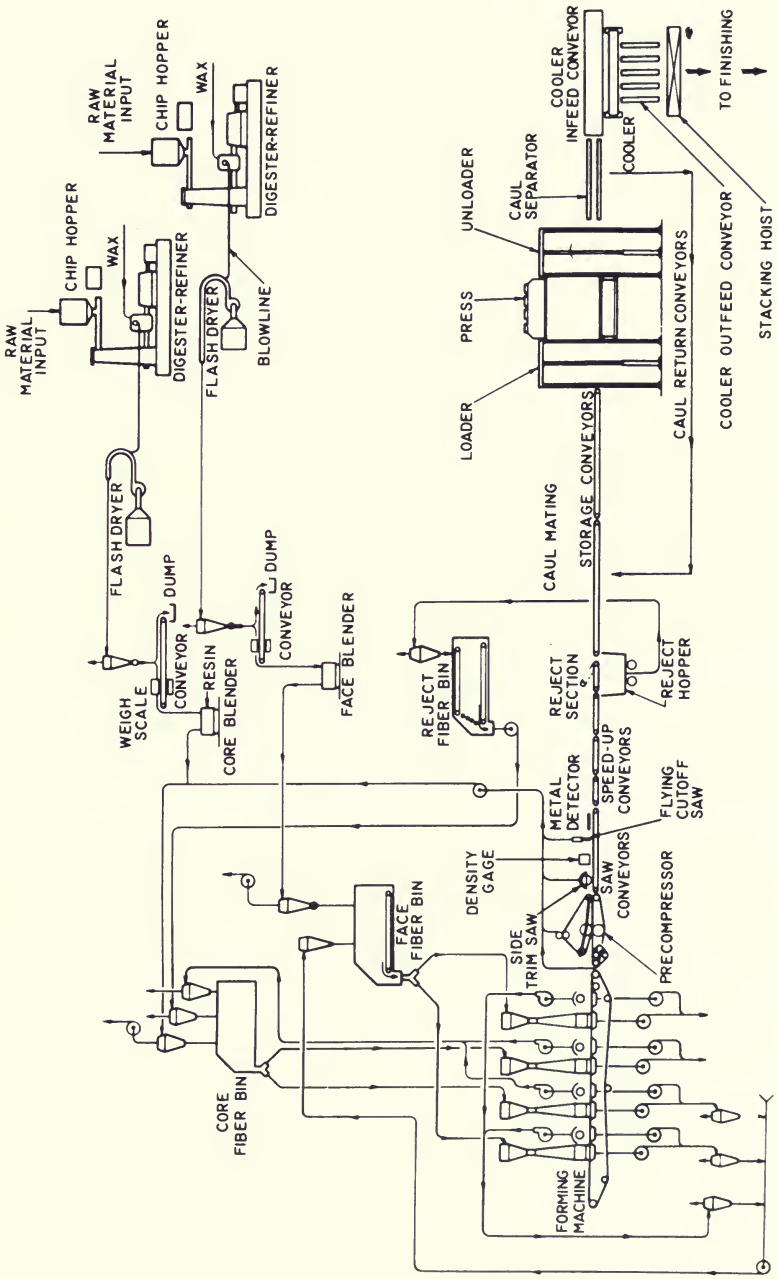


Figure 23-67.—Flow chart for a typical dry-process medium-density fiberboard plant. (Drawing after Chryst and Rudman 1979.)

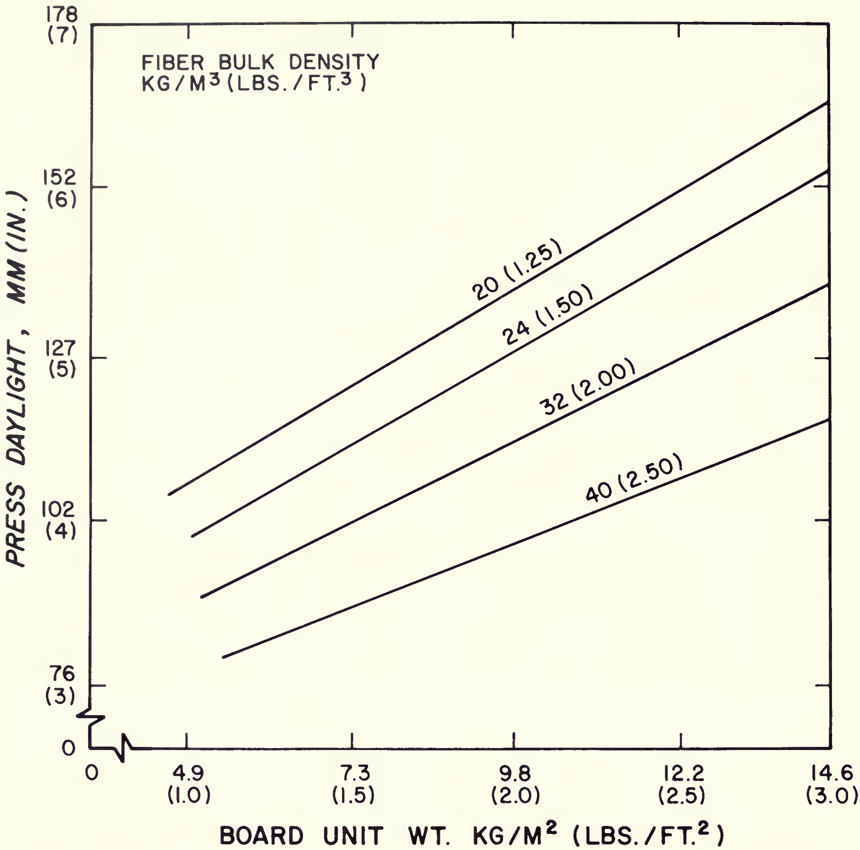


Figure 23-68.—Press daylight required for fiberboards with density of 47 pounds/cu ft, related to bulk density of the uncompressed fiber. (Drawing after Chryst and Rudman 1979.)

pounds/cu ft). Such pulp is produced only in pressurized refiners (sec. 23-6). Low bulk density of the furnish poses special problems in handling, transportation, and storage, and requires presses with sufficient daylight (maximum clearance between plates) to accommodate the thick mats (fig. 23-68). These press openings are dimensioned to accommodate the precompressed mat. Mats before precompression are much thicker (9 to 24 inches). Caulless systems transport the precompressed mat into the press by loader trays; such systems require an additional 3 inches of daylight.

A second unique element is the binder formulation. Since any resin with a high **tack** (stickiness) would prevent uniform distribution of the furnish, so-called *in situ* resin systems were developed by Allied Chemical Company in the early 1960's. Their low tackiness and viscosity make them suitable for application to bulky dry fiber furnish. The precondensation of these **in situ** resins is terminated at a very low molecular weight, which reduces their tackiness. The condensation is completed in the hot press.

The third unique element of the medium-density fiberboard process is radio-frequency curing of the resin during pressing. Unlike conductive heating between hot press platens, radio-frequency heating raises temperature uniformly regardless of the distance from the platen surface. In theory, every part of the mat should have the same time-temperature relationship during the compression period. Thus, compressibility of the mat should be uniform over its thickness at any given time, and density should not vary over the cross section of the finished board.

A uniform density over the board cross section is not always desirable. Many manufacturers produce boards with high face densities to increase bending strength and stiffness. In medium-density fiberboard, on the other hand, radio-frequency heating in the press produces uniform density and a solid edge, which allows smooth machining and finishing.

Urea-formaldehyde resins regularly used in the particleboard industry are also used for medium-density fiberboard, and about half of the existing plants use regular steam heated presses rather than radio frequency. The pressurized refiner, however, is still the typical pulping machine for medium-density fiberboard.

Drying, resin binder application, and forming.—Drying of fiber for medium-density fiberboard is accomplished in tube suspension dryers or flash dryers exactly like those used in other dry fiberboard processes (fig. 23-55).

Resin is generally applied to the dry fibers in short retention mixers (figs. 23-27 and 23-69). These mixers were developed for the particleboard industry, a significant advance from large, low velocity trough-type blenders (Knapp 1971). Short-retention mixers rely on rapid agitation to transfer resin from one fiber to another throughout the furnish. In more recent machines spray nozzles have been replaced by liquid adhesive delivery through shaft and rotating paddles or through injection into the rotating ring of furnish (fig. 23-69 center). Retention times are only a few seconds. Mixers of this type have been equipped with agitators especially suited for handling fiber (fig. 23-69 bottom).

With fiber furnish these machines sometimes distribute resin unevenly, developing resin spots visible on the finished board. Being considered as an alternative is injection of the urea-formaldehyde resin into blow pipes from the refiners. This is common practice in dry process hardboard manufacture where phenol-formaldehyde resins are used. Additional benefits (besides absence of glue spots) are: no tackiness, clean pneumatic ducts and cyclones, higher moisture content at dryer output (14 percent vs. 4-5 percent with blender), and no formaldehyde odor. Resin consumption, however, increases by about 10 percent (Haylock 1977).

Forming of the medium-density fiberboard mat is similar to forming of thin dry-formed hardboard mats. The vacuum former (fig. 23-58) is standard. Mat thickness is, of course, much greater, so that it may be questionable whether or not upper mat layers benefit from the vacuum.

A more sophisticated forming machine, the Rando-Wood-MDF former (fig. 23-70), which attempts to form the entire mat thickness simultaneously, was described by Wood (1976). A separator assembly separates the fibers from the

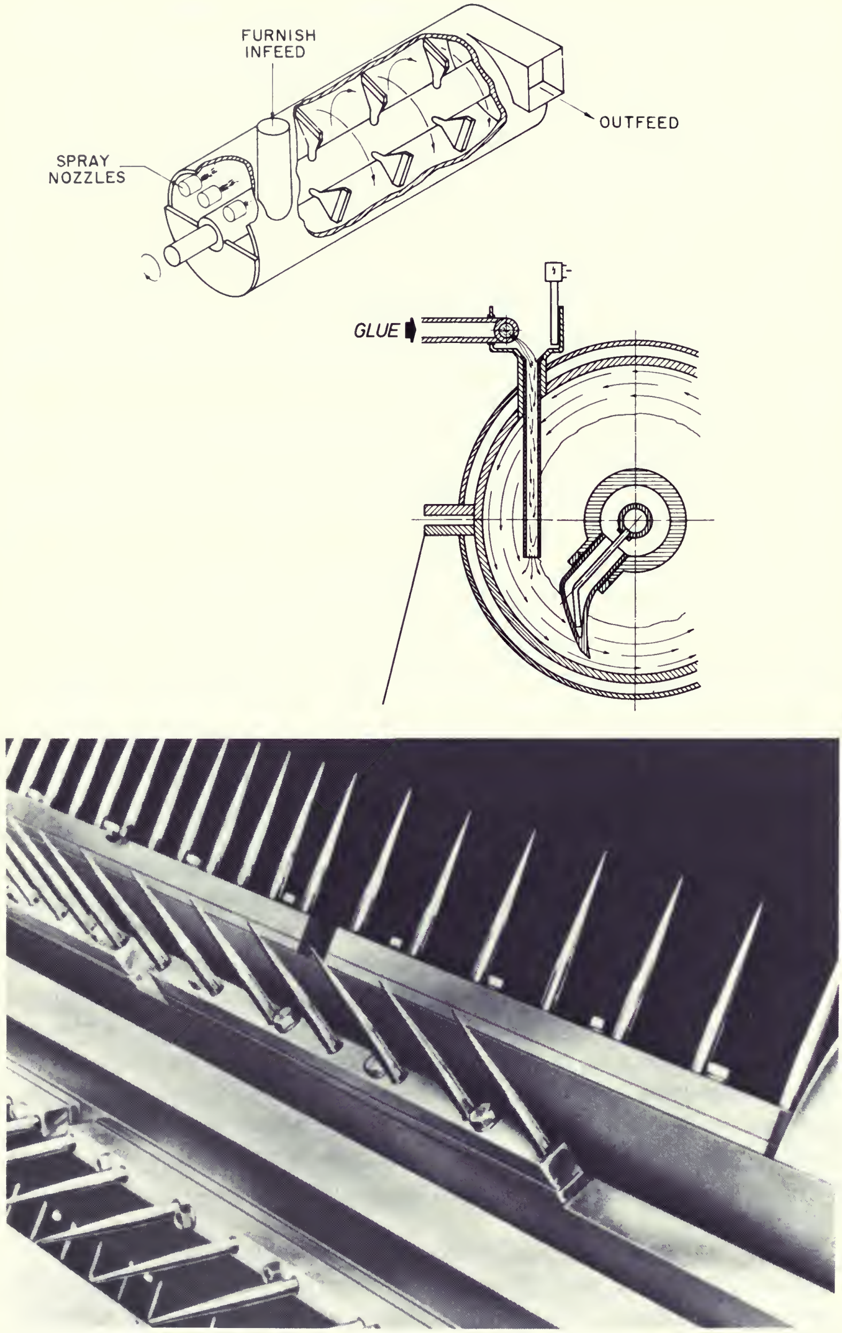


Figure 23-69.—Short retention blenders. (Top) Equipped with spray nozzles and paddle agitators. (Drawing after Maloney 1977.) (Center) Injection of liquid resin through external feeding pipes into ring of rotating furnish. (Drawing after Engles 1978.) (Bottom) Ring mixer for fiber furnish equipped with needle implements. (Photo from Engels 1978.)

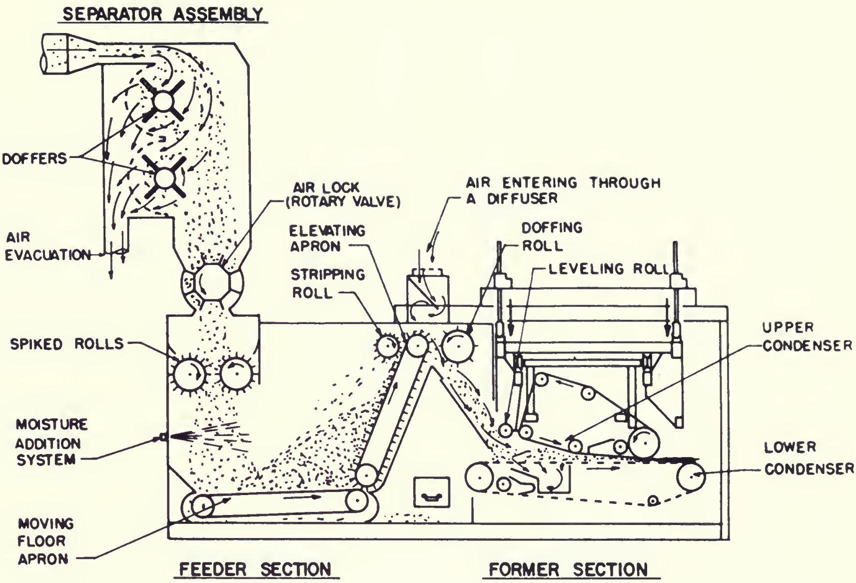


Figure 23-70.—Rando-Wood former. (Drawing after Wood 1976.)

air without condensing them. They are then fluffed by a pair of spike rolls and deposited on a moving-floor apron, where a stripping roll equalizes the flow before they enter the forming section of the machine. Here air is removed through perforations of the lower condenser and the fibers are deposited and packed into the wedge-shaped entry to the gap between the upper and lower condensers, simultaneously forming the entire cross section of the mat, with finer furnish fractions concentrated on both surfaces.

Another vacuum former is offered by the Swedish company Motala-Defibrator under the name "Pendistor" (fig. 23-71), with air impulses replacing the slower swing spout. It is said to produce superior uniformity in mats up to 9 feet wide. The thick mats (9 to 24 inches) are precompressed by continuous band presses (fig. 23-71 bottom) to a thickness of 3 to 6 inches. Mat trim waste and entire mats rejected because of excessive weight variation are returned to the forming station for reuse. Acceptable mats are transferred to the press loader either with or without cauls.

Pressing.—In the manufacture of thin boards, press cycles are largely designed to achieve desired total densification of the mat and efficient water and gas release; development of any particular density profile is secondary. For thick medium-density fiberboards and particleboards, however, density profile can be of primary importance; and press cycles are designed to manipulate this profile. In figure 23-72 two boards of equal average density differ in its distribution. Board A with high face density would have high modulus of elasticity and strength in bending, but low internal bond strength (tensile strength perpendicular to the board surface). Board B would have greater internal bond strength but

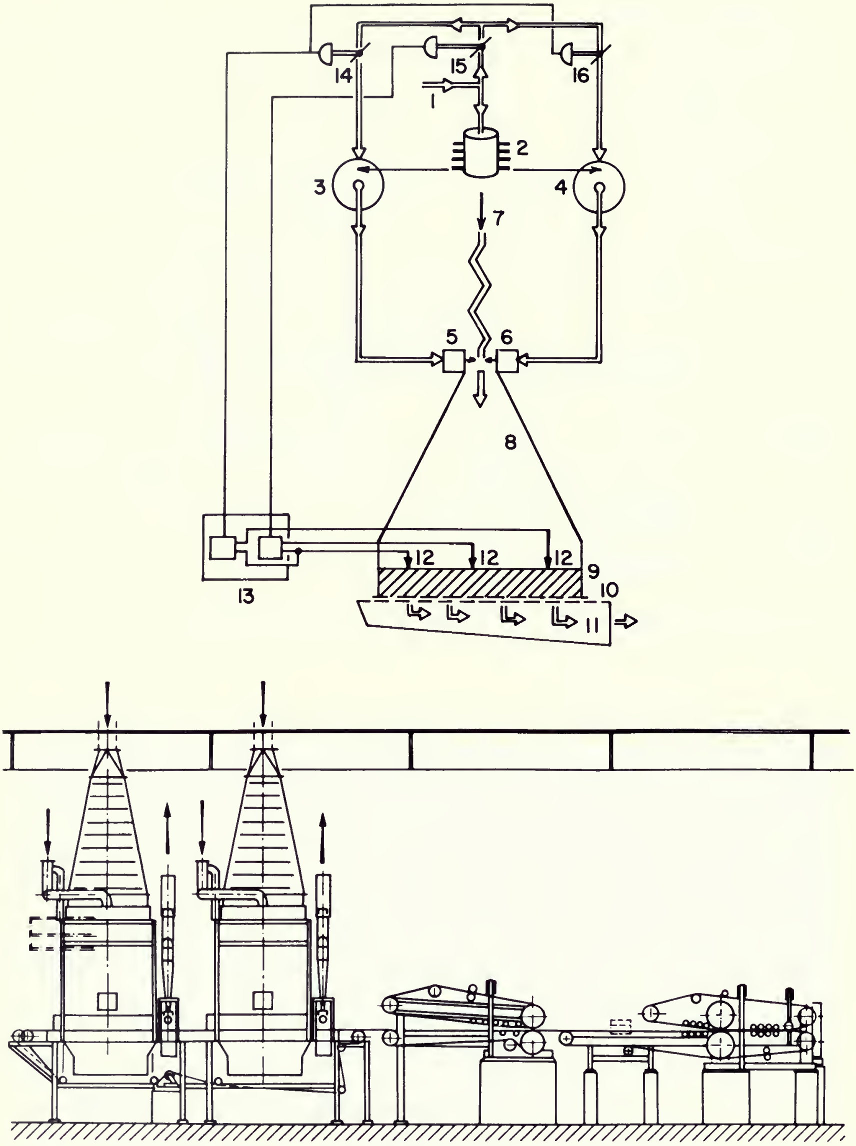


Figure 23-71.—Pendistor former.

(Top)
1. Control-air
2. Rotary valve
3, 4. Eddy-fluidistor
5, 6. Pneumatic chambers
7. Fiber inlet
8. Former
9. Mat
10. Forming screen
11. Suction box
12. Instruments for measuring mat thickness
13. Central control instrument
14, 15, 16. Throttles for air control

(Bottom) Pendistor forming station. Two formers are followed by a two-stage prepress. First press is low-pressure, second is high-pressure bandpress. (Drawing after Carlsson 1978.)

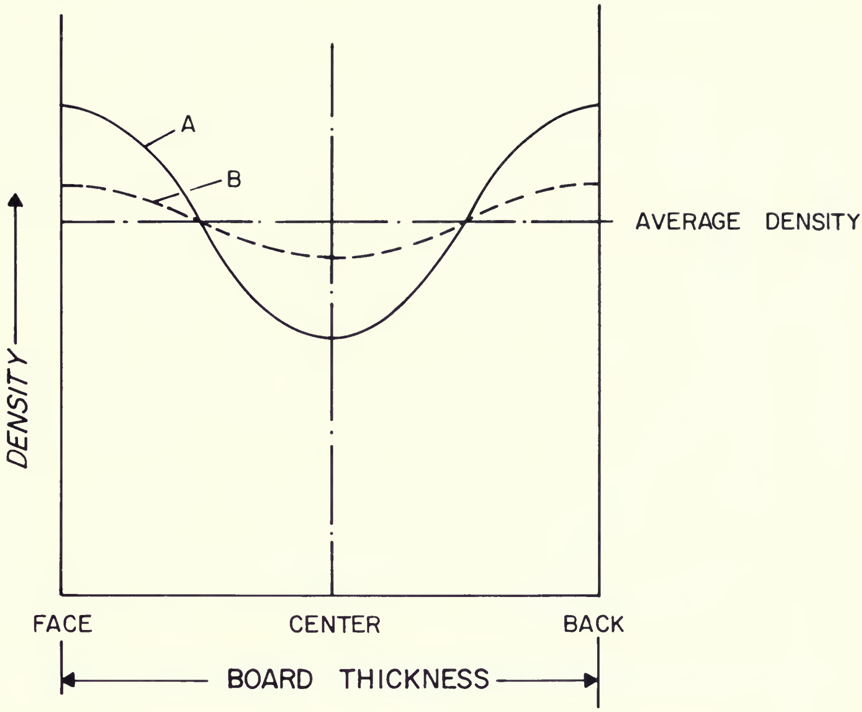


Figure 23-72.—Examples of density distributions over board cross section at constant average board density. (Drawing from Suchsland and Woodson 1985.)

lower bending properties. Board A, with its high-density contrast, would have a relatively porous board edge, poor machinability of the edge, and poor edge screw holding power; board B would have greatly improved edge properties.

The stops or gage bars employed in pressing of all thick medium-density fiberboard can be used to modify density profile. These stops determine density independent of the applied pressure, as long as the applied pressure is sufficient to close the press. Density contrast can be controlled, within certain limits, by controlling the closing time, a function of the applied pressure.

Density contrast in medium-density fiberboard is greatest at short closing time (fig. 23-73), obtained by application of high pressure. Reducing the pressure moderates density contrast until the pressure reached is too low to close the press by the end of the press cycle (point "2"), which in turn is determined by the press temperature and the curing characteristics of the resin.

At short closing times only thin surface layers are heated and therefore weakened before densification is complete, resulting in higher compression of the faces. At long closing times, the entire mat is heated while still under full pressure, and the various layers of the mat reach similar low compression strength levels at one time or another, reaching a more uniform densification and low density contrast.

Increasing the pressure to extreme values causes instantaneous closing of the press with no density contrast at all (point "1"). Here, no heat was transferred to

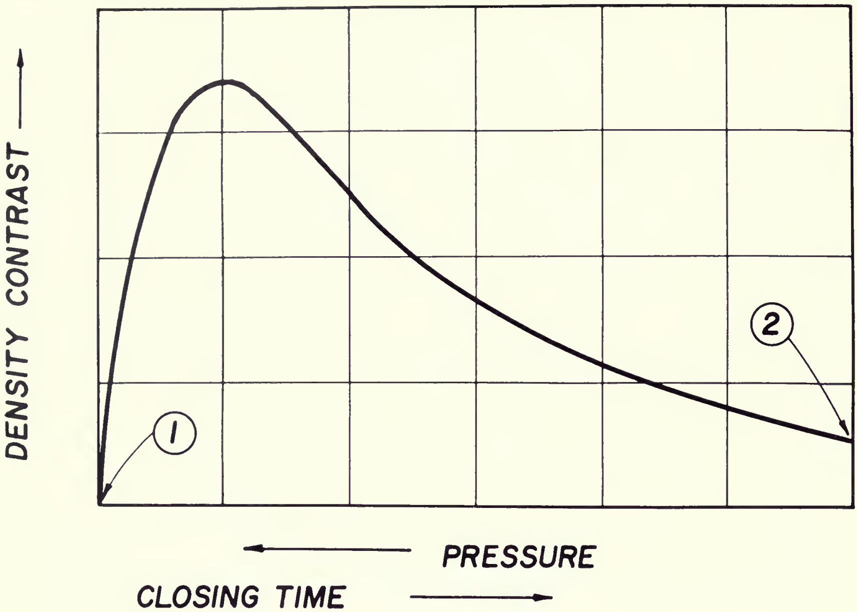


Figure 23-73.—Relationship between pressure or closing time and density contrast over cross section of medium-density fiberboard. (Drawing from Suchsland and Woodson 1974.)

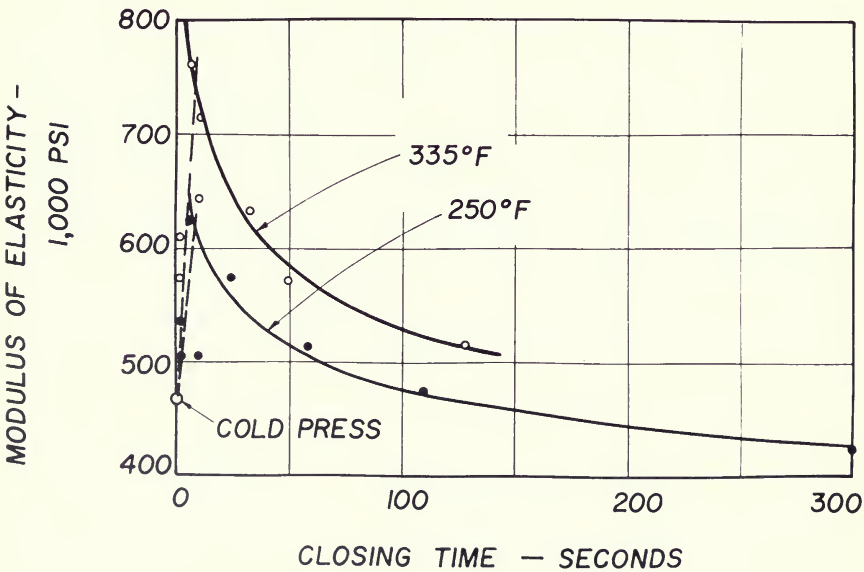


Figure 23-74.—Relationship between press closing time and modulus of elasticity in bending of experimental medium-density fiberboard pressed at two different platen temperatures. (Drawing from Suchsland and Woodson 1974.)

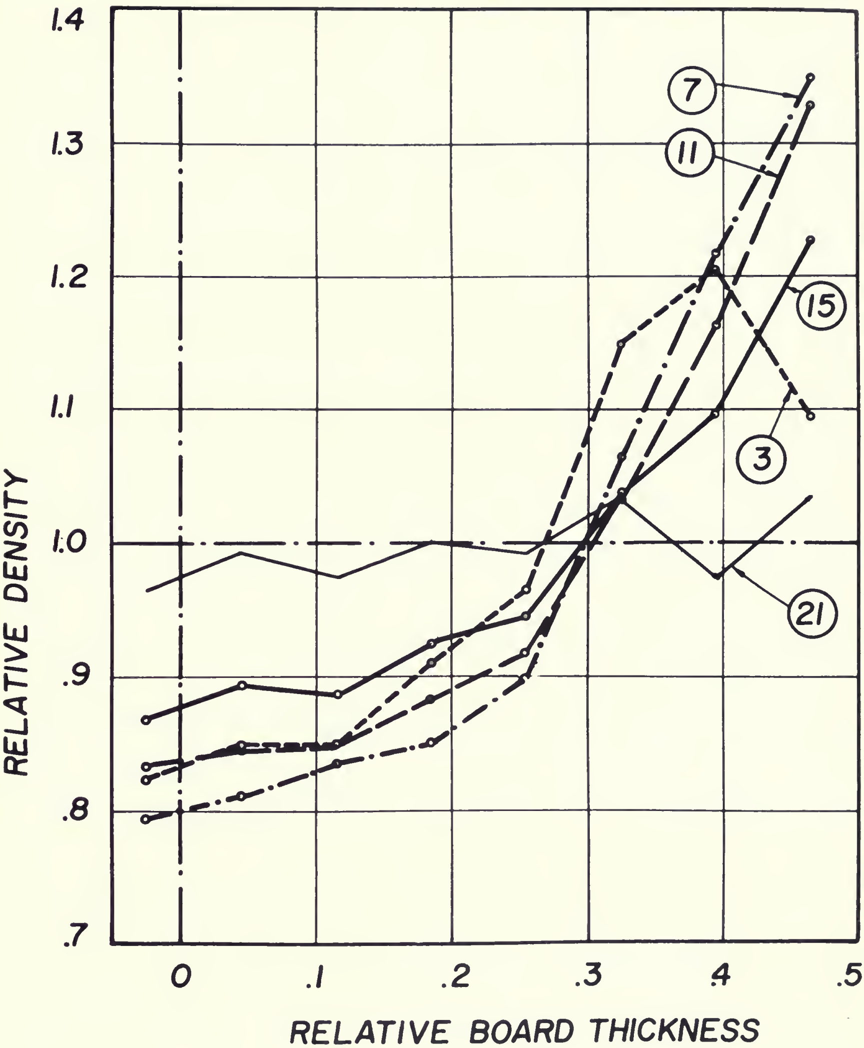


Figure 23-75.—Density profiles of ¾-inch experimental medium-density fiberboards pressed at a platen temperature of 335°F. (Drawing and data from Suchsland and Woodson 1974.)

Board no.	Pre-pressure	Pressure	Closing time
	Psi		Seconds
3	60	240	128
7	60	480	32
11	60	820	10
15	60	1,500	2
21	Pressed in unheated press		

any part of the mat before it was completely densified. This is equivalent to cold pressing, which produces no density contrast.

High press temperatures combined with short closing times yield medium-density fiberboards of high modulus of elasticity (fig. 23-74). Density profiles of some of the boards produced to obtain data for figure 23-74 are plotted in figure 23-75. Cold-pressed boards and those made at longest closing time had lowest densities in surface layers. To achieve reasonable closing times (0.5 to 1.5 minutes), practical pressures on the mat are between 500 and 750 psi. Total press time for a ¾-inch board may be 8 to 10 minutes.

The first medium density fiberboard plant (Deposit, N.Y.) was equipped with a high-frequency press. One of the remarkable properties of this board was its solid edge, ascribed to a lack of density contrast due to high-frequency heating. The uniform temperature rise over the board thickness produced by high-frequency heating favors more even moisture removal and uniform mat compression.

Subsequent investigations (Suchsland and Woodson 1974; Suchsland 1978) and practical experience have indicated that for boards ¾-inch thick or less, these differences are too slight to make the use of high frequency mandatory. There is little doubt, however, about the advantages of high-frequency heating for thicker boards (1 inch or more). About half the present medium-density fiberboard plants use high-frequency heating, while the other half uses either steam or hot water.

In a high-frequency-heated press (fig. 23-76), the electrodes, which can be thin sheets of copper or other conductive material are placed between press platens and mat. An electric field with nominal frequency of ten megacycles is established between the two electrodes causing the mat to heat up. The press

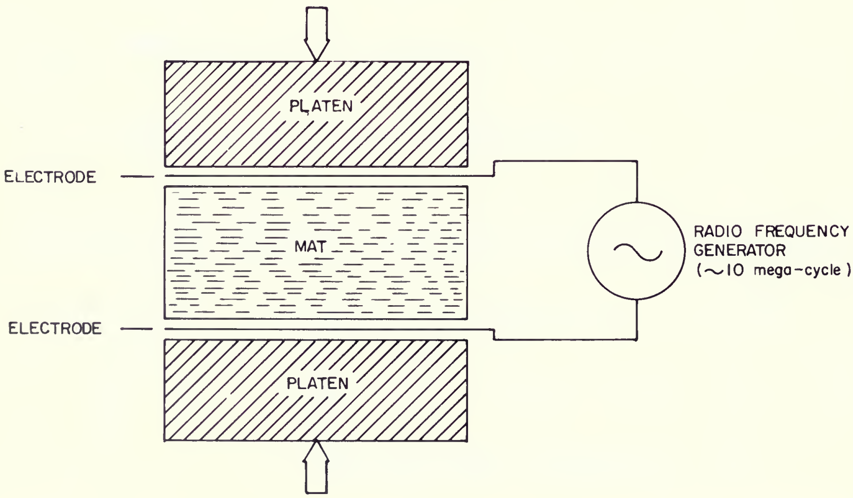


Figure 23-76.—Principle of radio-frequency-heated board press. (Drawing from Suchsland 1978.)

platens themselves are also heated, by steam or hot water, but only to a temperature slightly above 212°F to avoid condensation on the surfaces of the board.

A press size of 5 x 18 feet seems to be particularly suitable for the application of high-frequency heating. The power requirements increase with the number of openings. In one of the newer medium-density fiberboard plants a single-opening high-frequency press 8 feet wide and 65 feet long has been installed. It seems to be generally accepted that the use of high frequency reduces press cycle time and thus increases the output of a given press configuration. Capital costs and operating costs per unit output are higher than in the case of a press heated with either steam or hot water.

CONTINUOUS MENDE PROCESS

The Mende process (fig. 23-77) was developed in Germany and introduced in the United States in 1971 in an attempt to produce thin particleboard on a small scale economically. By 1976 fifty Mende plants were in operation, ten of them in the United States and four in Canada. Most are particleboard plants, but the machine can handle fibers as well. One of the U.S. installations is a fiberboard plant (Louisiana Pacific Corp., Oroville, Calif.)

The heart of the Mende process is the continuous press, comprised of a 10-foot-diameter, heated and rotating drum against which the mat is pressed by a steel band (fig. 23-77 and 23-78). Widths, i.e., drum lengths, available are 4, 5, 6, 7 and 8 feet. After less than one full revolution of the drum, the continuous board leaves the press and is cut to size. As the steel band carrying the mat approaches the press section, it is heated from below by infra-red heaters, which elevate the steel band temperature to about 250°F. Pressure is first applied as the mat passes between entrace roll and press drum (fig. 23-78), both of which are oil heated to a temperature of 355°F. The temperature at the press drum surface is about 300°F. Between entrance roll and heated return roll additional infrared heaters are installed to maintain the temperature of the steel band.

Between return roll and heating drum, pressure on the mat reaches a maximum. This pressure depends on the tension of the steel band, which can be controlled by adjusting the tension roll. As the band bends around the heating drum, it passes two more infrared heaters and two unheated pressure rolls, which press the mat to the final board thickness. As the band turns around the drive roll, the board is fully cured and is returned in the reverse direction over the forming station. The temperature of the board as it leaves the heating drum is 230°F.

Since the heating drum is in direct contact with the mat and therefore forms the surface, protection of the drum surface from scoring is essential. Several rotating brushes clean both drum and steel band. The steel band returns to the forming station via a water-cooled roll, which reduces its temperature to about 150 to 160°F, to prevent curing of the resin before the mat enters the press section.

The heating oil recirculates through a boiler heated by gas or other fuels. Temperature of each drum can be controlled separately. Table 23-8 shows the line speed for various board thicknesses.

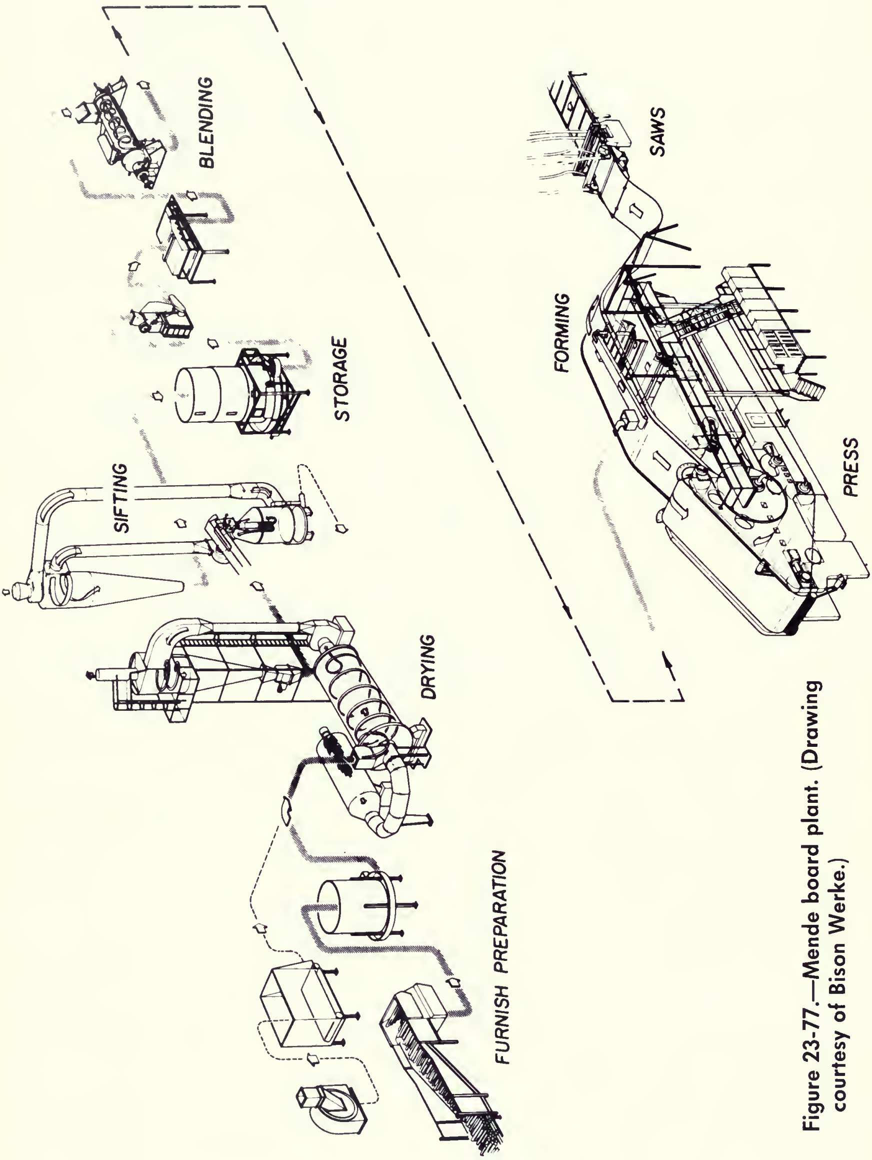


Figure 23-77.—Mende board plant. (Drawing courtesy of Bison Werke.)

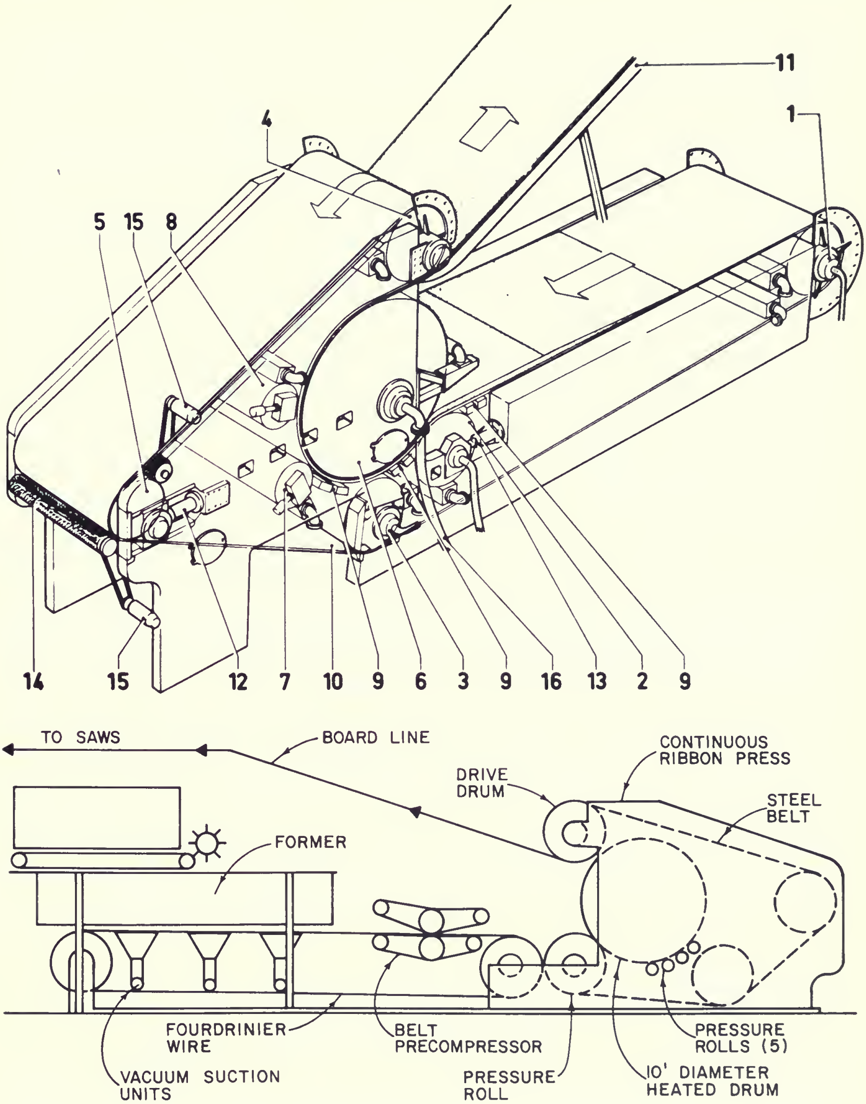


Figure 23-78.—(Top) Continuous Mende press for particleboard. (Drawing courtesy of Bison Werke.)

1. Cooling roll
2. Entrance roll
3. Return roll
4. Drive roll
5. Tension roll
6. Press drum
7. Pressure roll
8. Pressure roll
9. Infrared heaters
10. Steel band
11. Board return guide
12. Hydraulic cylinders for tensioning steel band
13. Hydraulic cylinders for pressure control
14. Cleaning brush
15. Drive for cleaning brush

(Bottom) Mende continuous press arranged to produce fiberboard. (Drawing after Wentworth 1971.)

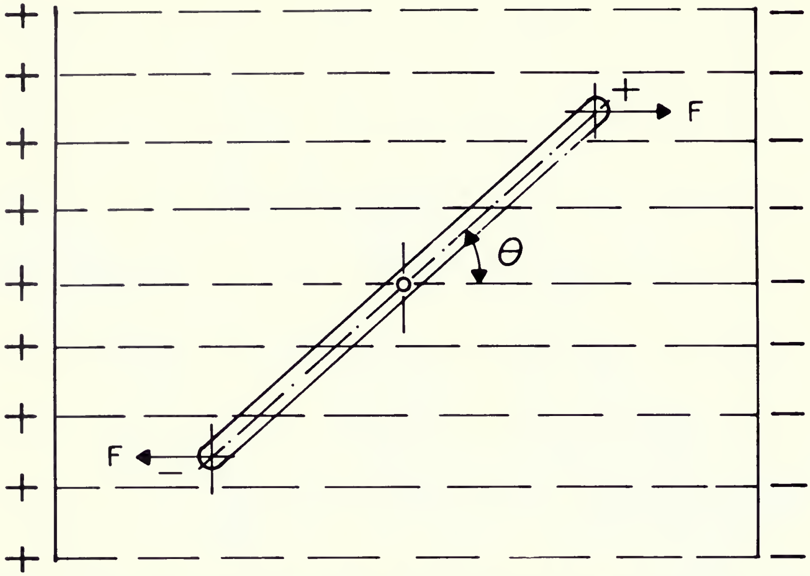


Figure 23-79.—Forces on dipole in electric field. Charge shown on dipole end is net result of minute charge separations occurring throughout the dipole. (Drawing from Suchsland and Woodson 1985).

TABLE 23-8—*Relationship between board thickness and line speed of the Mende continuous board process*[1]

Board thickness (mm/inches)	Line speed	
	Meters/minute	*Feet/minute*
3.0/.118	15.0	49.2
3.2/.126	14.0	45.9
4.2/.165	10.7	35.1
4.8/.189	9.4	30.8
5.6/.220	8.0	26.2
6.3/.248	7.0	22.9

[1]Data from Bison Werke, Springe, Germany; promotional literature.

For manufacture of fiberboard the process requires installation of a vacuum former, replacement of the steel band by a wire screen, and addition of a band prepress (fig. 23-78 bottom). Handling, drying, and blending equipment would be similar to that used in other dry processes.

BOARDS WITH ORIENTED FIBERS

Solid wood is strong in the grain direction due to the parallel alignment of the wood cells in that direction; this alignment also accounts for wood's lower strength properties and greater swelling and shrinking perpendicular to the fiber direction. Most particleboards and fiberboards randomize fiber orientation so that board properties in the plane of the board are the same in all directions. This randomization sacrifices part of the strength associated with aligned fibers, however.

Mechanical orientation of elongated particles and flakes, so that their configuration in the product is similar to that in solid wood, has reached commercial application (Elmendorf 1965; Snodgrass et al. 1973). An **electrical field** can also provide aligning forces to orient small fibers and fiber bundles in manufacturing dry-formed, high- and medium-density fiberboard. A fiber in a uniform electrical field acts like a dipole (fig. 23-79). The force couple acting on the dipole develops a torque tending to rotate the fiber axis to a position parallel to the electric field. The torque is largest at $\theta = 45°$. At angles near 90° the induced charge separation does not occur in the direction of the dipole axis, and at smaller angles the moment arm diminishes. An alternating field has a similar aligning effect when the frequency is low enough to allow a reversal of the charge separation between field changes. Frequencies of less than 100 cycles/second are most effective. Other important variables are the geometry of the particle or fiber, the moisture content and the strength of the field.

Talbott and Logan (1974) described a forming machine in which resin coated fibers having a moisture content of 9 to 15 percent fall through a series of closely-spaced vibrating strings and enter an electric field of 60 cycles/second and 1,500 to 3,750 volts/inch, causing substantial alignment of the descending fibers. The air-fiber mixture moves through the field at about 50 to 100 feet/minute. At the bottom of the forming box the fibers are filtered out of the air stream by a screen. Properties of experimental dry formed aligned fiberboards are shown in figure 23-80.

Industrial application of this method would benefit siding products (reduced linear expansion in the long dimension of the product) and might encourage the use of fiberboard in structural applications.

23-10 HEAT TREATMENT, TEMPERING, AND HUMIDIFICATION

Heat treatment by exposure to dry heat, and **tempering** (heat treatment preceded by adding drying oils to the pressed board) are optional processing steps following hot pressing to improve dimensional stability and to enhance mechanical board properties. These treatments are used only in the manufacture of thin medium- and high-density fiberboards. Insulation board, thick medium-density fiberboard, and particleboard are neither heat treated nor tempered.

Humidification adds water to bring fiberboard moisture content into equilibrium with expected air conditions in service, and follows heat treatment or tempering. In general, heat treating and tempering are more effective on wet-formed than on dry-formed board. Heat-treated, and particularly tempered, boards are substantially more expensive than untreated boards.

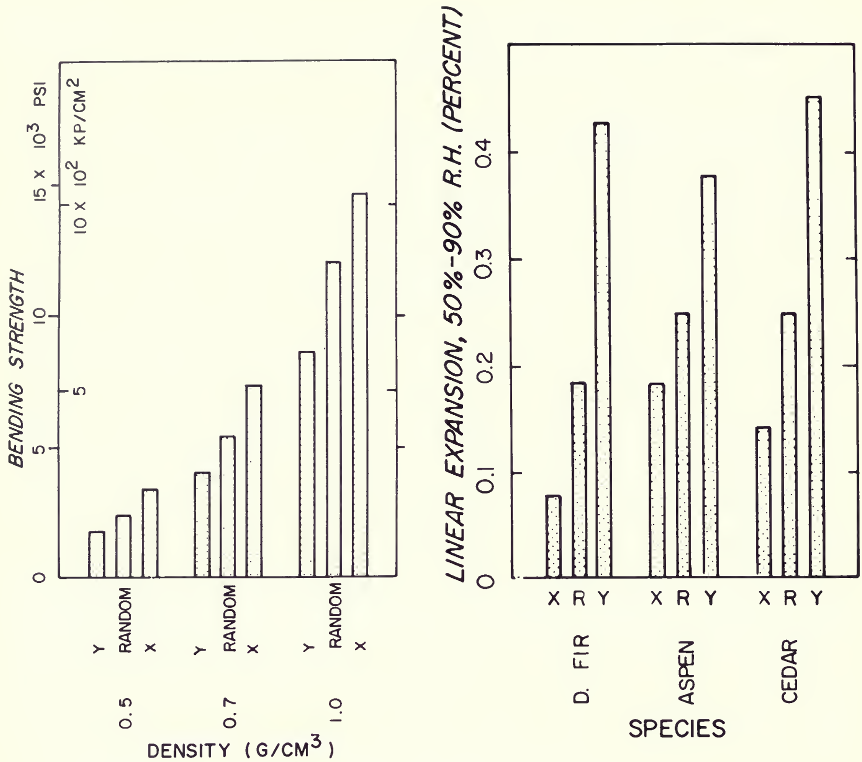


Figure 23-80.—Effect of alignment on properties of fiberboard. Random refers to unaligned boards, x and y refer to alignment of the fibers in the two principal directions of the board. The x direction is parallel to fiber alignment. (Left) Bending strength at three density levels; values are average of three species. (Right) Linear expansion in fiberboards of three species. (Drawings after Talbott 1974.)

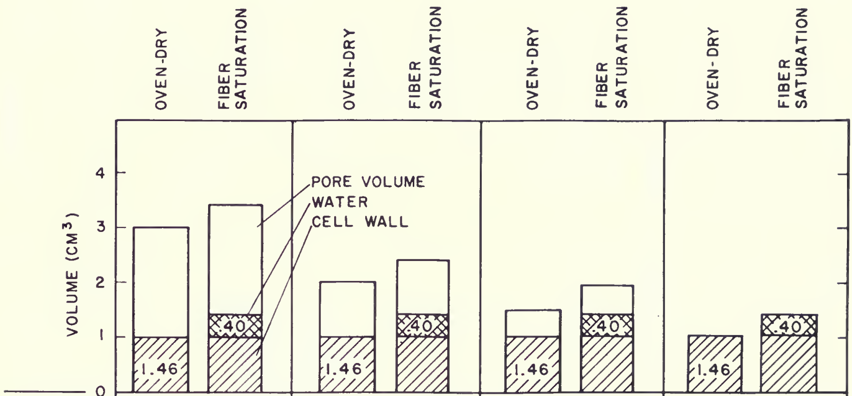
IMPROVEMENT OF BOARD PROPERTIES

Dimensional stabilization.—Reduction of dimensional changes of wood products resulting from adsorption and desorption of water in the cell wall (figs. 8-16, 8-17, and 8-19) is usually desirable, particularly in high-density products. Volumetric expansion of wood approximately equals the volume of water adsorbed by the cell wall. In densified wood products with reduced pore volume, the same amount of water will still be adsorbed under a given exposure condition, resulting in a greater relative volumetric expansion.

This is illustrated in figure 23-81, where 1 cm^3 of cell wall substance (specific gravity 1.46) at 100 percent relative humidity adsorbs 28 percent of its weight in water (1.46 x .28 = 0.40 g). This is the maximum amount of water the cell wall can adsorb. Additional water uptake would fill the pore volume without further swelling. The expansion of the cell wall by 0.4 cm^3 results in different relative volumetric expansion values, depending upon the total volume (cell wall plus pore volume) of the product. In the case of solid wood with a specific gravity of

0.49 (1 part cell wall, 2 parts pore volume) the volumetric expansion is 13 percent; in the case of hardboard with a specific gravity of 0.97 (1 part cell wall, ½-part pore volume), it would be 27 percent, and in the case of a paper with no pore volume at all, the volumetric expansion would be 40 percent.

Densified products, generally, swell in the direction of densification, which in fiberboard is in the direction of board thickness. Swelling in the plane of the board is very small, due to the mutual restraint of the "cross laminated" fibers.



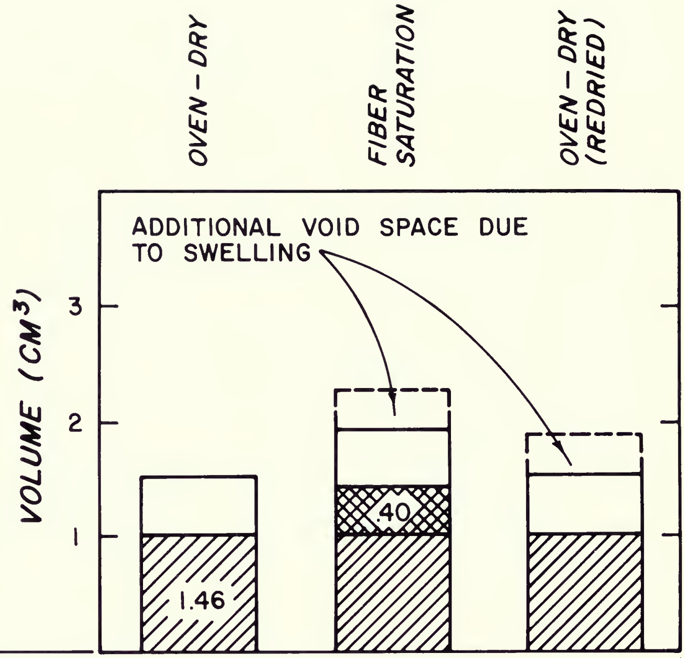
M.C. (%)	0	28	0	28	0	28	0	28
SP. GR.	.49	.43	.73	.58	.97	.77	1.46	1.04
VOL. (CM³)	3.0	3.4	2.0	2.4	1.5	1.9	1.0	1.4
$\frac{\Delta V}{V} \cdot 100$ (%)	–	13	–	20	–	27	–	40
	SOLID WOOD		PARTICLEBOARD		HARDBOARD		PAPER	

Figure 23-81.—Relationship between specific gravity and volumetric swelling of solid wood and densified wood products. (Drawing from Suchsland and Woodson 1985.)

In addition to the increased relative expansion resulting from the reduction of pore volume, densification causes swelling by **springback,** due to swelling forces causing partial failures of bonds between fibers, and creating additional void space. Part or all of this additional void space created during the swelling process is permanent and will not disappear upon redrying of the board (figs. 23-82 and 23-83). This adds substantially to the swelling of densified board such as particleboard and hardboard and is often accompanied by a permanent strength reduction.

Heat treatment reduces swelling in two ways; it reduces water absorption by the cell wall and helps resist the creation of voids during swelling by improving fiber bonds. High temperatures are more effective than low (fig. 23-84).

Linear expansion, i.e., the dimensional changes in the plane of the board upon moisture content change, and its modification are more complicated. Figure 23-85 shows the linear changes of a wet-process hardboard being exposed to a



	OVEN-DRY	FIBER SATURATION	OVEN-DRY (REDRIED)
M.C. (%)	0	28	0
SP. GR.	.97	.65	.80
VOL. (CM^3)	1.50	2.33	1.83
$\frac{\Delta V}{V} \cdot 100$ (%)	–	49	22
		HARDBOARD	

Figure 23-82.—Effect of *springback* on volumetric swelling of hardboard. (Drawing from Suchsland and Woodson 1985.)

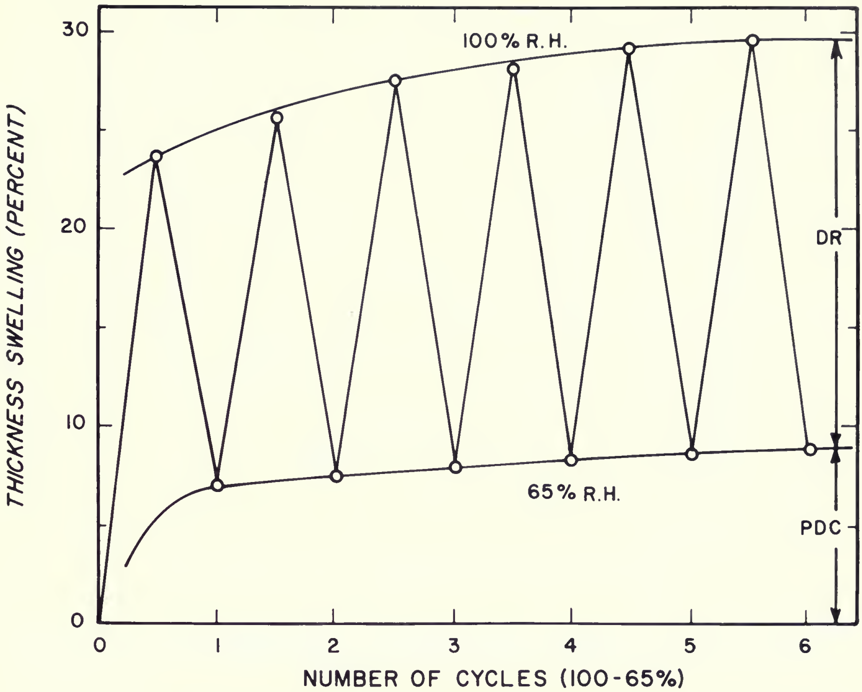


Figure 23-83.—Dimensional range (DR) and permanent dimensional change (PDC) in thickness swelling of wet-formed hardboard during cyclic exposure. PDC is equivalent to *springback*. (Drawing after Klinga and Back 1964.)

sequence of relative humidity cycles before and after a 2½-hour heat treatment at 190°C (375°F). While there is a net contraction of board dimensions as a result of the heat treatment, the actual dimensional changes between 30- and 100-percent relative humidity exposure have actually increased somewhat, whereas the component corresponding to the 65- to 90-percent relative humidity interval has been reduced.

Heat stabilization was at first believed to result from a cross-linking reaction in which water is eliminated between hydroxyl groups on two adjacent cellulose chains, with the formation of ether linkages. This has been disproved (Seborg et al. 1953), and Stamm (1964) has proposed that initial thermal degradation of wood results in furfural polymers of breakdown sugars, which are less hygroscopic than the hemicellulose from which they are formed. Spalt (1977) concluded that wax added to fiberboard furnish is redistributed during heat treatment, forming a monomolecular film on all fiber surfaces and increasing water repellency. Other theories ascribe the reduction of both the total swelling and of the permanent expansion component to cross linking between cellulose molecules by acetyl groups (Klinga and Back 1964).

The effect of tempering on dimensional changes is limited because the modern tempering process applies rather small quantities of oil to board surfaces only. Any reduction in water absorption and increase in strength properties is largely due to the heat treatment following application of tempering oil.

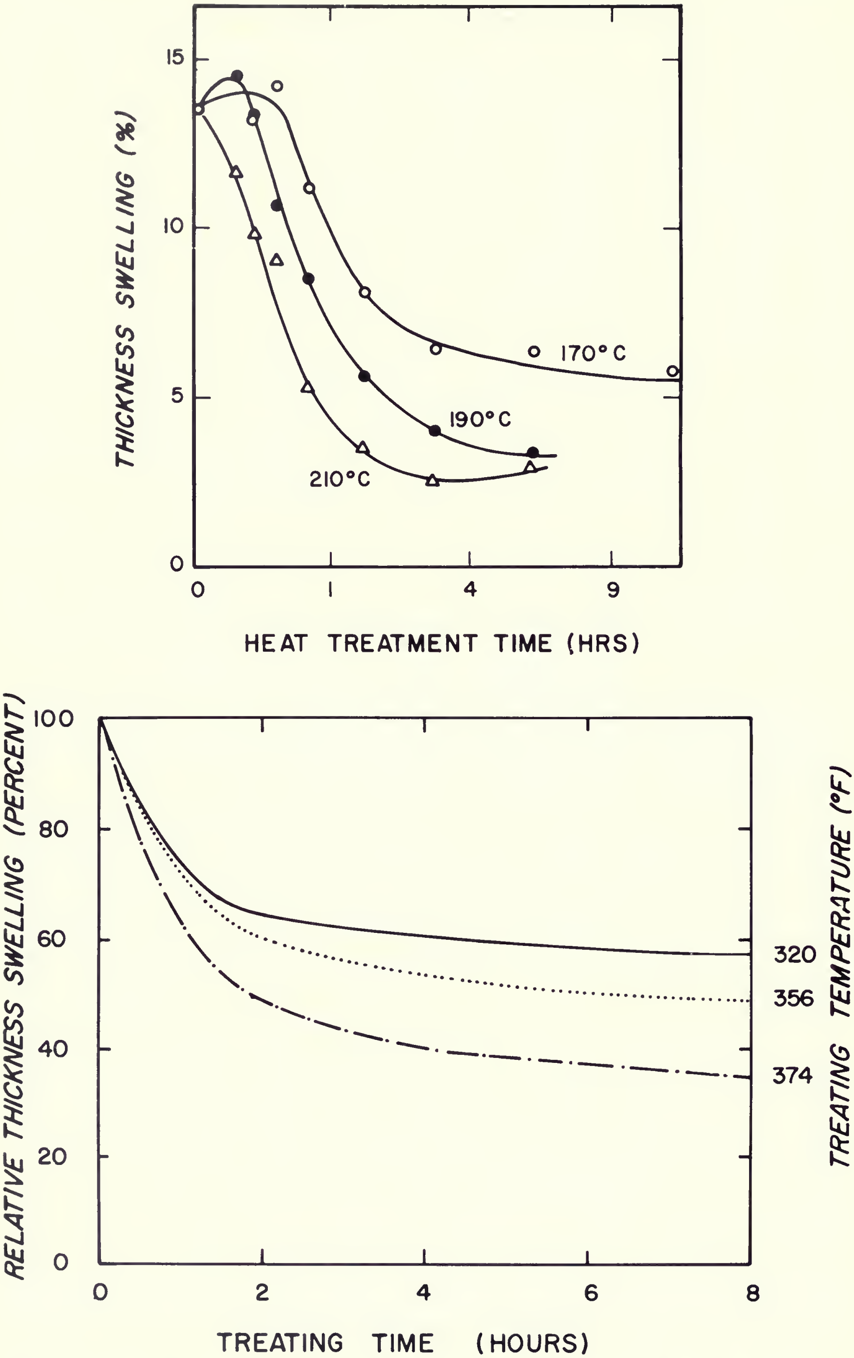


Figure 23-84.—Reduction of thickness swelling in hardboard after heat treatment at various temperatures and times. (Top) Percent expansion; drawing after Klinga and Back (1964). (Bottom) Relative thickness swelling in ⅛-inch hardboard related to that for no heat treatment; drawing after Brauns and Strand (1958).

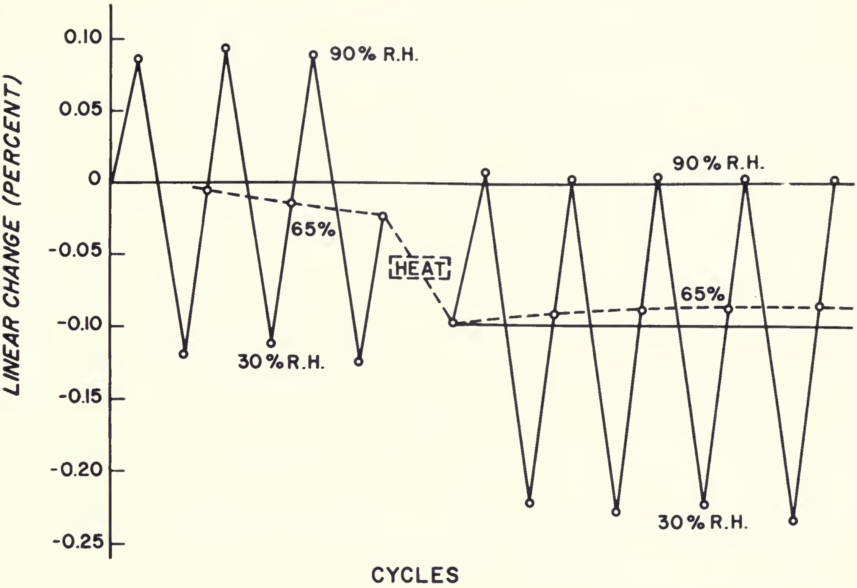


Figure 23-85.—Linear changes in response to cyclic exposure of ⅛-inch hardboard before and after heat treatment at 375°F for 2½ hours. (Drawings after Klinga and Back 1964.)

Improvement of strength properties.—Heat treatment improves mechanical properties by continuation of the bonding process started in the hot press. Figure 23-86 shows the hypothetical development of fiber bonding in the hot press and the simultaneous deterioration of the fiber strength. At the end of the press cycle the board has sufficient strength to maintain the target caliper after pressure release. The process of bond formation may continue during subsequent heat treatment even while fiber strength deteriorates from thermal degradation. The strength properties of the board will thus rise until the fiber becomes the weak link in the system. This explains the characteristic relationship between treating temperature, heating time, and board strength (figs. 23-87 and 23-88). Figure 23-89 shows the concurrent weight loss.

Oil tempering contributes little to most strength properties with the exception of bending stiffness and bending strength, properties very sensitive to surface quality improvement, particularly where both surfaces are coated, which is the practice in S2S manufacture. It substantially improves surface hardness, however, which is of great importance in premium quality factory finished wall panels.

The importance of tempering and heat treatment is reflected in the Commercial Standard for Basic Hardboard (U.S. Department of Commerce 1973a). Of five classes of hardboard, two are designated as "tempered" hardboard (table 23-9).

TABLE 23-9.—*Classification of hardboard in the Commercial Standard for Basic Hardboard—abbreviated*[1] (U.S. Department of Commerce 1973a)

Class and surface	Thickness
	Inches
1. Tempered	
S1S	½
S1S and S2S	1/10 to 3/8
2. Standard	
S1S and S2S	1/12 to ⅜
3. Service tempered	
S1S and S2S	⅛ to ⅜
4. Service	
S1S and S2S	⅛ to ½
S2S	⅝ to 1⅛
5. Industrialite	
S1S and S2S	⅜ to ½
S2S	⅝ to 1⅛

[1]See table 23-10 for thickness, water resistance, and mechanical properties.

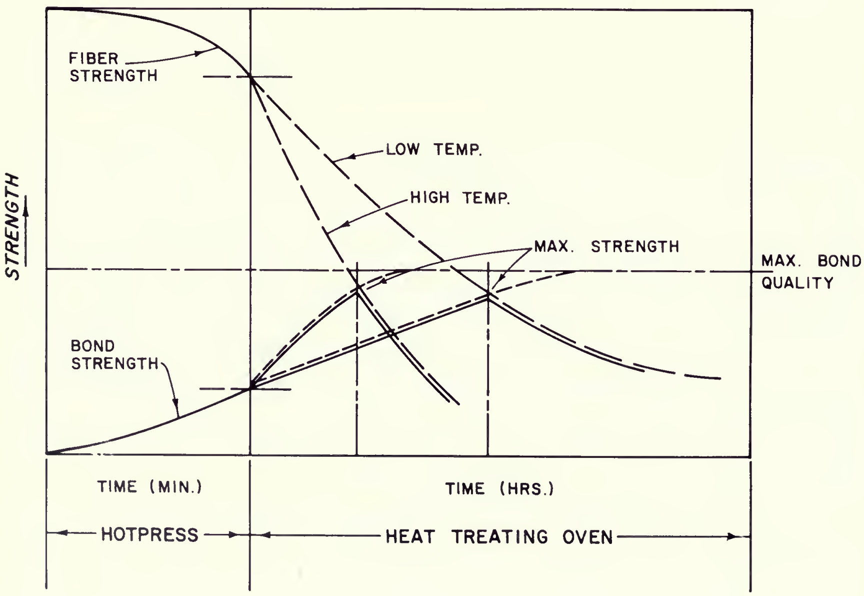


Figure 23-86.—Hypothetical development of board strength as affected by changing bond strength and fiber strength during pressing and heat treating. (Drawing from Suchsland and Woodson 1985.)

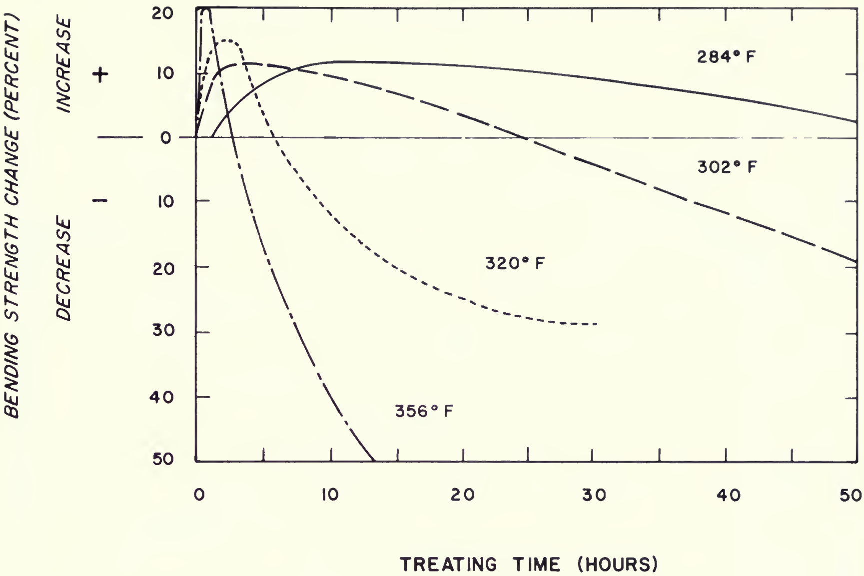


Figure 23-87.—Bending strength of ⅛-inch hardboard as affected by temperature and treating time. (Drawing after Voss 1952.)

INDUSTRIAL PRACTICES

A large percentage of all hardboard is heat treated, but tempering is limited to products where its benefits are essential. In some plants, all boards go through the heat treating line. Only a few small plants have no heat treating facilities.

Abitibi Corp. and U.S. Gypsum Co. temper about 80 percent of their S2S-wet-formed hardboard which is prefinished for use as interior wall paneling. Tempering provides improved paint hold-out, high abrasion, scratch and scar resistance, and general wear quality. Tempering also increases surface water resistance, which is very important for hardboard used to enclose showers, for instance. Most S2S boards are tempered on both surfaces.

A very much smaller percentage of S1S board is tempered. Siding is generally not tempered. Unfinished board used as drawer bottoms, furniture backs, and similar applications, is generally not tempered.

Tempering.—Oil tempering was patented by the Masonite Corp.; its objective was to substantially improve board properties by forcing considerable oil into the pressed hardboard. This was done by soaking the hot boards in heated oils for periods up to ½-hour. Most common is linseed oil, but soybean oil, tung oil, and tall oil are also used. Synthetic resins are sometimes blended with the oils. Quantities of oil absorbed by soaking are about 6 percent by weight, which for a 4- by 8-foot, ⅛-inch board with specific gravity of 1.0 would be equivalent 1.25 pounds of oil.

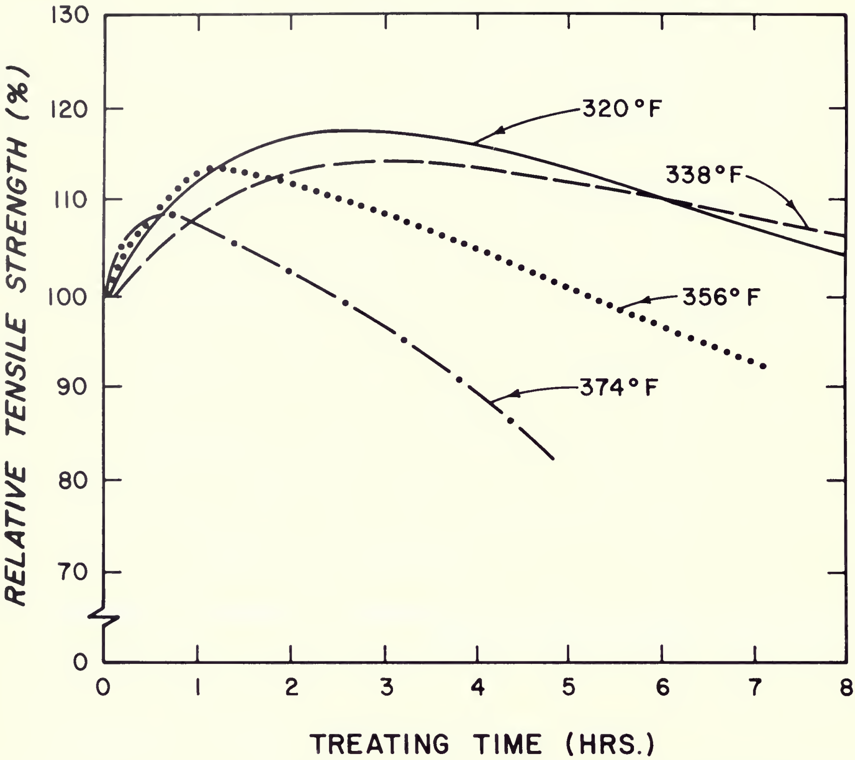


Figure 23-88.—Tensile strength of ⅛-inch hardboard as affected by temperature and treating time. (Drawing after Brauns and Strand 1958.)

Today oil is applied to one or both sides of the board by direct roll coaters or, in certain cases, precision roll coaters. In an **ordinary direct roll coater** (fig. 23-90) oil is fed into the nip between a rubber contact roll and a steel doctor roll, the amount applied being controlled by the gap between them. The contact roll also feeds the board through the machine.

The **precision roll coater** works like an off-set printer. An embossed steel roll transfers to the rubber contact roll a precise amount of oil, the amount being determined by the depth of the embossed pattern. Precision roll coaters can apply as little as 1½ ounce per 4- by 8-foot sheet. They are also used to temper embossed panels, where they will cover only the top of the embossed pattern without applying oil to the low spots.

The oil, whether applied by soaking or coating, is immediately oxidized in heating ovens which are also used to bake oil-treated boards and for heat treating boards without oil treatment.

Other uses of oil include the addition of drying oil to the furnish as described in section 23-7. The oil serves the same purpose as it does in the regular tempering process; it dries by oxidation and forms a thin hard layer on fiber surfaces, thereby improving inter-fiber bonding. Tempering oil is also used in

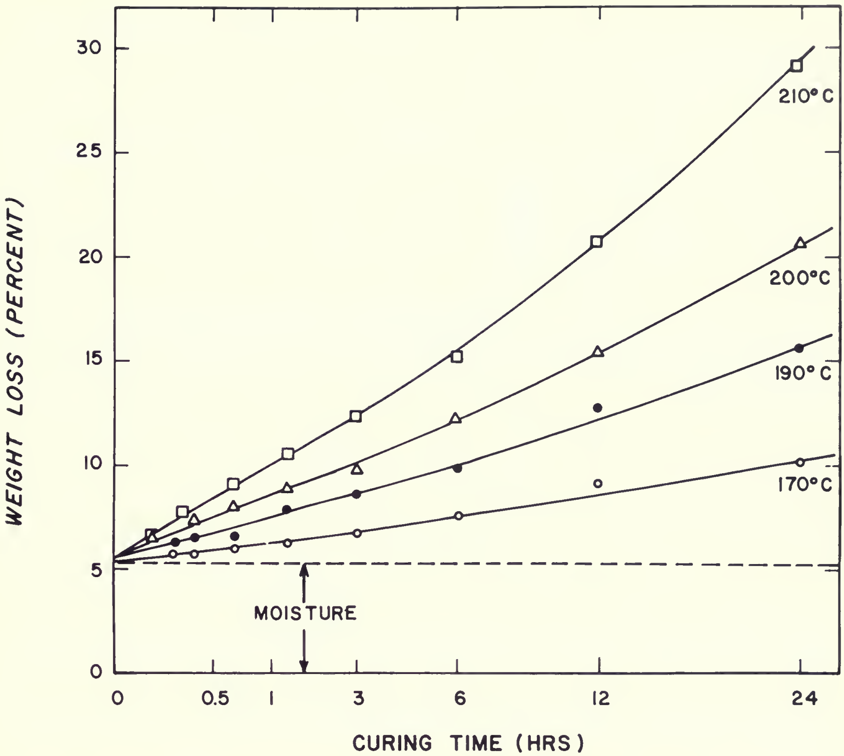


Figure 23-89.—Weight loss of ⅛-inch hardboard during heat (curing) treatment at various temperatures. (Drawing after Back and Klinga 1963.)

the manufacture of paper overlaid hardboard as described in section 23-8. The oil is applied to the back of the printed paper after which the paper is positioned on the wet mat. The oil reinforces the paper structure and bonds the paper to the mat.

Heat treating.—Heat treating of hardboard, oil treated or not, requires a board temperature of about 300°F. Close temperature and exposure time control is critical for two reasons. First, hardboard and especially the lower-density boards can ignite at temperatures of 300°F; second, heat treatment causes exothermic reactions, particularly in tempered hardboard. These reactions may raise the board temperature above oven temperature greatly increasing the fire danger.

Hot boards direct from the press are air-cooled prior to entering the heat treatment oven to limit board temperatures in the oven. Board temperatures are brought up to 300°F slowly and the heat of reaction is removed from the boards by circulating the air at high velocities (750 to 1,000 feet/minute).

Heat-treating ovens may be continuous, progressive, or of batch type. Continuous ovens provide a means of transporting the boards through the oven at a uniform speed. Boards can be suspended, supported on edge by pickets mounted

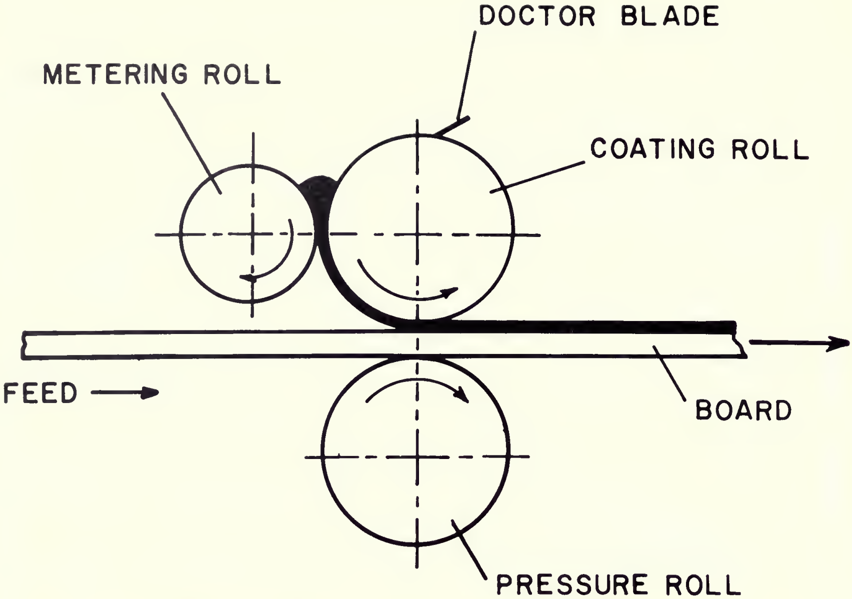


Figure 23-90.—Direct roll coater. (Drawing from Suchsland and Woodson 1985.)

on endless chains, or they can be moved by roller drives as in insulation board dryers.

In the progressive type or tunnel oven, boards travel on trucks or buggies, positioned either vertically on edge or horizontally, and separated by spacers. As one truck enters the oven another leaves it at the other end. Trucks travel on tracks and are either pushed by hand or moved intermittently by chain or hydraulic drives.

In the batch process, the oven is charged with loaded trucks or buggies, and the entire charge is treated together and then removed simultaneously. Heat treating time is about 3 hours.

Treating ovens can be coupled directly with the press, in which case the capacity and the length of the oven must be so designed that the output of the press can be accommodated continuously without interruption. With intermediate storage, the heat treating operation can be made independent of the press output.

Heat treating of tempered boards causes release of volatiles from the oil, which are considered air pollutants. In some states fume incinerators are mandatory on tempering ovens, encouraging limitation of oil quantities to surface treatments and to boards that benefit from the specific charcteristics of oil treatment. Heating ovens must be equipped with deluge systems which will flood the boards in the event of a fire. The water spray units are so arranged that the spray is directed into the spaces between boards.

Humidification.—Pressed hardboard, whether heat treated, tempered or untreated has a moisture content of essentially zero percent. In service hardboard will equilibrate with the surrounding air, which for the practical range of relative humidities is a moisture content between 3 and 10 percent (fig. 23-91). Such moisture changes cause linear expansion, which can buckle wall panels or siding, and when abrupt can bow, twist, and otherwise distort unrestrained sheets. Controlled preconditioning of the board to a moisture content midway in the range of expected service conditions minimizes buckling and other difficulties related to moisture content changes.

Humidification of hardboard is therefore standard procedure. The most common types of humidifiers are continuous- or progressive-type chambers following, and often integrated with, the heating oven. A wicket-type humidifer is diagrammed in figure 23-92.

A humidifier is like a dry kiln operated in reverse; high-humidity air is forced through the stacks of hardboard where it will give up some of its water vapor to the boards. (See fig. 23-93.) The air is then heated over steam coils, moisture is added by steam spray, and the air is cooled almost to saturation by water spray. The entire process is regulated by a dry- and wet-bulb controller.

Air conditions in the humidifier are limited by the danger of condensation which is destructive because the condensate is corrosive. Temperatures and relative humidities are, therefore moderate (140°F and 70 to 80 percent relative humidity). Higher temperatures and relative humidities would increase the moisture transfer rate but would require extremely well insulated chambers. Liquid water collecting on board surfaces causes water spots. Humidification cycles vary between 6 and 9 hours, depending on board thickness.

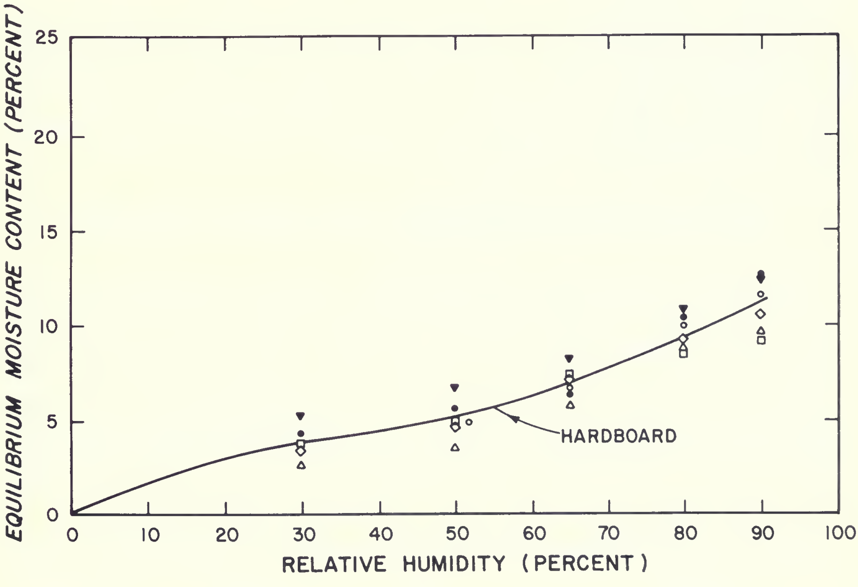


Figure 23-91.—Equilibrium moisture content of ¼-inch tempered hardboard manufactured by various manufacturers. (Drawing after McNatt 1974.)

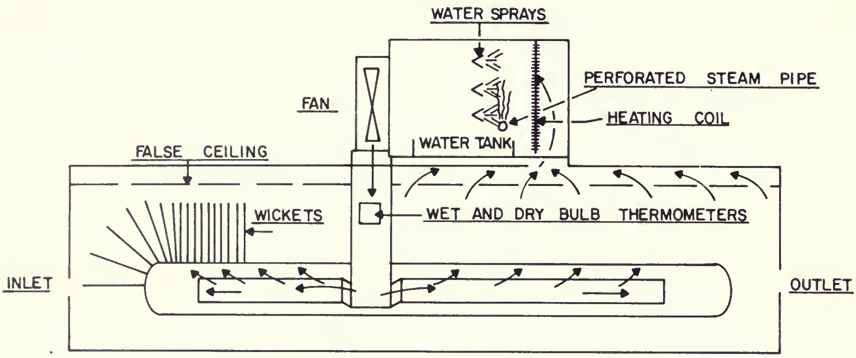


Figure 23-92.—Wicket-type continuous humidifier. (Drawing after Wehrle 1957.)

Other methods of humidification include the spraying of water on the back side of the board, followed by stacking (back to back), the application of vacuum to force moist air through the board, and the application of liquid water by roll coater followed by surface heating through contact rolls which causes dispersion of the water throughout the board.

23-11 FABRICATING AND FINISHING

Cutting fiberboards from the dimensions at which they are pressed to product dimensions, and laminating, scoring, and punching them is called **fabricating.** Fabrication of medium-density fiberboard is generally limited to cutting to size.

Very little hardboard and insulation-board, however, is sold as "brown board" in standard-size sheets. Most boards are extensively fabricated and **finished** to make products ready for installation. Many manufacturing lines produce exclusively interior paneling, or tileboard, or siding. This specialization influences raw material selection and pulping procedure.

INSULATION BOARD FABRICATING AND FINISHING

Figure 23-94 schematically represents the fabricating and finishing department of an insulation board plant producing single-thickness or laminated products, painted or asphalt coated. Such production lines are designed for great flexibility, permitting inclusion or omission of laminating, edge and surface machining, and finishing. As the first- and second-pass trim saws are coupled directly to the dryer, emergency storage is provided after these saws adequate for about one hour's production. For a description of the trim saws see paragraph *Two-pass tenoners* in sect. 18-20, fig. 18-224, and related discussion.

Dyer's (1960) description of the rest of the operation diagrammed in figure 23-94 is summarized as follows. To laminate boards following trimming, they

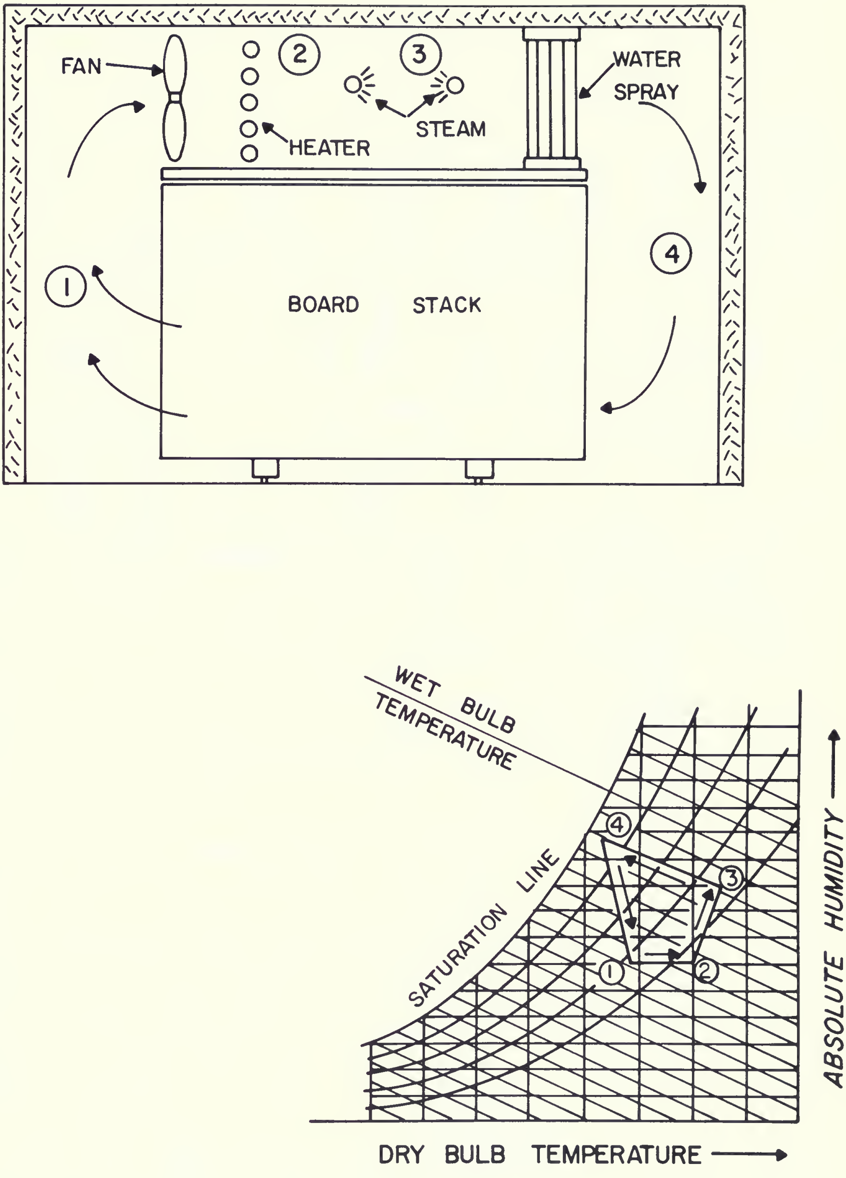


Figure 23-93.—Fiberboard humidification chamber. (Top) Air circulation. (Bottom) Humidifying process graphed on a psychometric chart. (Drawing after Vranizan 1968.)

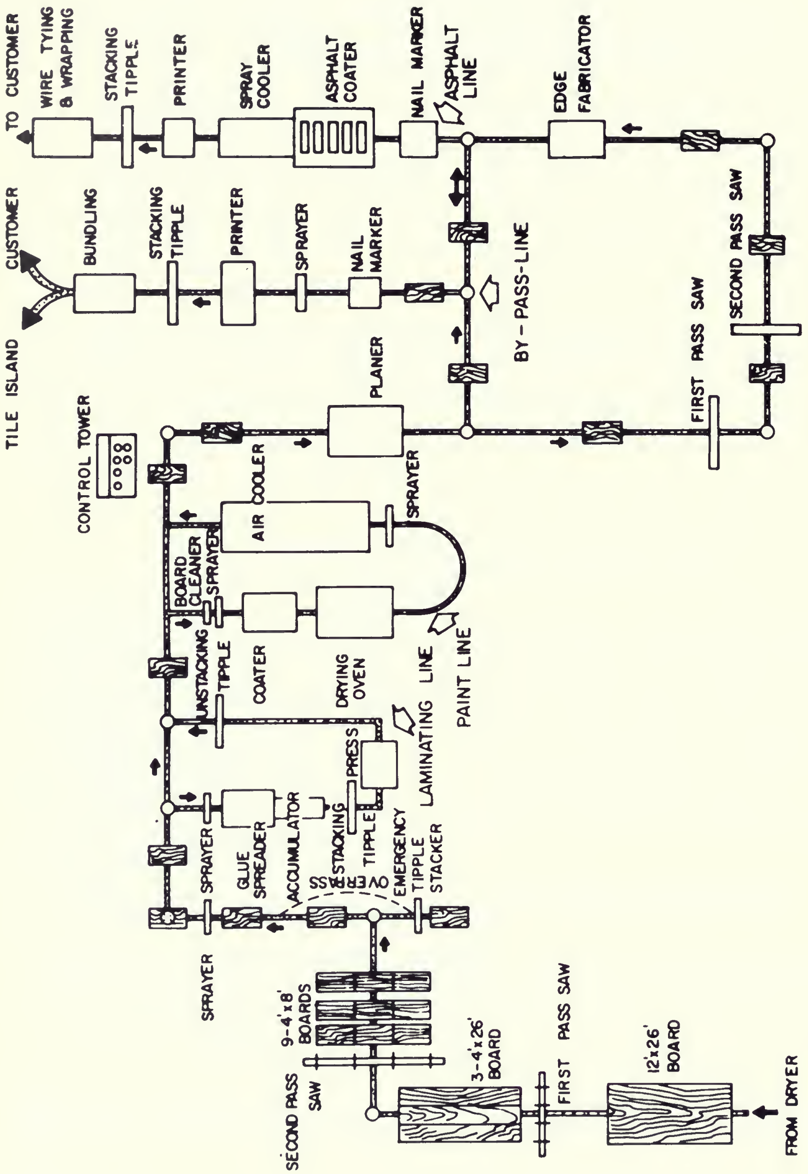


Figure 23-94.—Fabrication and finishing line in an insulation board plant. (Drawing after Dyer 1960.)

are water sprayed to increase moisture content 1 or 2 percent, spread with a quick setting glue to form sandwiches of desired thickness, pressed in a 50-inch-high pile of sandwichs, and unstacked. In the coating line following, boards are cleaned, water sprayed to equalize surface moisture, curtain coated, ovendried at 500°F for 30 seconds, and cooled. Coated boards then pass through a bottom-head planer. Those routed to the **asphalt line** pass through a roll coater which smoothly applies hot asphalt to both surfaces and all edges, and then through hot rolls (450-500°F) to "strike" the asphalt into the panels. Trademarked and bundled asphalt-coated panels are then warehoused. Painted panels for fabrication into ceiling tile are sanded on the unpainted side, sawn to tile size, drilled, edge machined, roll printed, dried, boxed, and palletized (Dyer 1960).

Acoustic tile is manufactured in ½-, ⅝-, and 1-inch thickness—the latter laminated. Holes in acoustic tile are either drilled or punched about ⅞ths of tile thickness.

Roof insulation is produced ½-inch thick and in thickness multiples of ½-inch; it is usually imbedded in hot asphalt or pitch on roof decks.

Asphalt impregnated sheathing is ½- or 25/32-inch thick, the latter laminated. Panels 4 by 8 feet and larger have square-cut edges for butt jointing; 2- by 8-foot panels have a V-joint on the long edge to form a tongue-and-groove joint.

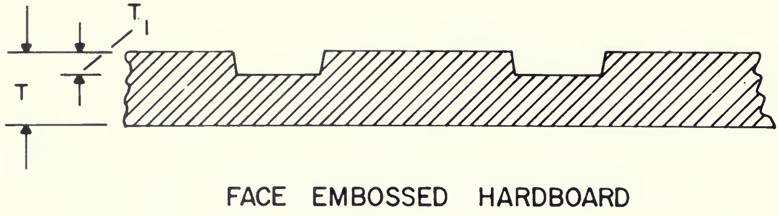
Embossing.—Decorative patterns can be embossed by passing surface-wetted boards under a profiled hot roll (500°F). The hot roll boils the water on contact, softening the board as the pattern is pressed into its surface. Smooth hot rolls are similarly used to iron (flatten) surfaces. Bevels cut in decorative insulation board are immediately wetted with paint and ironed with a hot shoe. Embossing and ironing are followed by another application of paint, usually water-based, and white.

HARDBOARD FABRICATING

Sanding.—Hardboard printing lines cannot tolerate thickness variations of more than 0.010 to 0.015 inch; hardboard for some furniture applications and for garage door panels also must be accurately thicknessed to fit grooves machined in wood rails. Thickness of S2S wet-formed boards is normally accurate enough for these purposes, but S1S panels must generally be back sanded to thickness. Sanding of dry-process boards not only thicknesses them, but also improves their printability.

Single-head, wide-belt sanders carrying abrasive grits of 24 to 36 may be located after board humidifiers and before panel trimmers. An open-grit abrasive belt of these grits will sand 40,000 to 50,000 panels. To improve surface quality with little stock removal some finishing lines use 320-400 grit. (See sect. 18-14 for further discussion of abrasive machining; see also fig. 18-137 for illustration of a wide planer with solid carbide knives sometimes employed to thickness hardboard.)

Trimming.—First-pass trimming of hardboard typically yields standard-width boards (4- or 5-feet wide). S2S boards may show chipped edges unless rounded by cutterheads following the trim saws. Shallow grooves may be machined the length of each panel to give a random-width plank effect and to



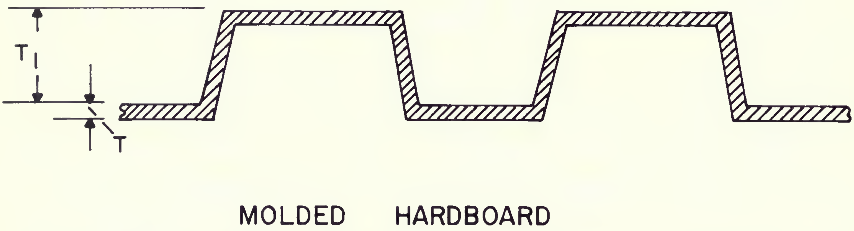


Figure 23-95.—(Top) Face embossed hardboard. (Bottom) Molded hardboard. (Drawing from Suchsland and Woodson 1985.)

indicate standard wall stud spacing of 16 inches. The score marks can be machined with saws or fixed scoring knives. From the first-pass trimmer, boards are transferred to a cross trimmer which cuts panels to length. Such a trimmer combination might process 7,000 4- by 16-foot panels in 8 hours. End saws (with breaker heads to hog trim waste) might typically last 40,000 to 50,000 cuts before dulling; center saws, cutterheads for rounding edges, and scoring saws must be exchanged every 4,000 or 5,000 cuts.

Punching.—Perforated hardboard (pegboard) is manufactured ⅛-inch thick with 3/16-inch holes, and ¼-inch thick with 9/32-inch-diameter holes, for use with matching hooks designed to support tools and other hardware in verical array. The holes are sheared by overhead cylindrical punches moving through holes in an upper clamp plate into bushings in a bed plate below the board. The withdrawal (up) stroke requires more power than the cutting stroke, tends to pull boards up, and to cause deformations of top board surfaces adjacent to holes. The decorative side of the hardboard is therefore turned down in the punch press.

Face embossing.—Embossing, in which certain portions of the mat are compressed more than others to simulate textures such as sawn or weathered wood and stone or brick walls, is accomplished during hot pressing by use of a profiled top caul (fig. 23-95 top). Depth of face embossing is limited by a maximum density under the embossed portion of the board (65 to 70 pounds/cu ft) above which blistering will occur. For wear resistance, low-density portions of embossed boards should weigh at least 40 to 41 pounds/cu ft. Embossing patterns on ¼-inch-thick hardboard typically do not exceed a 1/10-inch; on ⅛-inch boards patterns are shallower. Embossed boards are generally surface tempered and then sanded on the back side to assure thickness control. Some embossed boards are overlaid with printed paper mated to the textured surface; most, however, are printed only on the high spots.

Molding.—Dry-formed fiber mats can be molded during pressing (fig. 23-95 bottom) into corrugated panels or into door surfaces that simulate frame and panel construction. Flat sheets formed either wet or dry can be molded after pressing, but to a much lesser depth of draw.

HARDBOARD FINISHING

Finishing is a significant, capital- and energy-intensive phase of manufacturing hardboard siding, decorative board, and paneling. The ratio of finished to unfinished board can be as high as 9 to 1 in some operations. The finishing department may be an extension of the board manufacturing process, or independent and serving more than one board manufacturing plant. Categories of finished hardboard products are as follows:

- **Interior paneling** is typically printed with wood grain and grooved for plank appearance, or embossed and painted to simulate brick or stone walls. The substrate is usually ¼-inch S1S board with specific gravity of about 0.73. The ¼-inch thickness provides stiffness needed when the panels are mounted directly on 2- by 4-inch stud walls without the added support of gypsum-board dry wall. Wall paneling ⅛-inch thick is made at higher densities.
- **Decorative board** is paneling—normally not grooved—finished in solid colors or printed with designs other than wood grain. Such paneling includes vinyl overlaid boards with wall paper appearance, and tile boards—the latter used on bathroom walls and as shower enclosures, a demanding application. Light solid colors and high-gloss surfaces preclude use of S1S substrates because their screen backs release particles onto the wet finish; S2S substrates are therefore used. A board thickness of ⅛-inch is sufficient, since decorative boards are generally applied over gypsum dry wall.
- **Siding** is manufactured for application as panels or as lap siding. It can be smooth, or embossed to simulate rough-cut lumber. Siding boards are 7/16-inch thick and of relatively low density (about 1,500 pounds per thousand square feet). Both S1S and S2S hardboards are used.

Embossed boards for paneling and siding require base coat application with a **pile roll** to reach into embossed crevices; these applicator rolls are covered with a sleeve of soft material similar to pile carpeting. For two-tone effects, the high spots are then coated with the smooth roll of a **precision roll coater** (fig. 23-96). Embossed boards can usually tolerate more surface imperfections because defects are obscured by the embossed profile.

Finishing materials.—All hardboard finishes have three principal components:

- **Resin or binder** develops necessary adhesive and cohesive forces to form the film and bond it to the substrate, controlling water resistance,

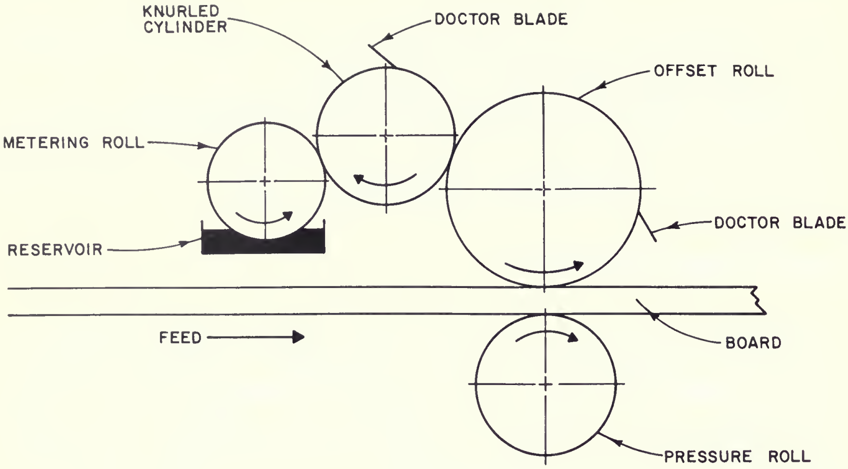


Figure 23-96.—Precision roll coater. (Drawing from Suchsland and Woodson 1985.)

chemical resistance, weatherability, and strength. Most commonly used are acrylic, alkyd, and polyester resins.

- **Pigments** provide color in coatings; they may be organic or inorganic.
- **Solvents,** which maintain the coating in a liquid state and control its viscosity, evaporate soon after application (with heat input) so that the coating can solidify. Usually they are organic compounds such as toluol or xylene, both of which have high rates of evaporation and require incineration to avoid air pollution; other organics with slower evaporation rates and not requiring incineration include butyl acetate, butyl cellusolve, and cellusolve acetate. Water is a cheap and safe solvent but water-borne finishes lack the water resistance obtainable with organic solvents.

Two alternatives to solvent-borne finishes are plasticized vinyl films, usually 6 mil (0.006 inch) thick and embossed with a cloth-weave pattern, and printed paper overlays laminated to the substrate with a water-based adhesive.

Interior wall paneling and decorative board.—With the layout diagrammed in figure 23-97, alternative coating machines provide flexibility to finish either grooved wood-grain printed interior paneling or decorative board. Boards fed into the line by a vacuum feeding device are brush cleaned before application of **fill coat** by two **reverse roll coaters** (fig. 23-98) each followed by a hot-air dryer and a chrome-plated polished roll rotating opposite to the board feed, thereby forcing the fill coat into surface pores and wiping the excess. The dried fill coat is abrasive buffed with 320-400 grit paper. If panels are grooved, the grooves are spray painted a dark color.

The **ground coat,** next applied, is background for the printed pattern. For grooved panels it is applied by precision roll coater to top surfaces, but not to grooves. Decorative panels, which do not have grooves, are curtain coated (fig. 23-99) to form smooth films over entire top surfaces.

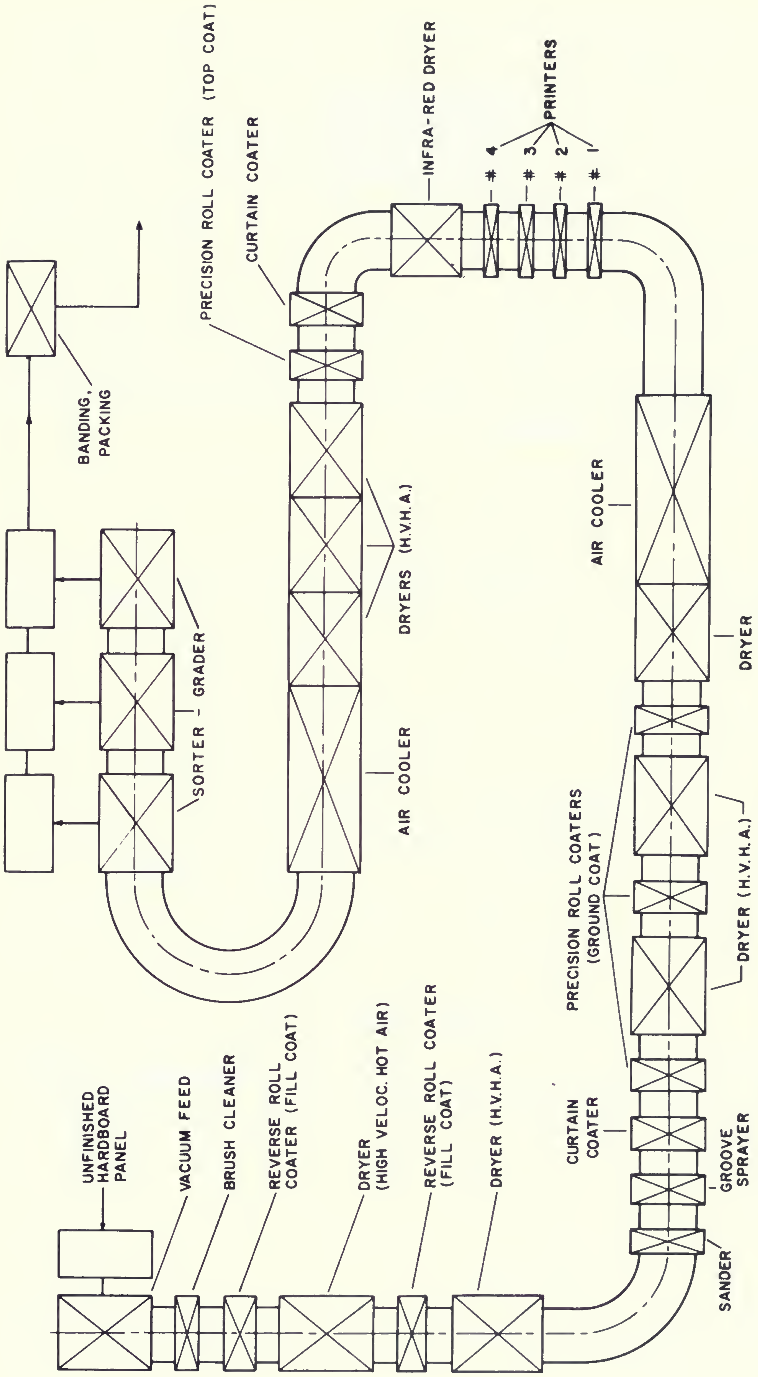


Figure 23-97.—Finishing line for wood-grain printed interior paneling or decorative board. H.V.H.A. means high-velocity hot air. (Drawing from Suchsland and Woodson 1985.)

After drying and cooling, wood grains and certain other decorative patterns are printed on the panels by one or more **offset printers** (fig. 23-100) in which a metering roll transfers printing ink to a gravure cylinder on which the desired pattern is engraved. A doctor blade removes ink from the cylinder except in the engraved areas. Ink collected in engraved areas is transferred by contact to the relatively soft offset (or print) roll which in turn transfers the ink to the substrate. To reproduce wood patterns based on photographs of real wood panels, three or four offset printers arranged in series and each applying a different color are commonly used.

A brick pattern containing three colors of brick would be applied (over a mortar-colored ground coat) with three printers—one for each color of brick. Print coats may dry sufficiently utilizing only heat stored in panels; gas-fired infra-red dryers may be used for additional heat. Some solid-color decorative boards may bypass the print line.

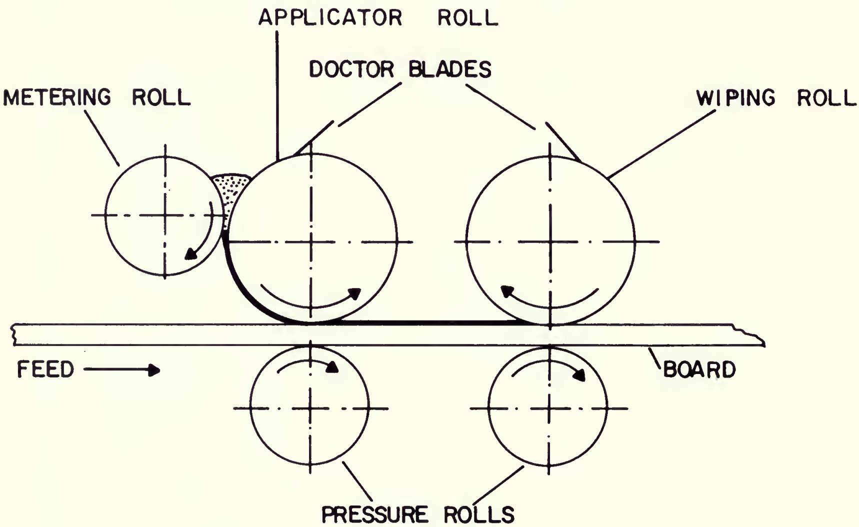


Figure 23-98.—Reverse roll coater. (Drawing from Suchsland and Woodson 1985.)

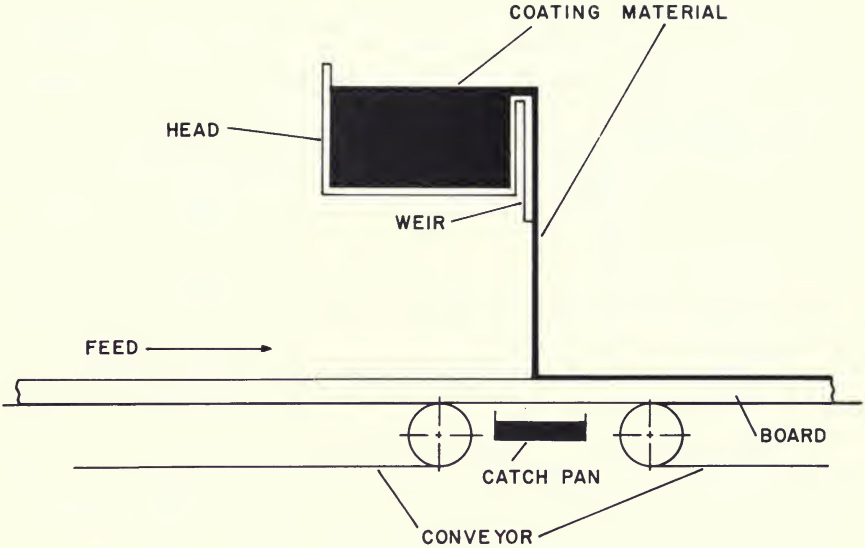


Figure 23-99.—Curtain coater. (Drawing from Suchsland and Woodson 1985.)

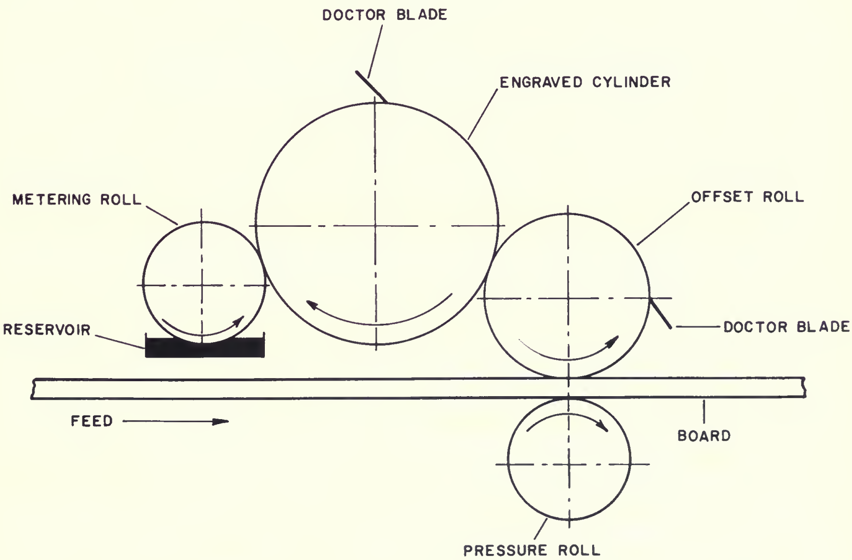


Figure 23-100.—Offset printer. (Drawing from Suchsland and Woodson 1985.)

A **top coat** is then applied to grooved and embossed panels by precision roll coater and to decorative boards by curtain coater, following which solvents are evaporated and surfaces heated to about 500°F. Boards are then cooled, graded, stacked, and packaged.

Thickness of finish coats are about as follows:

Product and coat	Thickness of dry coat
	Mil
¼-inch interior paneling	
Fill	0.3
Ground	.8
Top	.6
Total	1.7
Tile board	
Fill	.3
Ground	1.1
Top	.8 - 1.0
Total	2.2 - 2.4

Speeds of finishing lines similar to that shown in figure 23-97 are usually limited by the dryers; excessive dryer temperatures embrittle coatings. Typically ¼-inch-thick interior paneling is finished at 150 to 200 feet per minute. Tile boards, which have heavier top coats to resist high humidities, run slower—e.g., at about 120 fpm.

Siding.—Figure 23-101 shows a finishing line for siding, which typically operates at about 150 fpm. All coats on siding may be thermal set acrylic latex. The thickness of the coats (2.0-2.2 mills when dry, total) depends on the length of time for which the siding is guaranteed. Only about 30 percent of all hardboard siding is completely prefinished; 70 percent is only primed. Primed siding provides flexibility in color selection of final coats applied after installation, and also removes the burden of providing performance guarantees on the finished product.

Sanding the bottom surface of siding hardboard to reduce thickness variation is particularly important for two-tone embossed products, where high spots are coated with precision roll coaters.

Single-color regular embossed siding is coated with direct-roll coaters equipped with pile rolls. Lightly embossed boards and flat boards are curtain coated. The solvent is removed in a dryer and the resin cured in an oven yielding a board surface temperature of about 300°F. Curing is followed by 1 minute of air cooling, grading, and packing.

Vinyl and paper overlays.—In typical overlay finishing lines a latex glue is applied to the hardboard substrate by a direct roll coater. The glue is dried by infra-red energy and the overlay then applied by a heated-roll press. Excess overlay is trimmed by knives or abrasive wheels.

In a method used by Abitibi Corporation, a printed paper is applied to the wet mat of S1S board prior to pressing with embossed caul plates. After fabrication an accent coat is applied by pile coater to the surface of the paper overlay, after which a direct roll coater picks surplus paint off all high spots. This leaves the

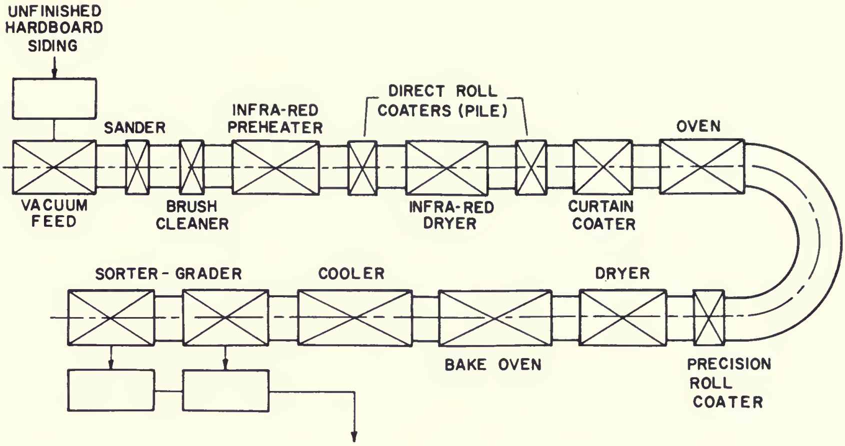


Figure 23-101.—Finishing line for hardboard siding. (Drawing from Suchsland and Woodson 1985.)

accent coat, applied by the pile coater, only in the low spots. A top coat is then applied over the entire surface; the sequence is shown in figure 23-102.

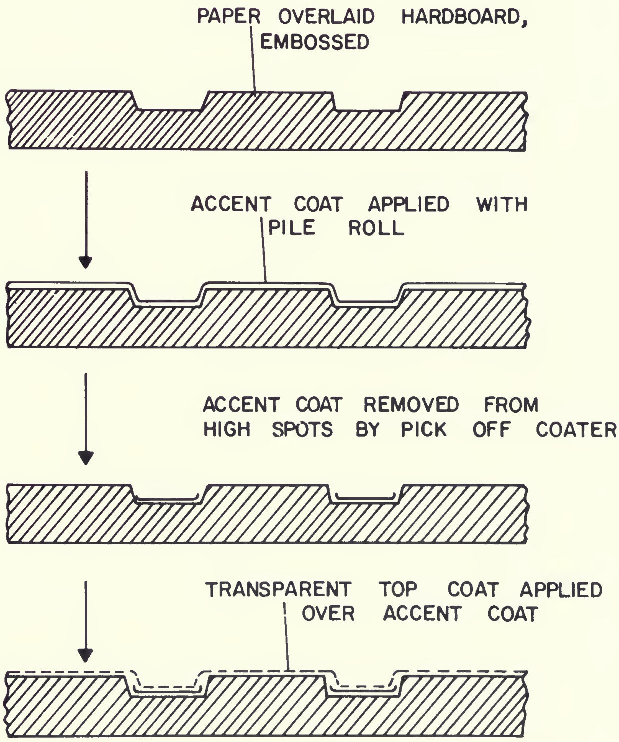


Figure 23-102.—Finishing sequence for paper-overlaid embossed hardboard by the Abitibi Corporation process. (Drawing from Suchsland and Woodson 1985.)

TABLE 23-10.—*Classification of basic hardboard by surface finish, thickness, water resistance, and mechanical properties* (U.S. Department of Commerce 1982)[1]

Class	Nominal thickness	Water resistance (max av per panel): Water absorption based on weight	Water resistance (max av per panel): Thickness swelling	Modulus of rupture (min av per panel)	Tensile strength (min av per panel): Parallel to surface	Tensile strength (min av per panel): Perpendicular to surface
	inch	*percent*	*percent*	*psi*	*psi*	*psi*
1 Tempered	1/12	30	25	6000	3000	130
	1/10, 1/8, 3/16	25	20			
	1/4	20	15			
	5/16	15	10			
	3/8	10	9			
2 Standard	1/12	40	30	4500	2200	90
	1/10, 1/8, 3/16	35	25			
	1/4	25	20			
	5/16	20	15			
	3/8	15	10			
3 Service-Tempered	1/8	35	30	4500	2000	75
	3/16	30	30			
	1/4	30	25			
	3/8	20	15			

	1/8	45	35			
	3/16	40	35			
	1/4	40	30			
	3/8	35	25			
	7/16	35	25			
	1/2	30	20			
4	5/8	25	20	3000	1500	50
Service	11/16	25	20			
	3/4					
	13/16					
	7/8	20	15			
	1					
	1 1/8					
	1/4	50	30			
	3/8	40	25			
	7/16	40	25			
	1/2	35	25			
5	5/8	30	20			
Industrialite	11/16	30	20	2000	1000	25
	3/4					
	13/16					
	7/8	25	20			
	1					
	1 1/8					

[1]Water resistance values are based on water absorption and thickness swell when boards are water soaked.

23-12 BOARD STANDARDS AND PROPERTIES

COMMERCIAL HARDBOARDS

Hardboard standards.—Hardboard product standards do not distinguish between medium- and high-density boards, but define hardboard as fiberboard compressed to a density of 31 pounds/cu ft or greater (specific gravity $\geqslant 0.50$). The three voluntary product standards for hardboard are as follows:

Product	Standard	Reference
Basic hardboard	PS 58-73	U.S. Department of Commerce (1973a)
Prefinished hardboard paneling	PS 59-73	U.S. Department of Commerce (1973c)
Hardboard siding	PS 60-73	U.S. Department of Commerce (1973d)

The **basic hardboard standard** makes no reference to end use but classifies hardboards as S1S or S2S, and by tensile strength parallel and perpendicular to the surface (table 23-10).

The **prefinished hardboard paneling standard** classifies boards into two quality classes according to resistance to heat and humidity and according to resistance to abrasion, scraping, fading, and staining, and according to coating adhesion, gloss, and washability. Paneling property requirements are in addition to those for basic hardboard.

Hardboard siding is intended for exterior exposure, so weatherability, stability of finish, and dimensional stability are specified in the product standard. Linear expansion of siding first equilibrated at 50 percent relative humidity and then at 90 percent, cannot exceed the following percentages:

Type of siding and thickness	Maximum linear expansion
Inch	*Percent*
Lap	
0.325-0.375	0.38
over .376	.40
Panel	
0.220-0.265	.36
.325-.375	.38
over .376	.40

Thick medium-density fiberboard is not covered by the hardboard standards and is discussed in the next subsection.

TABLE 23-11.—*Identification of 1/8- and 1/4-inch-thick hardboard panels evaluated by Werren and McNatt* (1975; text footnote 5)[1]

Letter designation of manufacturer[2]	Method of felting	Condition at pressing	Designation of surfaces
A[3]	Wet	Wet	Screenback
B	Wet	Wet	Screenback
C	Wet	Dry	S2S
D	Air	Dry	S2S
E[3]	Wet	Wet	Screenback
F	Wet	Wet	Screenback
G	Wet	Wet	Screenback
H	Wet	Dry	S2S
J[3]	Air	Wet	Screenback
K	Air	Dry	S2S
L	Air	Dry	S2S

[1]Ten or 20 panels of each of the two thicknesses from each manufacturer were evaluated. S2S means smooth on both sides.

[2]I is not part of the series.

[3]These hardboards are emphasized in data plots associated with discussion of this experiment.

Hardboard properties.—Within each manufacturing plant properties of commercial hardboards vary as processes are modified and composition of wood furnish is altered. Properties of hardboards manufactured in different plants also vary significantly. Werren and McNatt (1975),[5] in cooperation with the American Hardboard Association and eleven hardboard manufacturers, evaluated and summarized these differences. Of the 11 hardboards evaluated, seven were wet felted (five wet pressed and two dry pressed), and four were air felted (one wet pressed and three dry pressed); the wet-pressed boards had one screened surface and the dry-pressed boards were S2S, i.e., smooth on both faces (table 23-11).

[5]Werren, F., and J.D. McNatt, 1975. Basic properties and their variability in 20 commercial hardboards. U.S. Dep. Agric. For. Serv., For. Prod. Lab. Internal Rep., Madison, Wis.

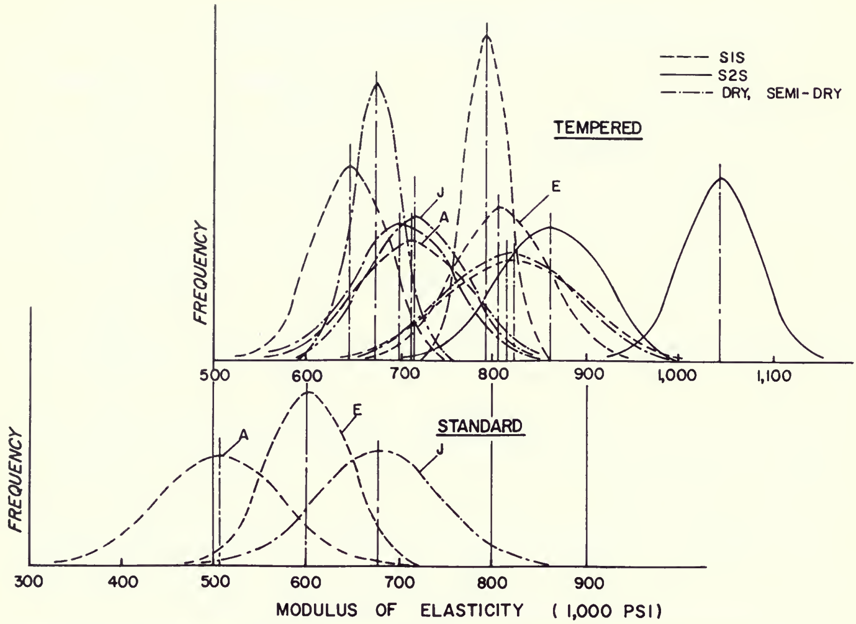


Figure 23-103.—Modulus of elasticity in bending of ¼-inch-thick commercial hardboards tested at 6 to 8 percent moisture content. (Top) Eleven tempered hardboards. (Bottom) Three standard hardboards. See table 23-11 for descriptions of boards tested. (Drawing from Suchsland and Woodson 1985, based on data from Werren and McNatt 1975, text footnote 5.)

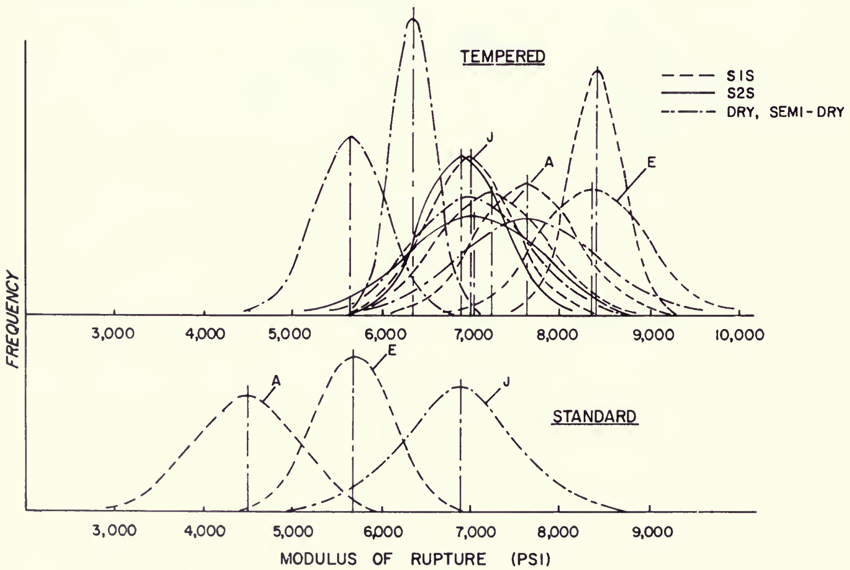


Figure 23-104.—Modulus of rupture of ¼-inch-thick commercial hardboards tested at 6 to 8 percent moisture content. (Top) Eleven tempered hardboards. (Bottom) Three standard hardboards. See table 23-11 for descriptions of boards tested. (Drawing from Suchsland and Woodson 1985, based on data from Werren and McNatt 1975, text footnote 5.)

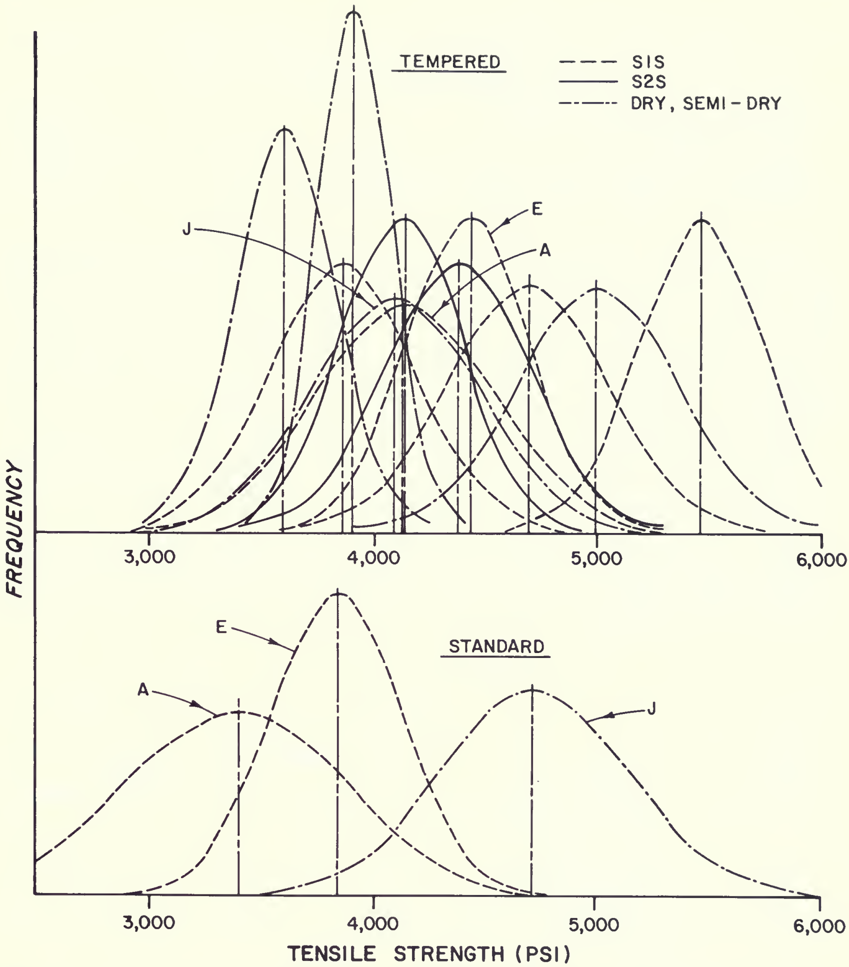


Figure 23-105.—Tensile strength parallel to surface of ¼-inch-thick commercial hardboards tested at 6 to 8 percent moisture content. (Top) Eleven tempered hardboards. (Bottom) Three standard hardboards. See table 23-11 for descriptions of boards tested. (Drawing from Suchsland and Woodson 1985, based on data from Werren and McNatt 1975, text footnote 5.)

The variability found by Werren and McNatt in ¼-inch hardboards is illustrated in the following figures (magnitude of variation in ⅛-inch boards was comparable):

Property	Figure
Modulus of elasticity in bending	23-103
Modulus of rupture	23-104
Tensile strength parallell to surface	23-105
Tensile strength perpendicular to surface (internal bond strength)	23-106

Average properties of the boards described in table 23-11 are tabulated as follows:

Properties	Table
Specific gravity, and modulus of elasticity, stress at proportional limit, and modulus of rupture in bending	23-12
Tensile and compressive strengths	23-13
Shear properties	23-14
Stability and moisture content when water soaked	23-15
Stability and moisture content at various relative humidities	23-16

Specific gravity of these eleven hardboards appeared to be a dominant variable only for internal bond strength; it averaged about 100 psi at a specific gravity of 0.94 and increased linearly to 500 psi at a specific gravity of 1.05 (r = 0.74). Within any one board type, however, specific gravity is probably correlated with a number of mechanical properties; among board types, however, factors such as tempering and wood species are dominant.

The effect of tempering was greatest on properties related to strength of surface layers (e.g., bending and tensile strength) and least on those related to center layers (e.g., internal bond strength).

Linear expansion appeared to be greater in dry-formed than in wet-formed boards, suggesting that dry-formed boards may have a greater component of vertical fiber orientation.

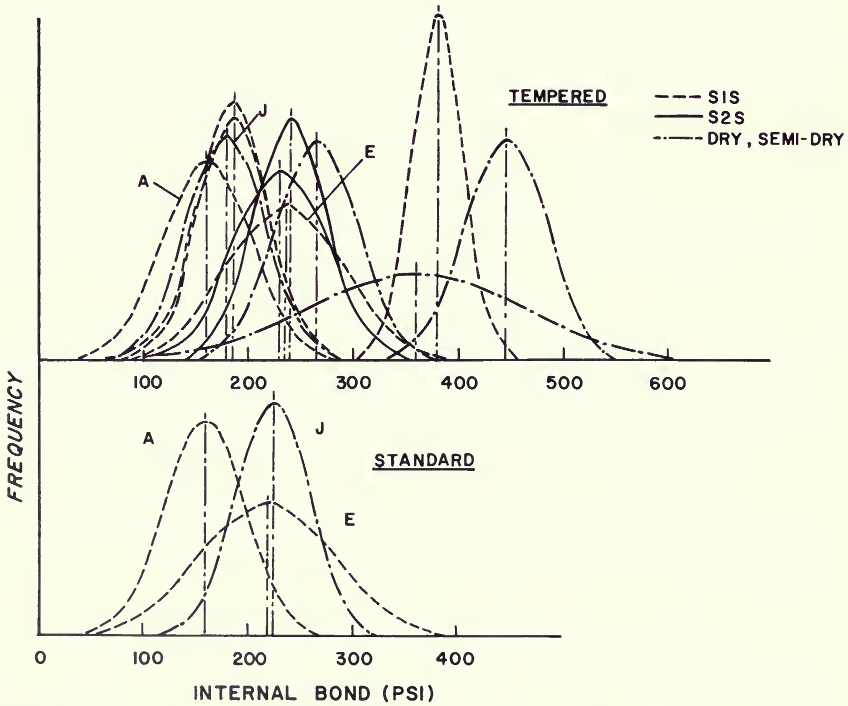


Figure 23-106.—Tensile strength perpendicular to surface (internal bond strength) of ¼-inch-thick commercial hardboards tested at 6 to 8 percent moisture content. (Top) Eleven tempered hardboards. (Bottom) Three standard hardboards. See table 23-11 for descriptions of boards tested. (Drawing from Suchsland and Woodson 1985, based on data from Werren and McNatt 1975, text footnote 5.)

TABLE 23-12.—*Specific gravity and elastic and strength properties in static bending of 11 commercial hardboards evaluated by Werren and McNatt* (1975, see text footnote 5)[1]

Hardboard thickness and type[2]	Moisture content	Specific gravity[3]	Modulus of elasticity	Stress at proportional limit	Modulus of rupture
	Percent		*Thousand psi*	*Psi*	*Psi*
			TEMPERED		
¼-inch thick					
A	7.3	0.95	710	3,730	7,230
B	7.6	.93	820	3,850	7,630
C	5.7	.98	860	2,730	6,910
D	6.4	1.03	815	3,240	7,650
E	6.3	.99	805	3,270	8,360
F	7.8	.96	645	2,580	6,990
G	6.4	.98	790	3,440	8,410
H	6.1	.97	1,040	3,820	7,060
J	8.1	.97	715	2,650	7,010
K	5.8	1.02	670	2,600	6,360
L	7.2	1.02	700	2,050	5,650
			STANDARD		
¼-inch thick					
A	6.9	.92	505	2,020	4,490
E	5.4	.95	600	2,310	5,690
J	7.7	.98	675	2,930	6,890
			TEMPERED		
⅛-inch thick					
A	6.7	.95	735	3,740	8,780
E	6.6	.96	635	2,920	7,120
J	7.9	.96	555	2,840	7,150
			STANDARD		
⅛-inch thick					
A	7.6	.88	515	2,320	5,280
E	5.7	.93	495	1,970	5,160
J	7.8	.89	450	2,350	5,570

[1]Each value based on 100 determinations.
[2]See table 23-11 for description of the hardboards.
[3]Based on volume at test and weight when ovendried.

TABLE 23-13.—*Elastic and strength properties in tension parallel and perpendicular, and in compression parallel, to the surface of 11 commercial hardboards evaluated by Werren and McNatt* (1975, see text footnote 5)[1,2]

Hardboard thickness and type[3]	Tension parallel: Modulus of elasticity[4]	Tension parallel: Tensile strength	Internal bond strength	Compression parallel: Modulus of elasticity[4]	Compression parallel: Compressive strength
	Thousand psi	*Psi*	*Psi*	*Thousand psi*	*Psi*
			TEMPERED		
¼-inch thick					
A	795	4,140	160	730	4,020
B	875	4,690	185	760	4,590
C	965	4,130	240	780	4,520
D	1,010	5,000	360	800	5,900
E	830	4,430	235	715	4,620
F	680	3,870	185	595	3,800
G	835	5,470	380	755	4,920
H	1,035	4,380	230	925	5,880
J	680	4,100	180	650	3,740
K	720	3,920	445	700	4,230
L	845	3,610	265	785	4,180
			STANDARD		
¼-inch thick					
A	715	3,400	160	690	2,890
E	740	3,830	220	720	3,460
J	745	4,720	225	720	3,780
			TEMPERED		
⅛-inch thick					
A	910	5,640	260	835	4,990
E	850	4,690	280	815	4,410
J	740	4,590	190	690	4,220
			STANDARD		
⅛-inch thick					
A	660	4,070	140	700	3,130
E	680	3,690	250	695	3,350
J	630	4,000	190	650	3,100

[1]Each value is an average based on 100 determinations, except modulus of elasticity for ¼-inch standard and both ⅛-inch-thick boards are based on 50 determinations.

[2]Tests made according to ASTM D 1037; material at equilibrium at time of test.

[3]See table 23-11 for description of the hardboards.

[4]Based on secant modulus at 20 percent of maximum stress.

TABLE 23-14.—*Interlaminar and edgewise shear properties of 11 commercial hardboards evaluated by Werren and McNatt* (1975; see text footnote 5)[1,2]

Hardboard thickness and type[3]	Interlaminar shear: Modulus of rigidity[4]	Interlaminar shear: Shear strength	Edgewise shear: Shear modulus	Edgewise shear: Shear strength
	Thousand psi	*Psi*	*Thousand psi*	*Psi*
		TEMPERED		
¼-inch thick				
A	78.0	430	295	2,850
B	95.5	490	310	3,200
C	87.5	565	350	2,860
D	200.0	840	335	3,440
E	120.0	485	330	2,860
F	71.0	495	290	2,550
G	96.5	850	350	3,410
H	125.5	540	405	2,880
J	66.0	455	315	2,980
K	130.0	815	295	3,120
L	159.5	705	305	2,860
		STANDARD		
¼-inch thick				
A	71.5[5]	410	240	2,060
E	106.0[5]	440	285	2,440
J	93.0[5]	520	325	2,970
		TEMPERED[6]		
⅛-inch thick				
A	—	620	320	3,610
E	—	600	300	3,380
J	—	510	285	3,180
		STANDARD[6]		
⅛-inch thick				
A	—	520	245	2,360
E	—	500	260	2,610
J	—	490	245	2,590

[1]Each value based on 50 determinations unless otherwise noted.
[2]Tests made according to ASTM D 1037 or ASTM D 3044; material in equilibrium at time of test.
[3]See table 23-11 for description of hardboards.
[4]Based on secant modulus at 20 percent of maximum stress.
[5]Based on 30 determinations.
[6]Due to extremely small deformations, elastic modulus could not be determined for interlaminar shear.

TABLE 23-15.—*Effect of water soaking on moisture content, linear expansion, and thickness swell of six ¼-inch-thick, tempered, commercial hardboards evaluated by Werren and McNatt* (1975, see text footnote 5)[1,2]

Hardboard type and statistic	After soaking for — (hours)						
	2	4	28	76	94	158	264
	Percent						
Type A							
Moisture content	10.2	13.9	22.2	31.0	33.3	36.6	39.3
Linear expansion	.41	.52	.64	.66	.68	.67	.69
Thickness swell	5.7	10.8	17.1	18.6	18.6	21.1	21.2
Type C							
Moisture content	11.6	19.9	31.2	45.0	48.4	51.1	54.4
Linear expansion	.32	.48	.58	.56	.69	.60	.72
Thickness swell	11.6	17.9	22.2	23.4	23.6	24.6	25.0
Type E							
Moisture content	8.3	9.7	14.2	20.4	21.5	24.3	27.8
Linear expansion	.42	.50	.61	.68	.69	.64	.70
Thickness swell	4.8	6.8	10.0	10.8	11.0	12.2	13.3
Type G							
Moisture content	9.4	12.2	20.7	29.0	31.3	35.2	39.5
Linear expansion	.45	.53	.68	.69	.71	.75	.76
Thickness swell	5.9	9.0	15.7	17.9	18.5	19.7	21.9
Type J							
Moisture content	11.4	14.3	25.3	35.5	39.3	44.3	49.6
Linear expansion	.57	.65	.82	.83	.89	.87	.88
Thickness swell	9.2	13.2	22.0	24.1	24.7	26.2	28.1
Type L							
Moisture content	10.2	12.8	22.7	33.0	37.9	44.6	48.1
Linear expansion	.46	.57	.73	.75	.85	.87	.86
Thickness swell	8.0	12.8	23.2	25.4	25.6	27.6	28.6

[1]Each value is the average for two specimens expressed as a percent of calculated ovendry measurements determined from dimensions and weights of two matched specimens.

[2]See table 23-11 for description of hardboards.

TABLE 23-16.—*Effect of relative humidity on moisture content, linear expansion, and thickness swell of six ¼-inch tempered commercial hardboards evaluated by Werren and McNatt* (1975; see text footnote 5)[1,2]

Hardboard type and statistic	At relative humidity of — (percent) 30	64	80	90	97
	Percent				
Type A					
Moisture content	3.7	7.1	10.0	12.8	24.3
Linear expansion	.18	.32	.36	.45	.64
Thickness swell	2.0	4.3	6.7	10.6	20.8
Type C					
Moisture content	2.8	5.4	8.3	10.6	28.2
Linear expansion	.10	.20	.30	.33	.68
Thickness swell	1.2	3.3	6.8	10.3	24.2
Type E					
Moisture content	2.9	5.6	8.0	9.7	17.2
Linear expansion	.16	.32	.35	.48	.62
Thickness swell	.8	2.9	5.8	7.5	13.7
Type G					
Moisture content	3.3	6.2	9.1	11.4	24.1
Linear expansion	.18	.33	.39	.49	.67
Thickness swell	.8	3.3	6.3	9.2	21.4
Type J					
Moisture content	3.9	7.5	10.8	13.5	32.0
Linear expansion	.25	.45	.53	.63	.84
Thickness swell	1.3	4.2	8.0	11.7	28.3
Type L					
Moisture content	3.8	7.1	10.3	13.2	32.5
Linear expansion	.20	.35	.46	.52	.85
Thickness swell	1.7	3.8	7.9	11.7	30.6

[1]Values expressed as a percent of ovendry value; each value is based on one specimen except those at 97 percent relative humidity are the average for two specimens.

[2]See table 23-11 for description of hardboards.

COMMERCIAL MEDIUM-DENISTY FIBERBOARDS

Standards.—Property requirements of thick medium-density fiberboard for interior use are specified in a standard co-sponsored by the American Hardboard Association and the National Particleboard Association; some major requirements from this standard are shown in table 23-17.

Properties.—Suchsland et al. (1978) evaluated properties of eight commercial medium-density fiberboards, from a total of 11 such boards being manufactured at time of test in 1975 (table 23-18). They found that average board densities varied among manufacturers from about 0.72 to about 0.95 g/cm^3, and also varied significantly within board type (fig. 23-107).

They found that most boards had considerable density variation in cross section, faces being denser than cores. Enhancement of modulus of elasticity in bending provided by this density gradient is shown in figure 23-108 in which the density variation of each board is represented by a horizontal line at the level of its modulus of elasticity. The length of each line indicates the density gradient from face (right end of line) to core (left end of line), and average board density is indicated by the numbered circle between extremes. Face density appeared strongly correlated with modulus of elasticity in bending. A similar relationship between core density and internal bond strength in tension perpendicular to the face was not found.

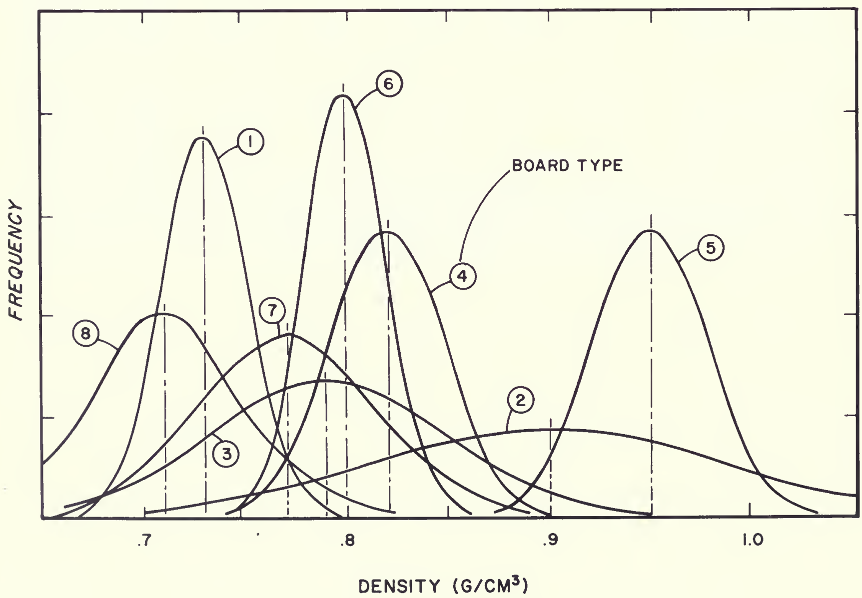


Figure 23-107.—Normal distribution curves for board densities of eight commercially manufactured medium-density fiberboards. (Drawing from Suchsland et al. 1978.)

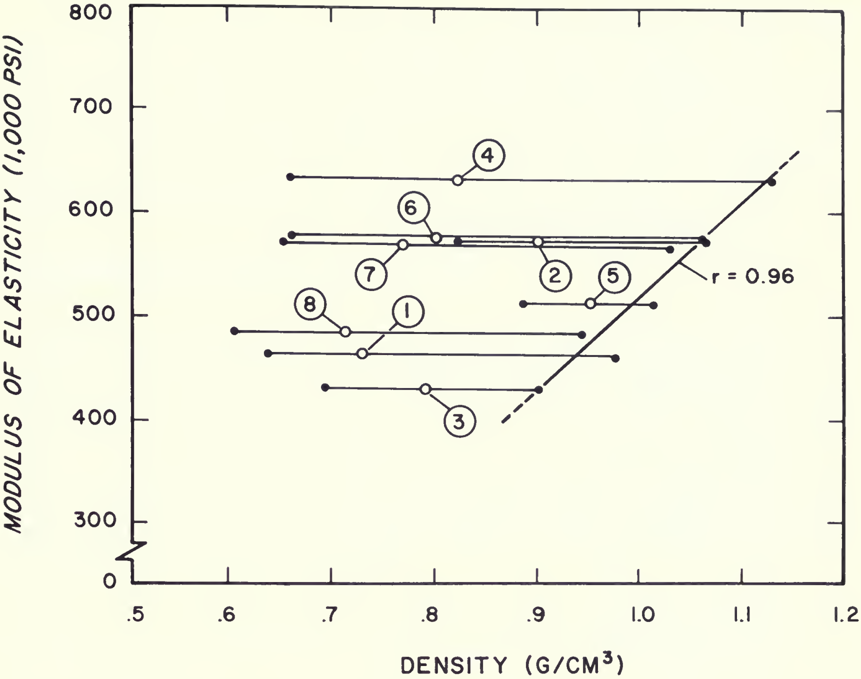


Figure 23-108.—Modulus of elasticity in bending as related to density of eight types of commercially manufactured medium-density fiberboard. Horizontal lines indicate density gradient from board surface (right end of line) to board center (left end). (Drawing from Suchsland et al. 1978.)

TABLE 23-17.—*Property requirements of thick medium-density fiberboard in two thickness classes* (U.S. Department of Commerce 1980)

Property	Thickness class: 13/16-inch and thinner	Thickness class: 7/8-inch and thicker
Modulus of rupture, psi	3,000	2,800
Modulus of elasticity, psi	300,000	250,000
Internal bond strength, psi (tensile strength perpendicular to surface)	90	80
Linear expansion, percent[1]	0.30[2]	0.30
Screwholding strength, pounds		
Face	325	300
Edge	275	225

[1]Between 50- and 90-percent relative humidities.

[2]For boards ⅜-inch thick or less (nominal), the maximum linear expansion value is 0.35 percent.

TABLE 23-18.—*Average physical and mechanical properties of eight commercial medium-density fiberboards* (Data from Suchsland et al. 1978)

Mill no.	Density	MOR	MOE	IB	Screw withdrawal, edge	Screw withdrawal, face	Thickness swelling 47-93% RH	Residual thickness swelling	Linear expansion 47-95% RH
	g/cm	*psi*	*1,000 psi*	*psi*	*Pounds*		*Percent*		
1.	.73	4,837	466	125	257	326	9.59	4.36	0.360
2.	.90	4,932	576	136	325	407	6.32	1.61	.391
3.	.79	3,366	432	282	330	445	6.26	2.48	.611
4.	.82	5,703	635	121	252	326	8.88	2.83	.346
5.	.95	3,565	517	133	405	509	11.44	5.45	.577
6.	.80	5,278	578	103	315	404	10.49	4.52	.376
7.	.77	5,421	572	179	360	464	8.74	3.18	.440
8.	.71	5,107	858	158	324	416	8.17	3.03	.413

For reasons not entirely clear, all of the eight commercial boards tested exceeded the maximum linear expansion allowed by the standard (table 23-18). Many properties are not included in the standard because they are not easily tested or because they are not important in all applications. Surface smoothness is one such property. Suchsland et al. (1978) found that at redried condition after a 24-hour water soak, all of the medium-density fiberboards tested were significantly smoother than commercial conventional particleboard.

COMMERCIAL INSULATION BOARD

Insulation board standards.—Voluntary Product Standard PS 57-73 (U.S. Department of Commerce 1973b) describes property requirements and test methods for insulation board and defines it as fiberboard in the density range from 10 to 31 pounds/cu ft (specific gravity of 0.16 to 0.50). The standard establishes 11 types of insulation board and several classes (table 23-19).

Property requirements vary with board type and class; in general, however, insulation board does not have great strength. Minimum values for the most demanding end uses are as follows:

Property	Minimum for most demanding use
Modulus of rupture, psi	
Dry	500
Wet	95
After accelerated aging	50 percent of dry value
Modulus of elasticity, psi	40,000
Tensile strength parallel to surface, psi	300
Tensile strength perpendicular to surface, pounds/square foot	1,000

In the most demanding use, linear expansion between 50 and 90 percent relative humidity cannot exceed 0.5 percent.

Of the properties listed in the standard, the thermal conductivity "k" (Btu/hr/sq ft/inch thickness/°F temperature differential) is perhaps most important; its minimum specified value varies with board type and use class, but is in the range from 0.38 to 0.40. Insulation board conducts heat at less than half the rate of an equal thickness of solid wood; the "k" value for softwood is about 0.80 and that of hardwood about 1.10.

Actual properties of commercial insulation board are not available in the literature.

TABLE 23-19.—*Types, classes, and intended uses of insulation board* (U.S. Department of Commerce 1973b)

Type	Class	Name	Intended use
I.		Sound deadening board	In wall assemblies to control sound transmission
II		Building board	As a base for interior finishes.
III.		Insulating formboard	As a permanent form for poured-in-place reinforced gypsum or lightweight concrete aggregate roof construction.
IV		Sheathing:	
	1	Regular-density	As wall sheathing in frame construction where method of application and/or thickness determines adequacy of racking resistance.
	2	Intermediate-density	As wall sheathing where usual method of application provides adequate racking resistance.
	3	Nail-base	As wall sheathing where usual method of application provides adequate racking resistance, and in addition, exterior siding materials, such as wood or asbestos shingles, can be directly applied with special nails.
V		Shingle backer	As an undercoursing for wood or asbestos cement shingles.
VI		Roof insulating board	As above-deck insulation under built-up roofing.
VII.		Ceiling tiles and panels:	
	1	Nonacoustical	As decorative wall and ceiling coverings.
	2	Acoustical	As decorative, sound absorbing wall and ceiling coverings.
VIII		Insulating roof deck	As roof decking for flat, pitched, or shed-type open-beamed, ceiling-roof construction.
IX		Insulating wallboard	As a general-purpose product used for decorative wall and ceiling covering.

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24

Structural Flakeboards and Composites

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CHAPTER 24

Structural Flakeboards and Composites

CONTENTS

CHAPTER 24

Structural Flakeboards and Composites

Production of particleboard products from comminuted wood and a binder, and of composites utilizing such products, has increased rapidly in the United States since World War II (fig. 29-13). The furniture plants of the East and South utilize much hardwood plant residue for particleboard and fiberboard; most particleboard made in the United States, however, is softwood.

The manufacture of fiberboards—one type of particleboard well suited for use of hardwoods—is discussed in chapter 23.

The manufacture of interior-grade non-structural particleboards, typically made in the United States from softwood planer shavings and plywood trim, is exhaustively described in a number of readily available texts and proceedings, some of which are listed as follows:

Mitlin (1968)	Moslemi (1974ab)	Maloney (1977)
FAO (1975)	Deppe and Ernst (1977)	Miller (1977)

European Particleboard Manufacturers Trade Association (1979)

An additional source of continuously updated information is the Particleboard Symposium Proceedings edited by T. M. Maloney, and published annually (beginning in 1967) by Washington State University, Pullman. Also, FORINTEK Canada Corp., Ottawa, Canada, periodically publishes proceedings of symposia on particleboard and structural flakeboard.

This chapter is concerned with a segment of the particleboard industry—the manufacture of structural flakeboard—which is incompletely described in the literature and which appears to have the most promise for greatly increasing utilization of small hardwoods of low quality. During the 1970's, manufacture of structural panels from flakes of aspen (*Populus tremuloides* Michx.) emerged as a major industry in Canada; by mid 1981 several companies in the northern tier of Midwest and Eastern States of the United States were also producing—or had announced intention to produce—structural flakeboard from aspen (table 24-1 and fig. 24-1). Also in 1981, one plant in New Brunswick, Canada and another in New Hampshire in the United States were using some *Betula* and *Acer* species in mixture with less dense softwoods and aspen. Not listed in table 24-1 or figure 24-1 is the Georgia Pacific Corp. waferboard plant in Woodland, Maine; with annual capacity of 166 million sq ft, 3/8-inch basis, it uses softwoods only.

At the end of 1980, there were no plants producing structural flakeboard from the mixtures of more-or-less dense hardwoods that typically grow on southern pine sites, but the potential for such production is very large. In 1981 the Martin group of companies of Alexandria, La., began construction of such a plant in Lemoyen, La.; and began operating in 1983, with planned production capacity of 120 million sq ft per year, 3/8-inch basis. Later in 1981, Louisiana Pacific Corp. announced plans to produce hardwood flakeboard in Corrigan, Texas; annual capacity of this plant is projected at 125 million sq ft, 3/8-inch basis, with startup also scheduled for 1983.

This chapter concentrates on research results, largely derived from work at the Pineville, La. laboratory of the Southern Forest Experiment Station, that form the foundation of this new southern hardwood industry.

Some economic feasilibity studies related to this emerging industry are listed in section 24-26.

Figure 24-1.—Locations of plants operating, under construction, or planned, for the manufacture of hardwood structural flakeboard, based on data available in early 1982.

TABLE 24-1.—*Location, type, and annual capacity of existing and planned North American structural flakeboard plants using hardwoods, as of early 1982*[1,2]

Country and company	*Location*	*Board type*	*Annual capacity (3/8-inch basis)*
			Million sq ft
Canada			
Grant Waferboard[3]	Englehart, Ont.	Waferboard	150
Great Lakes Forest Products Ltd.[4]	Thunder Bay, Ont.	Waferboard	127
MacMillan Bloedel Industries, Ltd.[4] (Thunder Bay Division)	Thunder Bay, Ont.	Waferboard	130
MacMillan Bloedel Industries, Ltd.[4] (Hudson Bay Division)	Hudson Bay, Sask.	Waferboard	150
Malette Waferboard[4]	St. Georges-de-Champlain, Que.	Waferboard	130
Normick Perron, Inc.[4]	LaSarre, Que.	Waferboard	50
Northwood Pulp and Timber Ltd.[4]	Chatham, N.B.	Waferboard	150
Waferboard Corp. Ltd.[4]	Timmons, Ont.	Waferboard	69
Weldwood of Canada Ltd.[4]	Longlac, Ont.	Waferboard	110
Weldwood of Canada Ltd.[4]	Slave Lake, Alta.	Waferboard	120
United States			
Blandin Wood Products Co. #1[4]	Grand Rapids, Minn.	Waferboard	90
Blandin Wood Products. Co. #2[4]	Grand Rapids, Minn.	Waferboard	180
Diamond International Corp.[3]	Winn, Maine (or elsewhere)	Oriented-strand board	165
Elmendorf Board Corp.[4]	Claremont, N.H.	Oriented-strand board	100
Louisiana Pacific Corp.[5]	Corrigan, Tex.	Oriented waferboard	125
Louisiana Pacific Corp.[5]	Houlton, Maine	Oriented waferboard	130
Louisiana Pacific Corp.[4]	Hayward, Wis.	Waferboard and oriented waferboard	128[6]
Martin group of companies[5]	Lemoyen, La.	Waferboard	120
Northwood Panelboard Co.[5]	Bemidji, Minn.	Waferboard	190
Potlatch Corp.[5]	Cook, Minn.	Oriented-strand board	155
Potlatch Corp.[4]	Midge Lake, Minn.	Oriented-strand board/waferboard	155
Weyerhaeuser Co.[5]	Grayling, Mich.	Oriented-strand board	215

[1]Based on data from Forest Industries (1979, 1980), Hickson (1980), and correspondence with companies listed.

[2]See figure 24-1 for map of plant locations.

[3]In planning stage

[4]In operation

[5]Under construction.

[6]Capacity increased in 1982 to about 256 million sq ft, 3/8-inch basis.

24-1 DEFINITIONS OF STRUCTURAL FLAKEBOARDS[1]

Vajda (1978a) observed that structural-grade particleboards are called by some sources **particleboards**, by others **flakeboards**, and by still others **waferboard**, or **strandboard**. All of these terms refer mainly to the types of particles used to manufacture the panel product. His definitions of essential terms follows:

- **Particles**, the generic term for any kind of wood particles, may be of random size or of specified length, width, and thickness; they may be cut parallel to the grain or across the grain. Some sources include mechanically pulped wood fibers within this generic term.
- **Flakes** are particles cut parallel to the grain in the 0-90 mode (figs. 18-1, 18-98 top, 18-104ABCD, and 18-264 through 18-269).
- **Wafers** are large, square flakes, used in **waferboard**. (See wafers in upper and lower left corners of fig. 18-274A.)
- **Strands** are flakes whose length is at least three or four times greater than their width; this slenderness ratio promotes alignment in **oriented-strand boards.** (See figs. 18-264 and 18-274B.)
- **Semi-flakes** or **chip flakes** are cut from conventional pulp chips or longer and narrower **maxi-chips** or **fingerlings** by a ring-type flaker (figs.18-270 and 18-271); resulting flakes have some cross grain. (See ring-flaked wood in figures 18-274ABC.)
- **Random particles** are produced on a hammermill or hog-type machine (fig. 18-276 through 18-279) from shavings, sawdust, or other mill residue.

Vajda (1974) also noted that particleboards of various sorts have been manufactured in quantity in North America since 1940 and that some of the products have been used in load-bearing applications; some examples follow:

- Particleboard in mobile home **decking** (i.e., floor systems)
- Hardboard in exterior siding
- Particleboard in vertical siding and exterior sheathing
- Hardboard (1/8- to 1/4-inch thick) in stressed-skin applications
- Particleboard and hardboard in self-supporting, but non-critical, load-bearing applications in furniture and as shelving.

Until the advent of **structural flakeboard** however, none of these products was accepted in building construction for general structural applications. This lack of acceptance was due partly to insufficient strength retention on exposure to weather or to fluctuations in temperature and humidity (in the case of particleboard), and partly because of excessive weight and density (in the case of hardboard). Additionally, ample supplies of lumber and plywood available at reasonable prices satisfied the needs of the building industry.

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[1]See sections 24-19 and 24-20 (figures 24-50 through 24-54) for illustrations of composite panels.

To impart resistance to fluctuations in humidity and temperature, and to rain wetting, structural flakeboards are bonded with exterior resins—chiefly phenol-formaldehyde formulations. (See sec. 24-5.)

All of the commercially manufactured structural flakeboards are formed in three layers, i.e., with a core layer and two face layers. Flakes in the face layers generally are thinner and may also be longer than those in the core layer. In most **waferboards**, flakes within all three layers are randomly placed with regard to grain direction (fig. 24-2 top).

In **oriented-strand boards** (fig. 24-2 bottom), flakes in the two face layers are aligned with grain parallel to the major panel axis, e.g., parallel to the 8-foot edges of 4- by 8-foot panels. Core flakes may be randomly disposed, but more commonly are aligned at right angles to those in the face layers.

24-2 STANDARDS

Tentative standards and specifications for structural flakeboard were adopted in 1980 and 1981 and continue to evolve. In general terms, the industry seeks a product which can replace the construction exterior grade (CDX) plywood marketed in the United States. Vajda (1978a) summarized the significant properties of CDX plywood as follows:

Property	Value
Modulus of rupture in bending	
Along the grain	8,000 psi
Across the grain	4,000 psi
Modulus of elasticity	
Along the grain	1,200,000 psi
Across the grain	500,000 psi
Linear expansion (30 to 90 percent relative humidity)	
Along the grain	0.10 percent
Across the grain	.14 percent

CDX plywood weighs about 36 pounds per cubic foot (dry basis) and retains 60 to 70 percent of its original strength under severe long-term exposure to weather or under tests which simulate such exposure (Vajda 1978a).

BUILDING CODES

Jorgensen (1978) described the history of requirements, codes, and U.S. Forest Service goals for properties of structural flakeboard. He noted that in late 1972 the New Jersey State Building Code approved the use of Canadian waferboard in thickness dimensions equivalent to those in use in Canada and equiv-

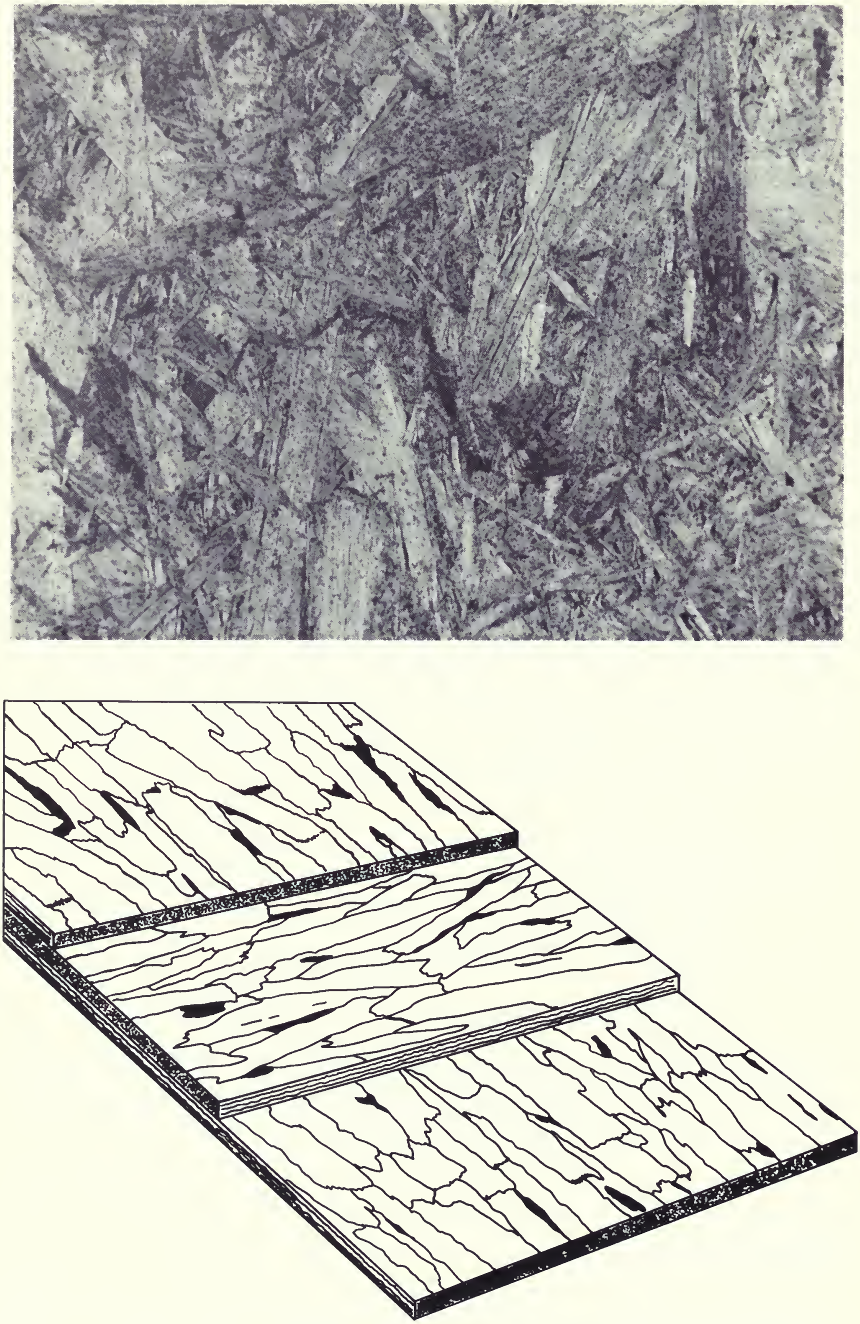

Figure 24-2.—Structural hardwood flakeboards. (Top) Three-layer waferboard with flakes randomly placed in each layer. (Bottom) Three-layer, oriented-strand board; flakes in the two face layers are aligned with grain parallel to the 8-foot edges of 4- by 8-foot panels, and those in the core at right angles to this.

alent to those specified in a Federal Housing Authority (FHA) Memorandum Approval. Waferboard continued to be used under the FHA Memorandum Approval until 1975 when a formal Materials Release was issued. Also during the years 1972-1975, West Coast model code approval was obtained for oriented-strand board, which has higher modulus of rupture and modulus of elasticity than board with random placement of flakes, when loaded in bending in the 8-foot direction in which the strands are aligned.

By 1978, Canadian and one U.S. waferboard were approved by the Building Officials' and Code Adminstrators' International (BOCA), the Southern Building Code Congress, and the International Conference of Building Officials. These panels conformed to type and grade 2B2 of Commercial Standard CS-236-66 (U.S. Department of Commerce, National Bureau of Standards 1966) which called for minimum average modulus of rupture of 2,500 psi and modulus of elasticity of 450,000 psi. They were approved for roof sheathing 3/8-inch thick secured to rafters spaced 16 inches center-to-center, or 7/16-inch thick on rafters with 24-inch spacing. For wall sheathing, approval came for 5/16-inch-thick panels secured to studs 16 inches on center, and for 3/8- or 7/16-inch panels on studs without corner bracing and spaced 24 inches center-to-center.

AMERICAN NATIONAL STANDARD FOR PROPERTIES

In 1980, the National Particleboard Association (1980) published an American National Standard For Mat-Formed Wood Particleboard. Type 2 particleboard—that bonded with phenol-formaldehyde resin or equivalent—made of wafers or flakes was required to have the properties shown in table 24-2.

PERFORMANCE STANDARDS FOR COMBINATION SUBFLOOR AND UNDERLAYMENT[2]

O'Halloran (1979) noted that a performance-based specification is an alternate to the more common commodity or product standard approach just described. Performance specifications are product approval documents, qualifying structural-use panel products emerging from new technology.

Specifications include criteria reflecting durability, structural performance, and dimensional stability when wet. Durability is based upon a cyclic wet-dry test reflecting a minimum satisfactory performance equal to a minimum 1-year's exposure to weathering conditions. Structural adequacy is demonstrated by concentrated static and impact tests in both a wet and dry condition. Finally, dimensional stability is based upon field and laboratory tests of a variety of panel products. Criteria for each of these areas are established from the laboratory and field work.

[2]Text under this heading is condensed from American Plywood Association (1980).

TABLE 24-2.—*Property requirements for waferboard and flakeboard bonded with phenol-formaldehyde resins or equivalent bonding systems* (National Particleboard Association 1980)

Property	Waferboard	Flakeboard
Grade	2-MW	2-MF
Length and width tolerance (inch)	+0 to −1/8	+0 to −1/8
Thickness tolerance, unsanded (inch)		
Panel average[1]	±0.030	±0.030
Within-panel[2]	±0.030	±0.030
Thickness tolerance, sanded (inch)		
Panel average[1]	±0.015	±0.015
Within panel[2]	±0.010	±0.010
Modulus of rupture (psi)[3]	2,500	3,000
Modulus of elasticity (psi)[3]	450,000	500,000
Internal bond strength (psi)[3]	50	50
Hardness (pounds)[3]	500	500
Linear expansion between 50- and 90-percent relative humidity (percent)[3]	0.20	0.20

[1]Panel average from nominal.

[2]Individual measurement from panel average.

[3]Five-panel average; the five-panel sample shall not contain any individual panel having this property more than 20 percent below the value tabulated.

From these criteria, the American Plywood Association (1980) published a manufacturing and performance standard for a wood-based structural panel intended for use as combination subfloor and underlayment when fastened to supports as specified. They termed the product APA RATED STURD-I-FLOOR® panels; the panels can be all veneer, composite with veneer faces and backs over wood particle cores, or all wood particles. Performance standards for this product follow.

Application.—The panels will withstand exposure expected in normal construction, but should not have an edge or surface permanently exposed to the weather. The major panel axis (generally the long dimension) is placed across supports spaced no further apart than the span rating, i.e., for composite or all particle panels the distances between centers of supports may be specified as 16, 20, or 24 inches. (Criteria for 48-inch span are under development.) Panels must be continuous over two or more spans. When applying thin resilient finish flooring, a layer of underlayment is recommended for panels without a veneer face. If underlayment is not used, nails should be set 1/16-inch deep (1/8-inch for 1-1/8-inch panels), but nail holes should not be filled. Edge joints should be filled and any surface roughness should be thoroughly sanded.

Fastening.—Nail-fastened floors should use 6d deformed-shank nails for panels 3/4-inch thick or less, and 8d deformed-shank nails for thicknesses of 7/8-inch through 1-1/8 inches. For 1-1/8-inch panels, 10d common nails may be used if supports are well seasoned. Nails should be drive 6 inches apart at panel edges and 10 inches apart at intermediate supports.

The floor decking can be field glued using adhesives meeting American Plywood Association specification AFG-01 or ASTM D 3498. A continuous bead of glue is applied on joists (double bead under butted joists) and in the groove of tongue-and-groove panels. Nail sizes are the same as specified above except that for panels 7/8-inch thick or less 8d common nails may be substituted if deformed-shank nails are not available. For panels 7/8-inch thick or less that are glued as well as nailed to supports, nails are spaced 12 inches on center at all bearings; for 1-1/8-inch panels, nails are spaced 6 inches on center at all bearings, except 10 inches on center at intermediate supports which are 32 inches on center or less.

Panel end joints are staggered and occur over framing. Panel end and edge joints are spaced 1/8-inch unless otherwise recommended by the panel manufacturer.

Structural performance.—When tested by procedures of American Plywood Association Test Method S-1 (ASTM E661) for **concentrated static and impact loads**, panels shall conform to the criteria of table 24-3. When tested by procedures of American Plywood Association Test Method S-2 for **uniform loads**, panels shall conform to the criteria of table 24-4. **Fastener performance** is based on lateral and withdrawal ultimate loads for 6d common smooth-shank nails, as follows:

Test condition	Lateral load	Withdrawal load
	Pounds	
Dry (at 65% RH)	210	20
Wet/redry	160	15

The lateral load is applied in single shear; the withdrawal load is measured on nails driven through the thickness of the panel normal to the face. Both tests are made according to American Plywood Association Test Method S-4.

Linear expansion.—Panels shall be tested by one of the following linear expansion procedures:

- APA Test Method P-1; **ovendry to vacuum-pressure-soak condition**. Specimens are 6 inches wide by 41 inches long. Specimen length is measured between inserted brass eyelets when ovendry and again after a cycle comprised of immersion in a pressure cylinder filled with water, an hour of vacuum (27 inches of mercury), and 2 hours of pressure (90 psi). Linear expansion along either the major or minor panel axis shall be no more than 0.50 percent from dry length.
- APA Test Method P-2; **ten percent moisture content to one side wetted**. Specimens measure 4 by 4 feet with only one cut edge; this edge may be protected against water. The other three edges are as prepared by the manufacturer and shall be left exposed to water. These unrestrained specimens are wetted on one side with water for 14 days; no liquid water impinges on the panel back but it is exposed to any humidity present. Free panel linear expansion shall be no more than 0.30 percent along the major axis and 0.35 percent across the minor axis. Additionally, thickness swell shall be no more than 25 percent of the thickness.

TABLE 24-3.—*Performance criteria for APA RATED STURD-I-FLOOR® panels under concentrated static and impact loads tested according to American Plywood Association Test Method S-1* (American Plywood Association 1980)

Span rating and test exposure conditions[1]	Minimum ultimate load		Maximum deflection under 200-pound load [3]static [4]impact
	Static	Following 75-foot-pound impact[4]	
	----------*Pounds*----------		------------------*Inch*------------------
16 inches			
Dry or wet/redry	550[2]	400	0.078
Wet................	400[3]	400	Not applicable
20 inches			
Dry or wet/redry	550[2]	400	.094
Wet................	400[3]	400	Not applicable
24 inches			
Dry or wet/redry	550[2]	400	.108
Wet................	400[3]	400	Not applicable

[1]Wet/redry is exposure to 3 days of continuous wetting followed by testing dry. Wet conditioning is exposure to 3 days of continuous wetting followed by testing wet.
[2]On a 1-inch disk at midspan 2.5 inches from panel edge to center of disk.
[3]On a 3-inch disk at midspan 2.5 inches from panel edge to center of disk.
[4]On a 3-inch disk at midspan 6 inches from panel edge to center of disk.

TABLE 24-4.—*Performance criteria for APA RATED STURD-I-FLOOR® panels under uniform load tested according to American Plywood Association Test Method S-2* (American Plywood Association 1980)

Span rating (inches)	Test exposure conditions[1]	Average deflection under uniform load of 100 lb/sq ft[2]	Minimum ultimate uniform load[2]
		Inch	*Lb/sq ft*
16	Dry or wet/redry.........	0.044	330
20	Dry or wet/redry.........	.053	330
24	Dry or wet/redry.........	.067	330

[1]Wet/redry is exposure to 3 days of continuous wetting followed by testing dry.

[2]Specimen width is at least 23-1/2 inches; specimen length is perpendicular to the support members (joists) and is equal to twice the center-to-center distance identified in the span rating. Specimen edges are unsupported except where they cross support members.

- APA Test Method P-3; **50- to 90-percent relative humidity**. Specimens are 3 inches wide and 41 inches long; these specimens are first exposed to relative humidity of 50 percent until stable, and then to 90 percent. Linear expansion shall not exceed 0.30 percent of the length at 50 percent relative humidity along the major axis, or 0.35 percent across the minor axis. Thickness swell shall be no more than 25 percent of thickness at 50 percent relative humidity. This method corresponds to ASTM D 1037 except for specimen size.
- APA Test Method P-4; **full-scale testing**. Full-scale restrained-panel linear expansion shall be not more than 0.20 percent along the major axis and 0.25 percent across the minor axis. By this test method a 16- by 16-foot lumber frame with specified joist spacing is fabricated and 4- by 8-foot specimens are nail-assembled to it with end joints staggered 4 feet. On this frame, the major panel axis of each specimen runs perpendicular to the joists. Overall dimensions of the assembly are measured on the panelled surface at the ends and middle, both along and across specimens' major panel axes. A continuous water spray is then applied to the top surface with a garden sprinkler for 14 consecutive days. Following wetting, the panel measurements are again taken.

Stability.—Stability index is an indicator of ability to stay flat in service; as measured by American Plywood Association Test Method P-5, it shall be 5.5 or greater. By this test panel stiffness both along and across the major panel axis is determined in dry panels; then linear expansion along and across the major panel axis is measured from ovendry to vacuum-pressure-soak condition. The stability index for each direction of each specimen is then calculated as:

$$A = \log_{10} [\pi^2 EI / L^2 \Phi] \tag{24-1}$$

where

A = stability index
EI = stiffness (lb-in.^{2}/ft)
Φ = linear expansion (in./in.) (Percent expansion divided by 100)
L = span (in.)

For the major panel axis, the span shall be the maximum span rating for which the panel is being qualified. For the cross-panel direction, the span is the maximum recommended interior nail spacing (generally 10 or 12 inches).

Bond durability.—Panels shall be rated for exposure 1 or exposure 2. Panels with **exposure 1 durability rating** are intended for protected construction uses where durability to resist moisture due to long construction delays, or other conditions of similar severity, is required. Composite and wood-based panels (not including those composed entirely of veneer) so rated shall satisfy the delamination requirements of American Plywood Association Test Method P-9 following moisture cycling according to their Test Method D-5. Under this test regime, 1- by 5-inch specimens are cut with long dimension parallel to major panel axis, placed in a pressure vessel, submerged in water at 150°F, subjected for 30 minutes to a vacuum of 15 inches of mercury, soaked at atmospheric pressure for 30 minutes, and then removed and dried for 6 hours at 180°F in an oven with forced air circulation; specimens are returned to the vacuum-soak cycle and dried for 15 hours, completing two unbalanced cycles. These unbalanced cycles are repeated until six cycles are run. Total time required is 3 days. Edges of each specimen are then probed with a blade-shaped square-ended tool measuring 1/4-inch wide and 0.012 inch thick at the tip. If a separation is found that is ¼-inch deep for one continuous inch, the specimen fails the test.

Panels with **exposure 2 durability rating** are intended for protected construction uses where moderate delays in providing protection may be expected or condiitons of high humidity and water leakage may exist. Composite and wood-based panels so rated (not including those composed entirely of veneer) shall satisfy the structural performance requirements described in the paragraph associated with tables 24-3 and 24-4 (including criteria for fasteners) after being wetted and redried as prescribed by American Plywood Association Test Method D-1. By this test method, specimens are submerged for 8 hours in water maintained at 150°F, and then dried at 180° until they attain their original, as-received, weight.

Mold and bacteria resistance.—For details of these tests, readers are referred to American Plywood Association Test Methods D-2 and D-3.

Dimensional tolerance and squareness of panels.—A **size** tolerance of plus, 0, minus 1/8-inch is allowed on specified length and on specified width. A **thickness** tolerance of plus or minus 1/32-inch is allowed on the trademark-specified thickness. Panels shall be **square** within 1/64-inch per lineal foot measured along the diagonals; all panels shall be manufactured so that a straight line drawn from one corner to the adjacent corner is within 1/16-inch of the panel edge.

Moisture content.—Moisture content of panels at time of shipment shall not exceed 18 percent of ovendry weight.

PERFORMANCE STANDARDS FOR SHEATHING[2]

The American Plywood Association (1980) has also published a manufacturing and performance standard for a wood-based panel intended for use as sheathing for roofs, subfloors, and walls when fastened to supports spaced in accordance with the span rating. The Association termed this product **APA RATED SHEATHING®;** the panels can be all veneer, composite with veneer faces and backs over wood particle cores, or all wood particles.

These panels will withstand exposure expected in normal construction but should not have an edge or surface permanently exposed to the weather; protection from the weather or long-term excessive humidity should be provided as soon as possible.

Roof sheathing application.—The major panel axis (the long dimension) shall be placed across supports spaced no further apart center-to-center than the panel span rating, and panels shall be continuous over two or more spans. Panels at overhangs shall not have upper surfaces permanently exposed to the weather.

Panels 1/2-inch in thickness or less shall be fastened with 6d common nails; 8d nails should be used for thicker panels. Nails should be spaced no more than 6 inches apart along panel edges and 12 inches apart at intermediate supports, with minimum edge distance of 3/8-inch. Other fastening systems that provide equivalent product performance may be used.

Panel end joints shall occur over framing. Panel end joints should be spaced 1/8-inch and panel edges 1/4-inch, unless otherwise recommended by the panel manufacturer. Panel edge clips should be used at midspan of unsupported edges for 7/16-inch and thinner panels rated only for roof sheathing and installed over supports spaced 24 inches center-to-center.

Subflooring application.—As with roof sheathing, the major panel axis should be placed across supports placed no further apart than the panel span rating, and panels shall be continuous over two or more spans. A separate structural finish floor or underlayment shall be installed over the subfloor. Nailing procedure is the same as for roof sheathing except that nails should be spaced 10 inches center-to-center at intermediate supports. Joint spaces should be the same as for roof sheathing.

Wall sheathing application—Panels with a rated wall span of 16 inches or roof span of 16 or 20 inches shall have a maximum stud spacing of 16 inches center-to-center. Panels with a wall or roof span rating of 24 inches, shall have a maximum stud spacing of 24 inches. Panels may be installed with the major panel axis either along or across the studs. All panel edges shall be nailed to framing for wall sections acting as bracing. Nailing procedure is the same as that for roof sheathing. Joint spacing should be the same as for roof sheathing.

Structural performance.—When tested by procedures of American Plywood Association Test Method S-1 for **concentrated static and impact loads**, panels shall conform to criteria of table 24-5. When tested by procedures of Ameican Plywood Association Test Method S-2 for **uniform loads,** panels shall conform to criteria of table 24-6. When tested by procedures of American Plywood Association Test Method S-3 for **wall racking**, panels shall conform to criteria of table 24-7. When tested by American Plywood Association Test Method S-4 ultimate **lateral and withdrawal loads for nails** in panels shall conform to criteria of table 24-8.

TABLE 24-5.—*Performance criteria for APA RATED SHEATHING® panels under concentrated and impact loads tested according to American Plywood Association Test Method S-1* (American Plywood Association 1980)

Span rating and test exposure conditions[1]	Minimum ultimate load		Maximum deflection under 200-pound load[4]
	Static[2]	Following impact[3/4]	
	----------*Pounds*----------		*Inch*
ROOF PANELS			
16 inches			
Dry or wet/redry	400	300	0.438
Wet................	400	300	Not applicable
20 inches			
Dry or wet/redry	400	300	.469
Wet................	400	300	Not applicable
24 inches			
Dry or wet/redry	400	300	.500
Wet................	400	300	Not applicable
32 inches			
Dry or wet/redry	400	300	.500
Wet................	400	300	Not applicable
42 inches			
Dry or wet/redry	400	300	.500
Wet................	400	300	Not applicable
48 inches			
Dry or wet/redry	400	300	.500
Wet................	400	300	Not applicable
SUBFLOOR PANELS			
16 inches			
Dry or wet/redry	400	400	.188
Wet................	400	400	Not applicable
20 inches			
Dry or wet/redry	400	400	.219
Wet................	400	400	Not applicable
24 inches			
Dry or wet/redry	400	400	.250
Wet................	400	400	Not applicable

[1]Wet/redry is exposed to 3 days of continuous wetting followed by testing dry. Wet conditioning is exposure to 3 days of continuous wetting and tested wet.

[2]On a 3-inch disk at midspan, 2.5 inches from panel edge to center of disk.

[3]Impact shall be 75 foot-pounds for span ratings up to 24 inches, 90 foot-pounds for 32 inches, 120 foot-pounds for 42 inches, and 150 foot-pounds for 48 inches center-to-center span.

[4]On a 3-inch disk at midspan, 6 inches from panel edge to center of disk.

TABLE 24-6.—*Performance criteria for APA RATED SHEATHING® under uniform load tested when dry or wet/redry*[1] *according to American Plywood Association Test Method S-2* (American Plywood Association 1980)

Application and span rating (inches)	Average deflection under uniform load[2,3]	Minimum ultimate uniform load[3]
	Inch	*Lb/sq ft*
Wall		
16	Not applicable	75[5]
24	Not applicable	75[5]
Roof		
16[4]	0.067	150
20[4]	.080	150
24[4]	.100	150
32	.133	150
42	.175	150
48	.200	150
Subfloor		
16	.044	330
20	.053	330
24	.067	330

[1]Wet/redry is exposure to 3 days of continuous wetting followed by testing dry.

[2]40 lb/sq ft for roof panels and 100 lb/sq ft for subfloor panels.

[3]Specimen width at least 23-1/2 inches; specimen length is perpendicular to the support members and is equal to twice the center-to-center distance identified in the span rating. Specimen edges are unsupported except where they cross support members.

[4]Panels with roof-16 and roof-20 ratings must also meet the performance requirements for Wall-16 rating. Panels with roof-24 rating must also meet requirements for wall-24 rating.

[5]The major panel axis is to be placed along the supports for testing wall-panel specimens.

TABLE 24-7.—*Performance criteria for APA RATED WALL SHEATHING® dry and wet panels*[1] *under racking loads tested according to American Association Test Method S-3* (American Plywood Association 1980)

Performance requirement	Panel condition	
	Dry	Wet
Average deflection (inch) at 150 lb/ft		
Total	0.20	0.28
Residual	.10	.14
Average deflection (inch) at 300 lb/ft		
Total	.60	.80
Residual	.30	.40
Minimum ultimate load (lb/ft)	650	500

[1]Applies to 16-inch maximum stud spacing using wall panels with 16-inch span rating, or roof panels with 16-inch or 20-inch span rating. Also applies to 24-inch maximum stud spacing using wall panels or roof panels with 24-inch span rating.

TABLE 24-8.—*Fastener performance criteria for APA RATED SHEATHING® panels nailed with 6d common smooth-shanked nails and tested according to American Plywood Association Test Method S-4* (American Plywood Association 1980)

End use and exposure condition[1]	Minimum ultimate load	
	Lateral	Withdrawal
	Pounds	
Wall		
Dry	120	Not applicable
Wet/redry	90	Not applicable
Roof		
Dry	120	20
Wet/redry	90	15
Subfloor		
Dry	210	20
Wet/redry	160	15

[1]Wet/redry is exposure to three days of continuous wetting followed by testing dry.

Linear expansion.—Criteria are the same as those listed in the previous sub-section describing APA RATED STURD-I-FLOOR® panels, except that thickness swell is not limited during Test Methods APA P-2 and P-3.

Stability.—The stability index shall be 5.2 or greater as computed by equation 24-1.

Bond durability.—Criteria are the same as those discussed in the prior paragraph describing *bond durability* of APA RATED STURD-I-FLOOR®, except that composite and wood-based panels (not including those composed entirely of veneer) shall satisfy the structural performance requirements described by tables 24-5, 24-6, and 24-8 (instead of tables 24-3 and 24-4) after being wetted and redryed by American Plywood Association Test Method D-1.

Mold and bacteria resistance.—Criteria are the same as those specified in the previous sub-section for APA RATED STURD-I-FLOOR® panels.

Dimensional tolerance and squareness of panels.—The criteria are the same as those specified in the previous sub-section for APA RATED STURD-I-FLOOR® panels.

Moisture content.—As for APA RATED STURD-I-FLOOR® panels, moisture content of sheathing panels shall not exceed 18 percent of their ovendry weight.

24-3 REVIEW OF PROPERTIES OF PINE-SITE HARDWOODS

Inclusion of hardwood bark in flakeboards usually diminishes their modulus of rupture, modulus of elasticity, internal bond strength, and screwholding capability (Murphey and Rishel 1969; Gertjejansen and Haygreen 1973; Kehr 1979; Starecki 1979; Wisherd and Wilson 1979; Rishel et al. 1980). In most cases, therefore, it is the properties of bark-free stemwood that are of interest to manufacturers of structural flakeboard.

Any plan for broad usage of the southern hardwood resource for flakeboard manufacture must take into account the **species mix**. This mix varies significantly with region, but southwide averages are indicative of some of the problems. Oaks comprise 47 percent of the 12-State volume of hardwoods growing among southern pines. Sweetgum and white oak are the most plentiful species, and hickory is third in abundance. (See discussion related to tables 2-7 through 2-18.)

In pine-site hardwoods measuring 6 inches in dbh, stemwood **specific gravity** based on ovendry weight and green volume ranges from 0.40 in yellow-poplar to 0.67 in post oak; the average for all hardwood species, weighted by volume of occurrence in the southern pinery, is 0.569. **Density** of stemwood (weighted ovendry basis) therefore averages 35.5 pounds per cubic foot in these small trees (table 7-7).

Sweetgum has the highest **moisture content** at 120.4 percent of ovendry weight, and green ash the lowest at 47.4 percent; weighted average for stemwood of all the pine-site hardwood species in trees measuring 6 inches in dbh is 79.3 percent (table 8-2).

Anatomy of the many species varies significantly. Impermeable woods such as post oak and white oak differ from more permeable woods in optimum wood moisture content for gluing, glue spread, and assembly time. Researchers have not yet fully explained, however, the reasons why post oak and white oak flakes are so difficult to bond.

The chemical makeup of stemwood of the pine-site hardwoods also varies significantly (tables 6-1 through 6-8), and stemwood pH varies from 4.35 in northern red oak to 5.74 in American elm (table 6-23). These chemical variations may cause bonding problems.

Mechanical properties of some of the woods are exceptional. Nine of the species (five oaks and four hickories) have modulus of elasticity values (table 10-6) higher than that for loblolly pine—a premium structural wood; modulus of rupture of wood of these nine species is in the range from 12,600 to 20,200 psi. Average modulus of elasticity of stemwood of all 22 of the principal hardwood species found on southern pine sites, weighted by the volumes in which they occur and measured at 12-percent moisture content, is 1,705,000 psi.

From this brief review of wood properties significant in flakeboard manufacture, it is evident that special technology is required to incorporate all these species—or a significant number of them—into a satisfactory product. The balance of the chapter describes this technology.

24-4 FLAKE MANUFACTURE, DRYING, AND STORAGE

Researchers agree that careful control of flake cutting, drying, classifying, and storing is essential to the manufacture of strong, stiff flakeboard panels.

FLAKE CUTTING

Optimum flakes for structural panels must be cut accurately in the 0-90 direction (fig. 18-1) to precisely prescribed thickness and length. Width is less critical; in waferboards flake width may approximate length, while in oriented-strand boards flake length is generally three or four times flake width.

Wafers are illustrated in the upper and lower left corners of figure 18-274A, and **strands** are shown in figures 18-264 and 18-274B; **semi-flakes** or **chip flakes**, which usually contain considerable cross grain, may be variable in length and width (see ring-flaked wood in figures 18-274ABC).

Slope of grain in flakes.—Flakeboards can be no stronger than the flakes from which they are made. Crossgrain in flakes significantly weakens them as shown by the following data from Price (1976) on tensile properties of 0.015-inch-thick sweetgum flakes tested at 7-percent moisture content over a 3/4-inch gauge length:

Property and slope of grain	Value
Degrees	*psi*
Tensile strength	
0	12,331
10	6,340
20	349
Modulus of elasticity	
0	624,500
10	521,500
20	418,500

Price's (1976) study also showed that the hot pressing operation, compacting flake mats to board thickness, increases face-flake density by 13.9 percent, tensile strength by 7.6 percent, and modulus of elasticity by 9.8 percent, but reduces both tensile strength and modulus of elasticity of core flakes by about 7 percent.

Surface smoothness of flakes.—As flakes are cut, they develop micro-checks similar to lathe checks in veneer (fig. 24-3 top). These checks, and the discontinuities in flakes arising from large vessels (fig. 24-3 bottom left), weaken flakes and contribute to large variations in their strength. Readers interested in further discussion of these effects are referred to work by Furuno et al.[3]

Southern hardwoods, e.g., the oaks, hickories, ashes, elms, red maple, sweetgum, and black tupelo all yield smoothest flakes if cut from wood heated a few hours in water held at about 150°F. See figure 18-238 for the most favorable temperature of individual hardwood species. Dry hardwood yields rough, splintery flakes poorly suited for strong panels.

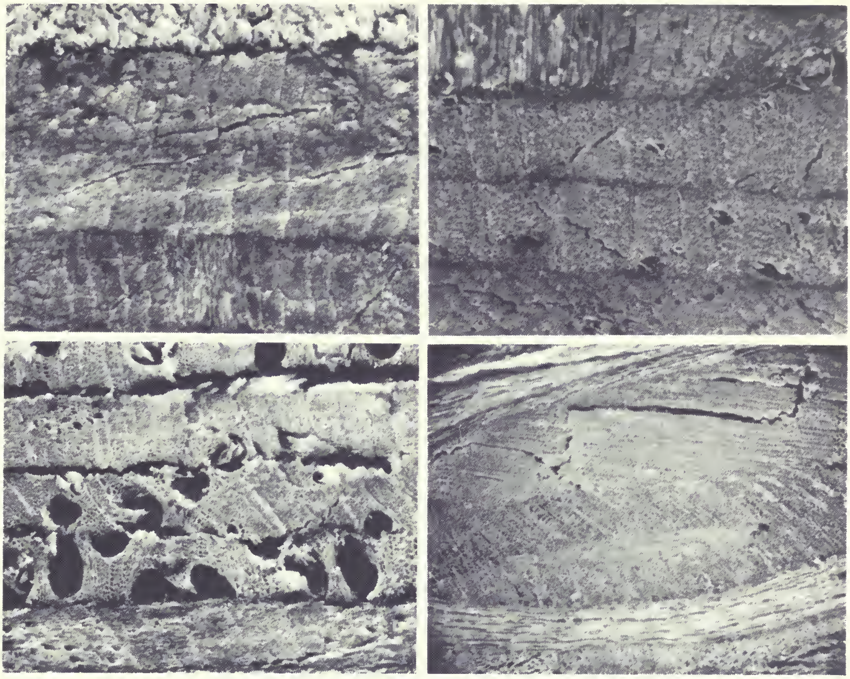

Figure 24-3.—Transverse micrographs of 0.020-inch-thick flakes illustrating zones of weakness from micro-checks formed when flakes were cut (top), and surface roughness attributable to cut vessels (bottom left). Checks may be further fractured during hot pressing (bottom right). (Photos from files of W. A. Côté, see text footnote[3].)

Length, width, and thickness of flakes.—The effects of flake dimensions on flakeboard properties are discussed and illustrated in section 24-9. In general, the 3-inch-long, 0.015-inch-thick flakes illustrated in figure 18-264 are near optimum for face flakes of sheathing panels in thickness of 3/4-inch or less. Core flakes can be thicker (perhaps 0.025 inch) and may be shorter (perhaps 1.5 inches long).

Selection of flaking machinery.—Machines to manufacture flakes, their power requirements, and their production capacities are described in section 18-25 and by figures 18-264 through 18-274C. Thin veneer, precisely cut from wet heated wood to prescribed length and width (fig. 18-264) approximates the optimum flake, with minimal crossgrain and precisely controlled thickness. Of the commercial machines available, the shaping-lathe headrig—or the roundup lathe that operates on the same principle (figs. 18-104ABCD and 18-252)—probably offers the best feed control and hence best control of flake thickness and avoidance of cross grain.

[3]Furuno, T., W. A. Côté, and C.-Y. Hse. 1981. Observation of microscopic factors affecting strength and dimensional properties of hardwood flakeboard. Study FS-SO-3201-29. South. For. Exp. Stn., U.S. Dep. Agric., For. Serv., Alexandria, La. (Manuscript in preparation.)

Some, but not all, authorities believe that disk flakers (figs. 18-265 and 18-266) offer next best control over flake thickness, and drum flakers (figs. 18-268 and 18-269) slightly less. Most agree that ring flakers (figs. 18-270 through 18-272) afford least control of flake dimensions.

Price and Lehmann (1978) compared three-layer structural flakeboards of sweetgum, southern red oak, and mockernut hickory made from 2-1/4-inch-long, 0.020-inch-thick flakes cut from green wood on a shaping-lathe headrig and on disk, drum, and ring flakers. The ring flaker produced 23.8 percent fines (from chips 2-1/4 inches long); the drum, lathe, and disk produced only 7,7, 3.5, and 2.2 percent fines, respectively (figs. 18-274ABC).

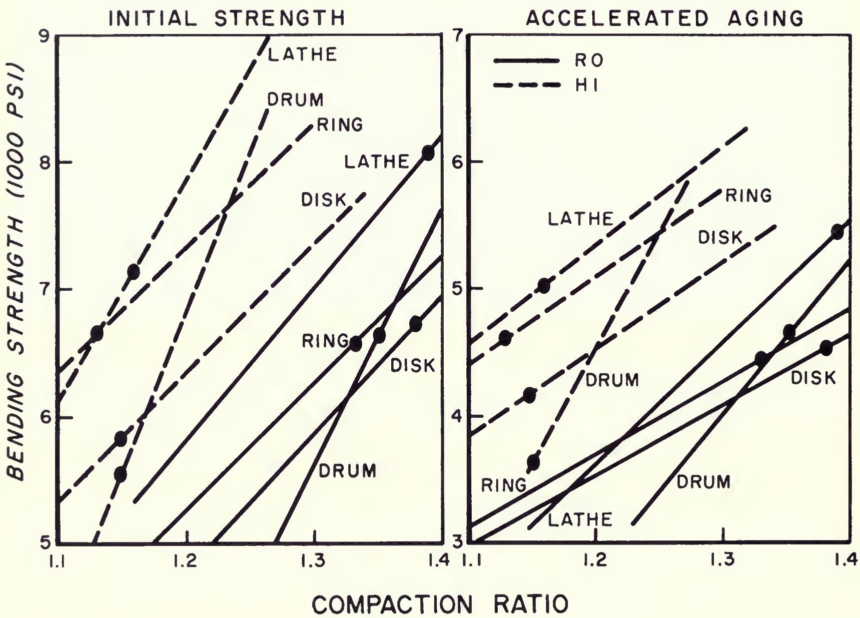

Figure 24-4.—Bending strength (modulus of rupture) related to compaction ratio of 1/2-inch-thick southern red oak and mockernut hickory panels made from 2-1/4-inch-long, 0.020-inch-thick flakes cut on four types of flakers. Panels fabricated at the target density of 52.6 lb/cu ft are accentuated. (Left) Initial strength at 50-percent relative humidity. (Right) Tested after accelerated aging. (Drawing after Price and Lehmann (1978.)

When **oak and hickory** boards were evaluated, bending strength and stiffness were higher in those made from shaping-lathe-cut flakes (figs. 24-4 and 24-5), and internal bond strength was greatest in panels of ring-cut flakes (fig. 24-6 and 24-7). Linear expansion values were low in panels of shaping-lathe-cut flakes pressed to low **compaction ratios** (i.e., ratio of panel density to wood density) and in those of drum-cut flakes pressed to high compaction ratios (fig. 24-8 bottom). Thickness swell in these oak and hickory panels, when subjected to the ovendry-vacuum-pressure-soak cycle, or to change in relative humidity from 30

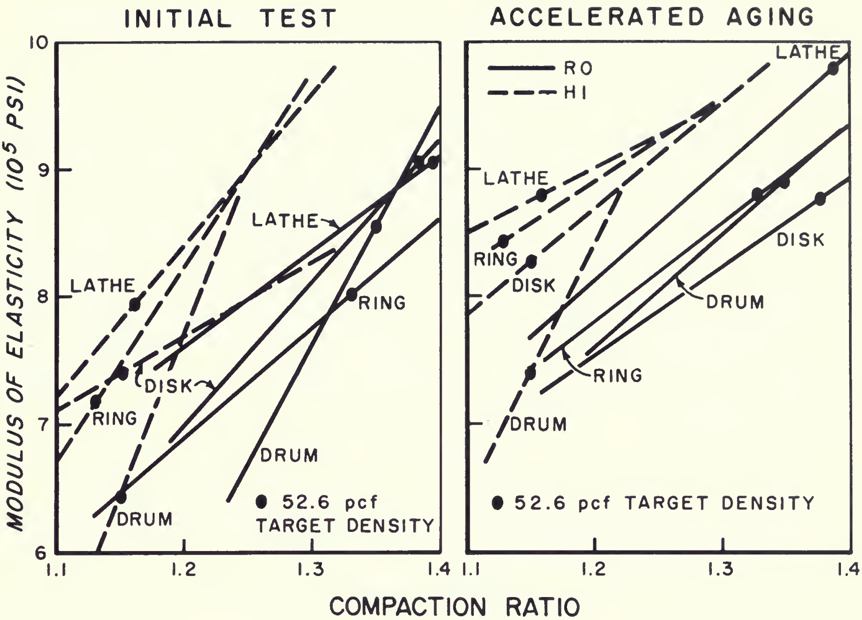

Figure 24-5.—Modulus of elasticity related to compaction ratio of 1/2-inch-thick southern red oak and mockernut hickory panels made from 2-1/4-inch-long, 0.020-inch-thick flakes cut on four types of flakers. Panels fabricated at the target density of 52.6 lb/cu ft are accentuated. (Left) After accelerated aging. (Drawing after Price and Lehmann 1978.)

to 90 percent, was least with shaping-lathe-cut flakes (figs. 24-8 top and 24-9).

At high **compaction ratios**, sweetgum panels had highest bending strength and stiffness when made from disk-cut flakes (figs. 24-10 and 24-11), but highest internal bond strength when made from ring-cut flakes. Sweetgum boards were most stable when fabricated from shaping-lathe-cut flakes (fig. 24-12).

Flake splitters.—Some of the southern hardwoods (e.g., sweetgum) yield very wide flakes that may fold and inhibit resin application; others (e.g., hickory) tend to form tubular flakes on which it is difficult to uniformly apply resin. In the laboratory, an ordinary household leaf shredder does a good job of reducing the width of such flakes. Several industrial machines are available for this purpose; e.g., see Sybertz and Sander (1975).

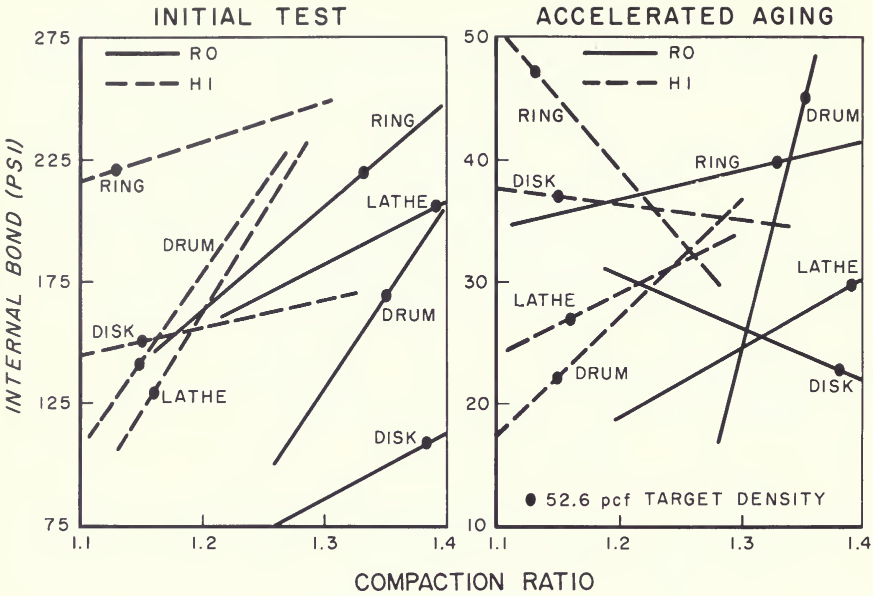

Figure 24-6.—Internal bond strength related to compaction ratio in 1/2-inch-thick southern red oak and mockernut hickory panels made from 2-1/4-inch-long, 0.020-inch-thick flakes cut on four types of flakers. Panels fabricated at the target density of 52.6 lb/cu ft are accentuated. (Left) Initial strength at 50 percent relative humidity. (Right) Strength after accelerated aging cycle. (Drawing after Price and Lehmann 1978.)

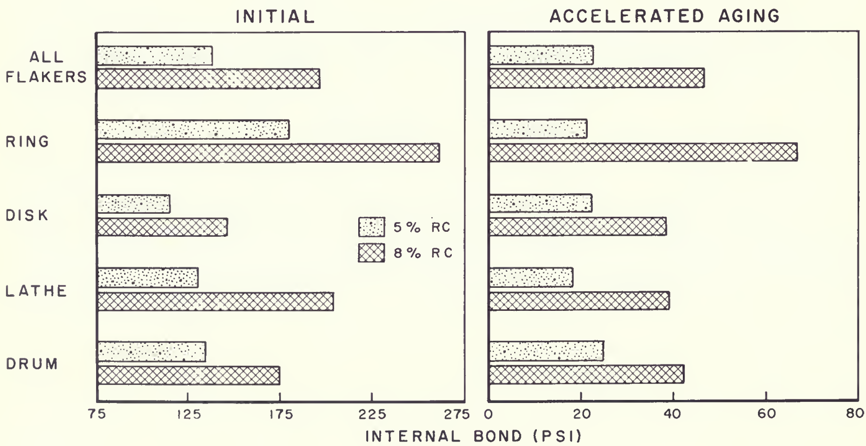

Figure 24-7.—Effect of 5- and 8-percent phenol-formaldehyde resin content (RC) on the average internal bond strength of 1/2-inch-thick southern red oak and mockernut hickory panels made from 2-1/4-inch-long, 0.020-inch-thick flakes cut on four types of flakers. Panels were fabricated at a target density of 52.6 lb/cu ft. (Left) Initial strength at 50 percent relative humidity. (Right) Strength after accelerated aging cycle. (Drawing after Price and Lehmann 1978.)

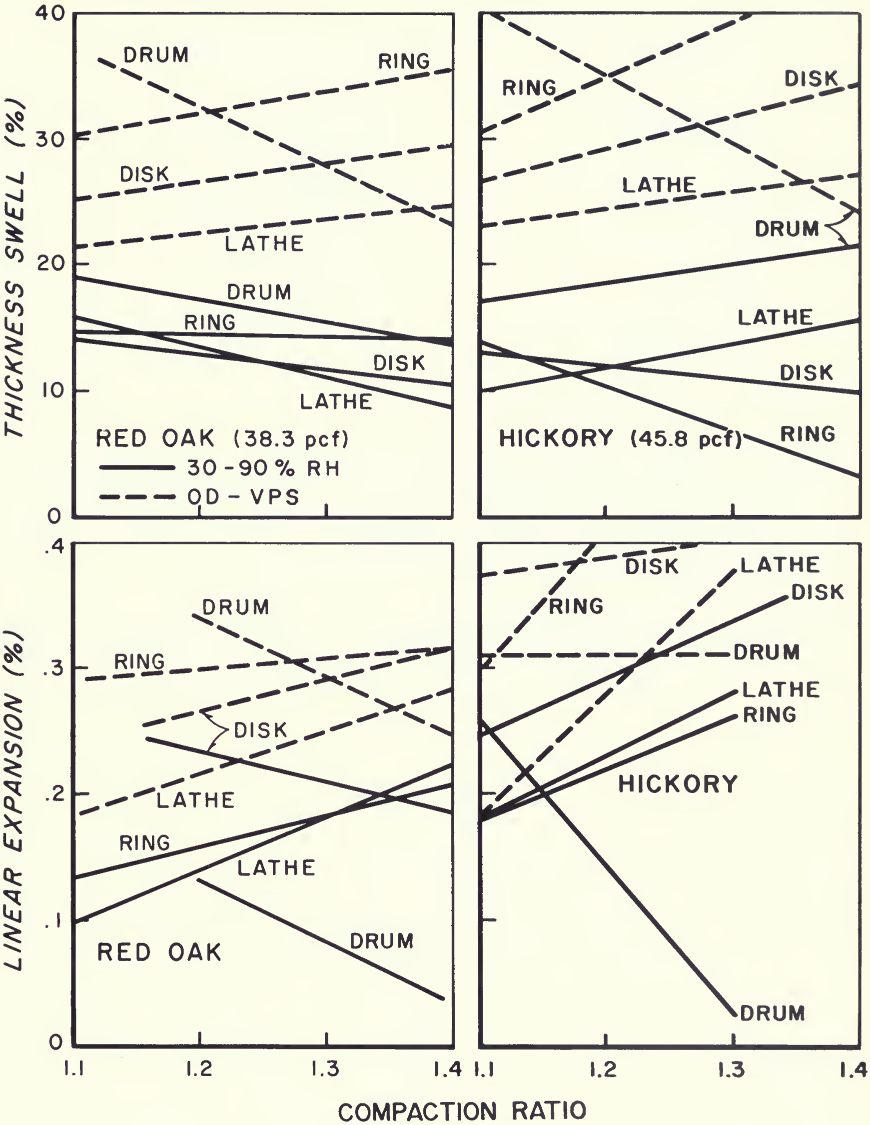

Figure 24-8.—Linear expansion and thickness swell related to compaction ratio in 1/2-inch-thick southern red oak and mockernut hickory panels made from 2-1/4-inch-long, 0.020-inch-thick flakes cut on four types of flakers, and subjected to a change of relative humidty (RH) from 30 to 90 percent or to an ovendry-vacuum-pressure-soak (OD-VPS) cycle. (Drawing after Price and Lehmann 1978.)

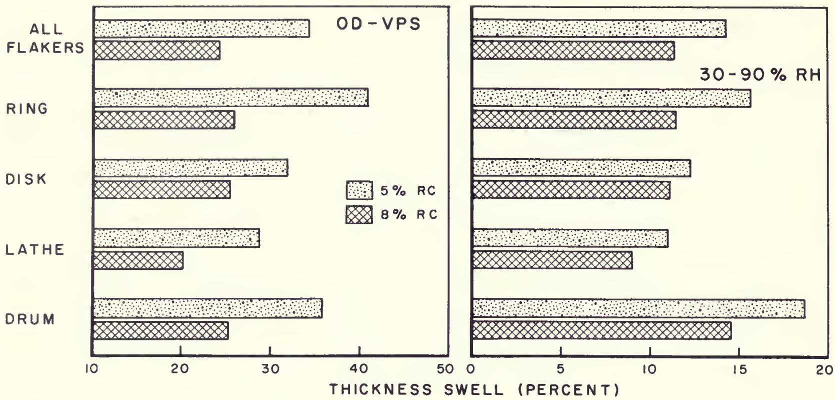

Figure 24-9.—Effect of 5- and 8-percent resin content (RC) on average percent of thickness swell of southern red oak and mockernut hickory panels (pooled data). The panels were fabricated 1/2-inch thick at a target density of 52.6 lb/cu ft with 2-1/4-inch-long, 0.020-inch-thick flakes cut on four types of flakers. (Left) After ovendry-vacuum-pressure-soak cycle. (Right) When cycled from 30 percent to 90 percent relative humidity. (Drawing after Price and Lehmann 1978.)

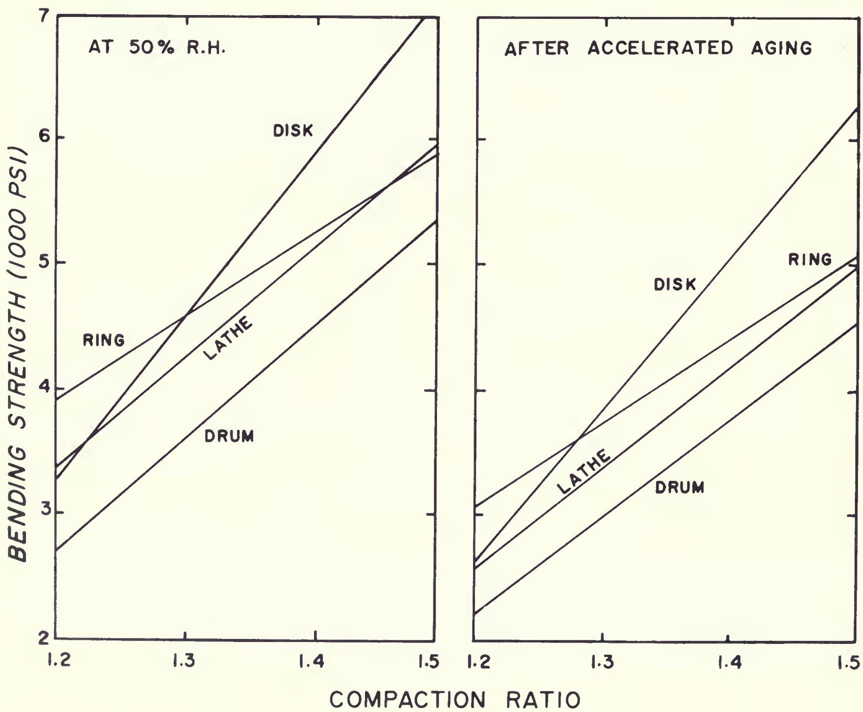

Figure 24-10.—Bending strength (modulus of rupture) related to compaction ratio of 1/2-inch-thick sweetgum panels made from 2-1/4-inch-long, 0.020-inch-thick flakes cut on four types of flakers. (Left) Tested at 50-percent relative humidity. (Right) Tested after accelerated aging cycle. (Drawing after Price and Lehmann 1978.)

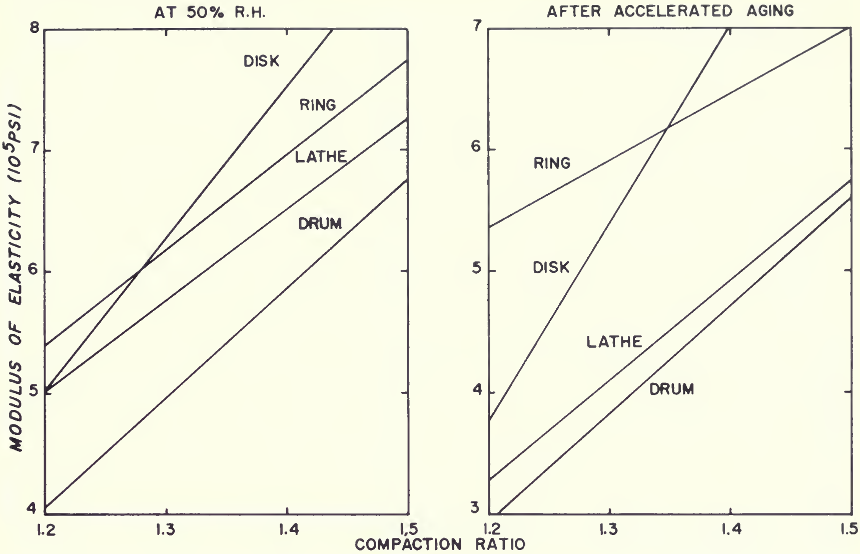

Figure 24-11.—Modulus of elasticity related to compaction ratio of 1/2-inch-thick sweetgum panels made from 2-1/4-inch-long, 0.020-inch-thick flakes cut on four types of flakers. (Left) Tested at 50-percent relative humidity. (Right) Tested after accelerated aging cycle. (Drawing after Price and Lehmann 1978.)

FLAKE DRYING[4]

Southern hardwood flakes will, for the most part, be cut from green, heated stemwood of species having average moisture content of about 79.3 percent (dry-weight basis). In most cases, the wood will be sorted, prior to flaking, into at least two species classes according to wood specific gravity. The high-density woods including the ash, hickory and oak species will have moisture contents from about 47 to about 74 percent; low-density woods such as sweetbay, sweetgum, and yellow-poplar will range from 100 to 120 percent moisture content, dry-weight basis (table 8-2). These particles will generally be 1-1/2 to 3 inches long and 0.015 to 0.025 inch thick. To dry such flakes, industry in North America largely relies on rotating-drum driers direct-fired by oil, natural gas, or dry woodwaste.

Rotary-drum dryers.—The rotary-drum-type dryer flash dries surface moisture from the wood particles and drives moisture from the interior of the particle to the surface. Hot gases of combustion and excess air are pulled through the drum by an induction fan. The small and light weight particles are air-conveyed through the dryer in a matter of seconds. Heavy and large particles are air-conveyed in the high temperature and high velocity channels of the dryer but begin to drop out of the gas stream as the velocity diminishes.

[4]With addition of illustrations and introductory material, this subsection is largely taken from Raddin (1975).

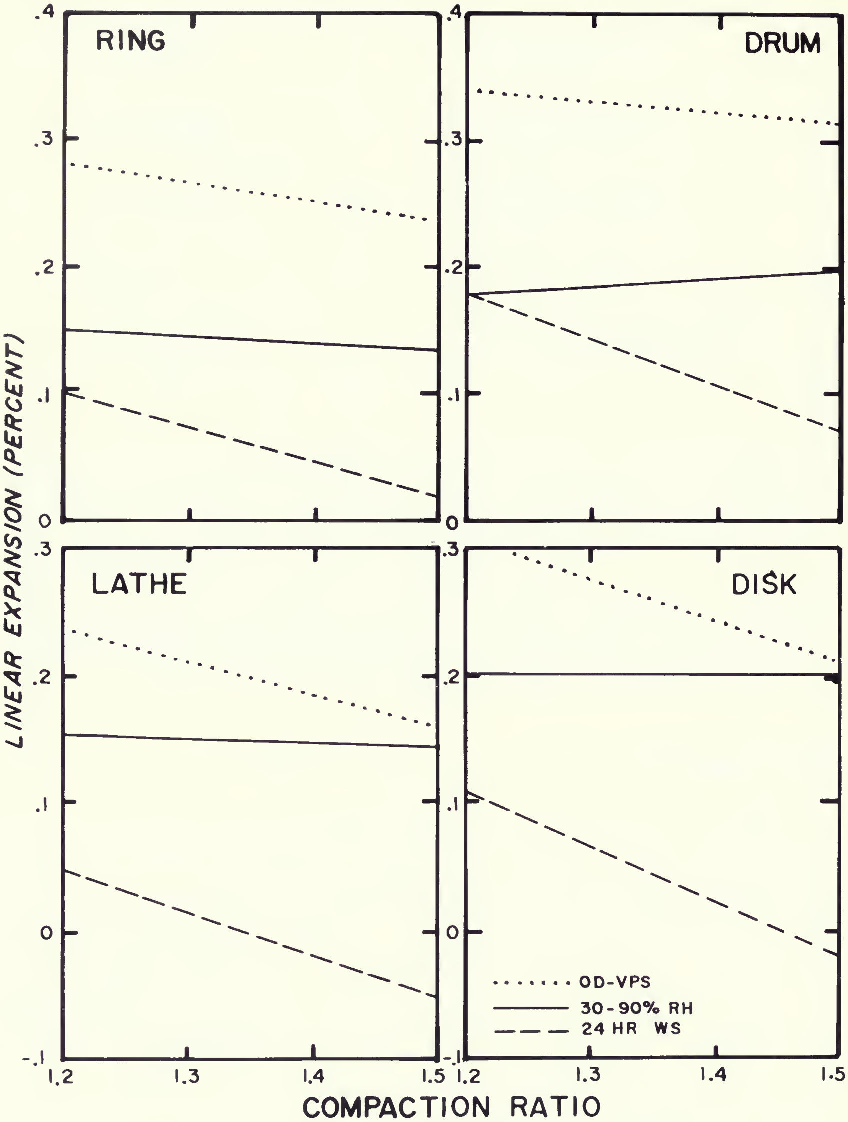

Figure 24-12.—Linear expansion under three exposure conditions related to compaction ratio for 1/2-inch-thick sweetgum panels made from 2-1/4-inch-long, 0.020-inch-thick flakes cut on four types of flakers. OD-VPS means ovendry-vacuum-pressure-soak cycle; WS means water soak (Drawing after Price and Lehmann 1978.)

They are then lifted by flights within the rotary drum and dropped into the gas stream again and again, each time advancing a distance along the drum axis determined by the particle weight, which decreases as drying progresses. This action allows time for moisture migration from the interior to the exterior of the particle. Heavy particles may take 5 to 6 minutes to travel through the dryer. The material and hot gases are separated by a cyclone collector at the dryer exit.

Gas temperatures at the furnace outlet where the wood particles enter the gas stream will reach a maximum of 1,800°F to dry flakes with 175 percent moisture content (dry basis) and higher. Normally, with wood at 67 to 100 percent moisture content (dry basis), the inlet gas temperature will be between 700 and 1,200F. The outlet gas temperature at the cyclone collector will be 160 to 250°F when drying flakes. Wood leaving the dryer will have a temperature of only 130 to 140°F; consequently there is little or no degradation of the wood.

Rotary-drum dryers have evaporative capacities up to 30,000 pounds of water per hour and are generally either one-pass or three-pass types.

One-pass rotary drum-dryers.—One-pass dryers vary in design, but all retain wet, heavy particles for a longer time in the drying zone than drier, lighter particles. In one design (fig. 24-13) a conical gas inlet carries flakes into a flighting system designed to disperse material throughout the dryer cross-section; in this design, dryer exhaust gases at 200° to 220°F may be recycled. Recycling of exhaust gases is difficult to accomplish without undue fire hazard. Typically, incoming gas temperature is 550° to 750°F; temperatures depend on species dried. Some dryer specialists suggest that the flighting systems, because they act as flow retarders, break the flakes more than three-pass suspension systems, and wear more rapidly. Single-pass dryers have less throughput and less control over dry flake moisture content than three-pass dryers.

Three-pass rotary-drum dryers.—The three-pass dryer (fig. 24-14), the type most widely used, has a center cylinder (first pass) with a high entrance gas velocity, up to 1,600 fpm, and high temperatures (e.g., 1,200°F). Successive passes through the middle and outer drum or annulus have lower velocities in the 640- to 320-fpm range and lower temperatures, depending on evaporation, with temperature at the exit cyclone of about 220° to 260°F to attain 3- to 4-percent moisture content of flakes. A regulator actuated by the outlet temperature of the gases modulates the furnace burner to control the moisture content of the particles leaving the dryer.

Thermal efficiency of the three-pass dryer is such that materials in the 100- to 185-percent range of moisture content (dry basis) require 1,500 to 1,900 Btu per pound of water evaporated. Materials in the 18- to 33-percent moisture range require 1,900 to 2,300 Btu per pound of water evaporated. Generally, the higher the temperature differential across the dryer and the higher the input moisture content, the greater the efficiency and the fewer the Btu required to evaporate a pound of water.

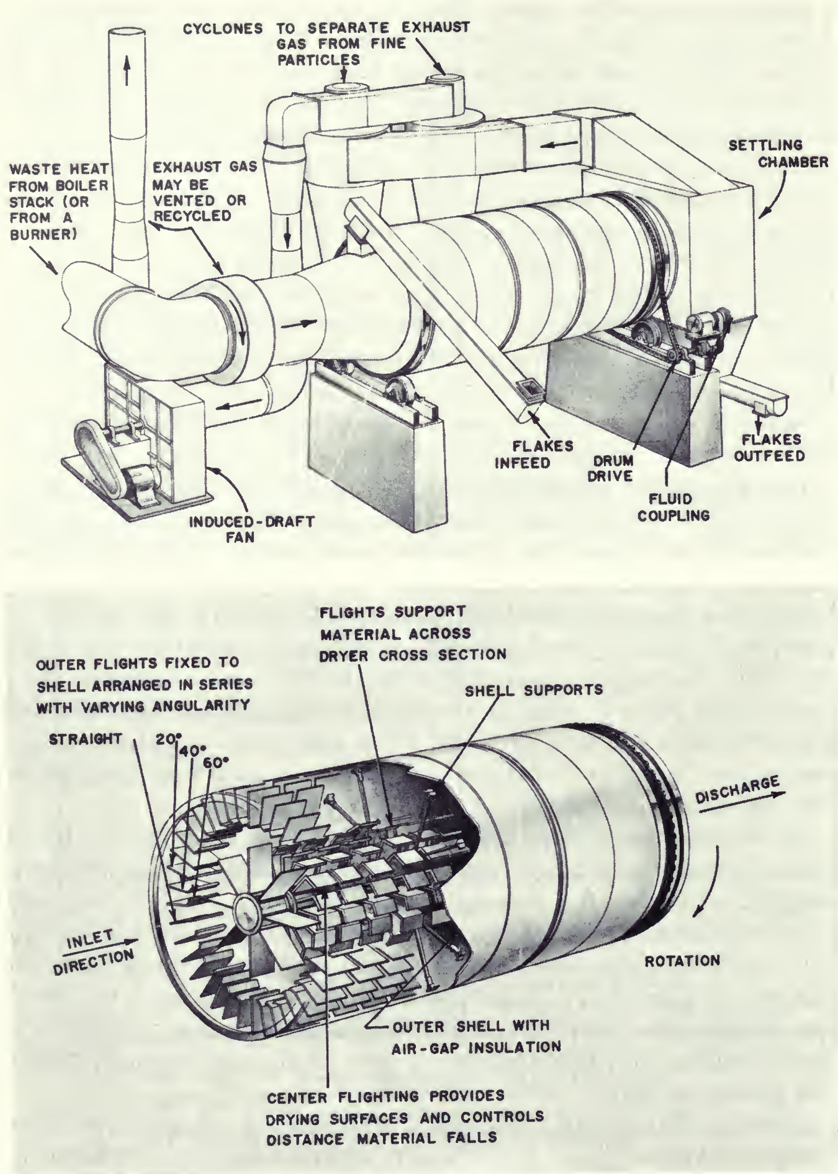

Figure 24-13.—One-pass rotary drum dryer. (Drawings from Rader Companies, Inc.)

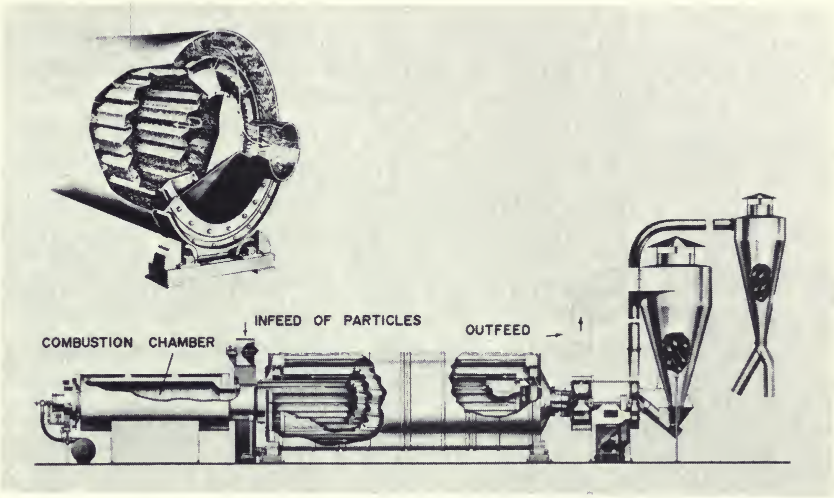

Figure 24-14.—Rotating three-pass drum dryer. (Bottom) Major components. Infeed of furnish and hot air to inner drum on left; discharge from outer drum to hot cyclone (to separate hot gases from the dry particles) and final cyclone on right. (Top) Flow-path of furnish from hot inner drum to intermediate drum to cooler outer drum. Baffles cause particles to tumble as they pass through the three drums. Outfeed end shown. (Drawings after Stillinger 1967.)

Typical statistics for a three-pass rotary-drum dryer for green, 0.020-inch-thick southern hardwood flakes vary with throughput as follows (personal correspondence May 3, 1982 with B. Ernt, MEC Company):

Statistic	Throughput of flakes/24 hours (dry-weight basis; 3- to 4-percent moisture content)	
	240 tons	*325 tons*
Inlet gas temperature, °F	900	1,000
Drum speed, rpm	7.5	7.5
Drum diameter, feet	12	12
Drum length, feet	48	60
System horsepower	250	310

Dryer feed.—Particle size should be reasonably consistent; for example, pulp chips and sawdust should not be mixed. Included with flakes, however, up to 15-percent fines can be dried without difficulty. If woods of different moisture contents are to be mixed before drying, they should be stored separately under roof, and the mix accurately metered and thoroughly blended before admission to the dryer.

The material to be dried must be admitted to the dryer through a rotary valve or other type of air seal to prevent induction of cold air. Although most infeeding devices such as screw-feed or belt-feed equipment deliver a uniform volume of material, a better system would provide a constant rate of input based on weight. Gradual changes of infeed rate cause no particular problem, but sudden changes cause the final moisture content of the output material to fluctuate. Induced air for combustion and conveying must be clean; induction of dust-laden air promotes fines and explosions.

At the discharge end of the dryer, a drop-out box is provided in which air velocity diminishes so that the flakes pass a fire dump and drop through an airlock to a conveyor to screens. The fines are carried beyond the drop-out box to a cyclone which collects them for use as dry fuel.

Recirculation.—Recirculation of exhaust gases from the dryer collector to the dryer inlet can reduce fuel required and reduce particulates in exhaust gases. The amount of recirculation varies inversely with the water evaporation requirement of the system. For example, if a dryer is operating at about 80 percent of its rated capacity, then only 20 to 30 percent of the gases could be recirculated. But if the dryer was using only 30 percent of its capacity, up to 50 to 60 percent could be recirculated.

Recirculation can increase fire hazard by burning of particles in the recirculated gases, particularly in the event of a plugged collector. Although commonly used in other industries, recirculation is being used in only a few board plants to date. Dryer manufacturers make special design provisions for recirculation, including furnace breaching for burning the particles while returning the gases to the dryer inlet, and extra elbows in ductwork to extinguish sparks; they should be consulted if recirculation of gases is being considered.

Pollution control.—Emission of particles with the gases from the primary dryer collector generally exceeds pollution standards. Dust collection systems following the dryer collector have difficulties because the steam content in the gases condenses in cold weather. Secondary, high efficiency multiple cyclone collectors are not always adequate. Impact or impingement type collectors will generally not work with fines because of their low mass and inertia. Bag collectors are particularly susceptible to any condensation, even with high-temperature resistant bags, and any spark or fire in the system will destroy the bags and frames, requiring costly replacement and down time.

Raddin (1975) noted that the Aerodyne Dust Collector (fig. 24-15) has proven effective. This unit has no moving parts, is constructed of steel, can be preheated to prevent condensation of steam, and is not easily damaged by fire. Its efficiency with wood dust and fiber is very high and particulate matter in the outlet gases to atmosphere will be about 0.01 to 0.02 grains per standard cubic foot, which is adequate to meet most emission standards. It is used as a secondary collector following the primary dryer collector which removes most of the conveyed material.

Emissions of particulates from dryer collectors have been measured in the range of 0.07 to 0.60 grains per standard cubic foot (dry without the dilutive effect of the steam). Standards call for 0.1 to 0.2 grains per standard cubic foot. Of the total emission, the proportion of hydrocarbons can be as high as 40 percent, particularly with conifers. The hydrocarbons are evident as a haze in the gases, and are measured by gas opacity.

The temperature at the dryer inlet will affect the generation of haze—the lower the better. Consequently, multiple stage drying at lower temperatures could reduce haze to acceptable levels. Recirculation of gases reduces haze also because the hydrocarbons burn when reintroduced to the furnace. Water scrubbing reduces hydrocarbons by agglomeration and cooling, but not substantially.

After-burning is an effective method but will nearly double the fuel cost unless the gases can be introduced into an existing boiler.

Heating alternatives.—Fuel costs for drying are high and increasing. The gas-fired, oil-fired, or combination burners commonly used in dryer furnaces

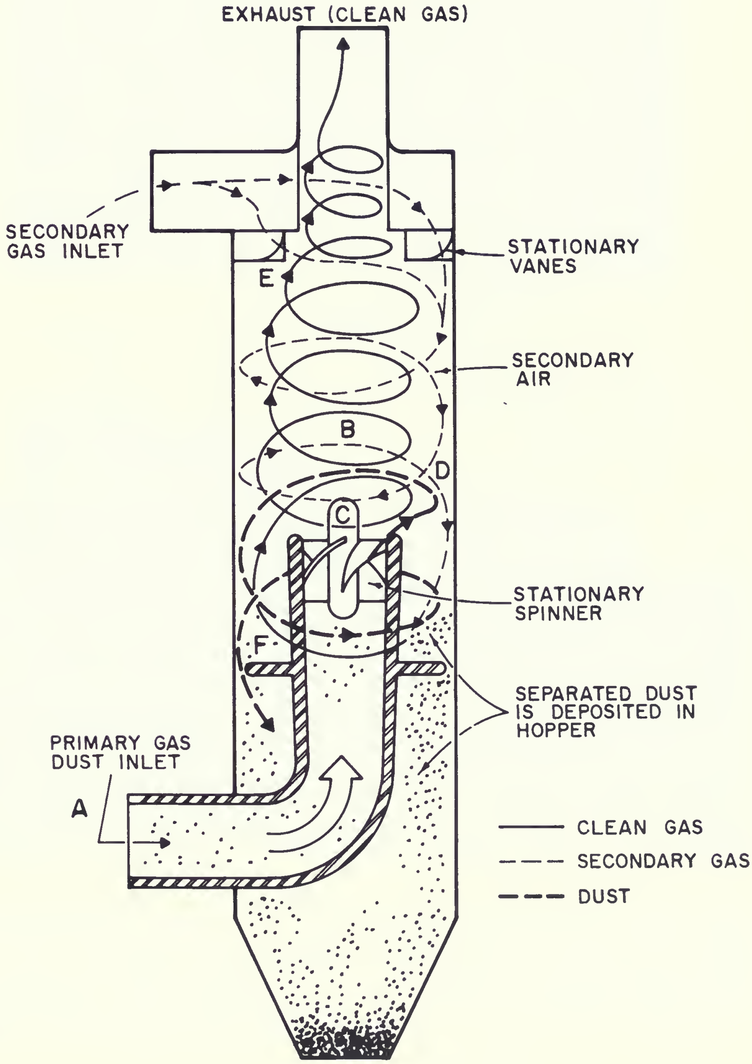

Figure 24-15.—Dust collector for use behind the primary collector at outfeed end of rotary-drum flake dryer. The dirty gas stream (A) enters collector chamber (B), past a stationary turning vane (C), which imparts a rotary motion to the flow (D). Centrifugal force directs the dust toward the outer wall of the collector where it is engaged by a secondary gas stream (E) and directed spirally downward (F). Clean gas exhausts at the top. (Drawing after Aerodyne Development Corporation.)

have been clean, simple, and very responsive for good moisture control. Uncertainties about supply and cost of these fuels, however, has made it necessary to investigate alternative methods of heating.

If the plant where the dryer is to be located has a steam generator, several alternatives are available, as follows:

- Flue gases from a steam generator will usually be at 400 to 600°F in the stack breaching and have substantial volume. These gases can be ducted directly to the dryer furnace. Control of temperature is accomplished by tempering with fresh air, adding additional heat with oil or gas, or a combination of both.
- Such flue gas for direct firing must be essentially free of combustible materials or they will contaminate the product. If the boiler does not have clean flue gas, then an air-to-gas heat exchanger can be used. This arrangement limits maximum air temperature to about 150°F lower than the flue gas supply temperature.
- Steam-to-air exchangers are widely used and are more compact than air-to-gas exchangers, for the high latent heat of the steam is available. High-pressure steam is required in the 600 psi (gauge pressure) range to attain air temperatures in the mid 300°F range. Application of steam-to-air exchangers is limited, therefore, to drying of low-moisture-content materials or to multi-stage drying.

Fuels for steam generators can, of course, be wood wastes available from forestry, lumber, woodworking, and board operations; there are many such installations, and well-proven equipment is available. (See ch. 26.) Also, both dry and green wood residues can be direct-fired (figs. 26-18 and 26-21) so that steam generation is not a necessary intermediate step.

SCREENING

Dry flakes, after passing a fire dump, are discharged from the dryer through an airlock and conveyed to a rotary-drum screen (fig. 24-16). Apertures in screens for face flakes are typically larger (e.g., 5/16-inch) than those in core-flake screens (e.g., 1/4-inch). Wire diameters are typically about 0.054 inch in screens for face flakes and 0.047 inch in screens for core flakes; for long screen life the wire must resist abrasion by the flakes. The screens tumble the flakes and remove excessively strandy material from face flakes (for use in cores), and fines from core flakes (for use as fuel). Typically each screen is revolved slowly by a 10 hp motor with screening capacities and dimensions about as follows:

Drum diameter and length	Hourly capacity
Feet	*Tons, ovendry*
6 by 20	7.5
8 by 20	10.0
10 by 25	12.5

As described by Maloney (1977, chapter 10) there are many alternative methods of screening particles, but rotary-drum screens are dominant in the flakeboard industry.

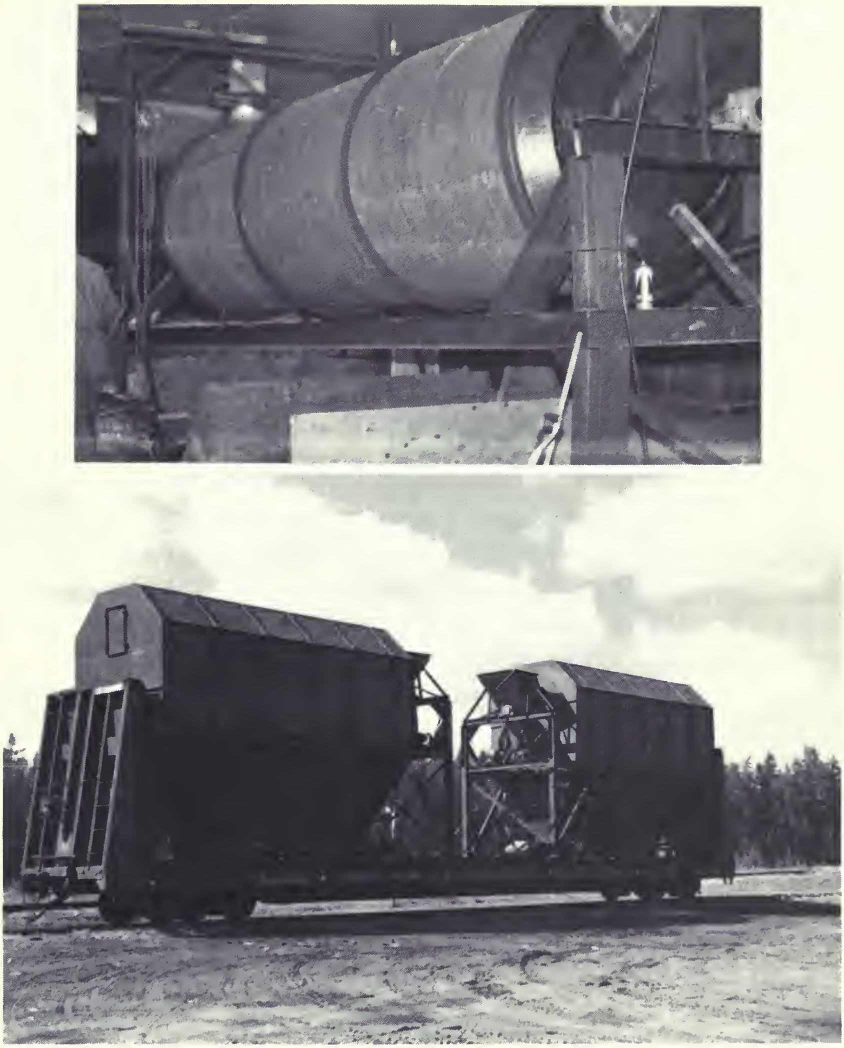

Figure 24-16.—(Top) Five-foot-diameter by 15-foot-long rotary screen for flakes. (Bottom) Two assemblies each containing a rotary screen. Unscreened flakes enter through the top-loaded hoppers visible at ends. Fines and dust exit through hoppers at the bottom of each assembly. Accepted flakes are retained within the screen cylinder and discharged from the end opposite the infeed hopper. (Photos from Precision Service and Engineering Ltd.)

STORAGE

In many regions it is usual to convey acceptable flakes from the screening operation to bulk interior storage in concrete-floored bins; in this arrangement flakes are removed from storage by front-end loaders and introduced into conveyors leading to resin blenders.

The frequent high humidity in the Southern States can dampen freshly dried flakes—if stored for several days—to a moisture content exceeding the 2-6 percent desirable when they are admitted to the resin blender.

Some plant designers feel that operations can be made less labor intensive, and flake moisture pickup avoided, if screened flakes are deposited in moving-bin storage (fig. 24-17), providing 1-1/2 to 2 hours of storage ahead of the resin blender; such bins have floors that move, thereby continuously conveying flakes to the blender. Power to drive bottom conveyor chains, picker rolls, and rake-back conveyor totals about 10 hp.

Designers concerned with flake transport should appreciate that thin, long, hardwood flakes for face layers are particularly difficult to handle. Conveyors must be of ample width, and with minimum discontinuities. Wide belts, deformed into semi-tubular shape, have proven effective. Bulk densities of 3-inch-long, 0.020-inch-thick hardwood flakes are about as follows (condensed from table 16-44):

	Red maple, sweetgum, and yellow-poplar		Oak and hickory	
Condition	Green	Dry	Green	Dry
	Lb/cu ft			
Loose	14.3	5.8	7.7	5.7
Blown into van	6.2	2.0	5.3	3.4
Settled in transport	18.4	—	10.5	—
Settled by vibration	10.8	4.2	7.7	2.8
Baled with pressures of				
12.5 psi	21.9	10.4	14.5	6.0
50.0 psi	22.4	10.4	14.5	6.0
100.0 psi	22.4	10.4	14.5	6.0

A more complete discussion of handling and storing particles is given on pages 264 through 281 of Maloney (1977) and in Moeltner and Young (1976).

24-5 RESIN SELECTION AND APPLICATION

Resin binders for structural flakeboards are in part determined by the conditions to which the panels will be exposed. There is some doubt about the suitability of resin-bonded flakeboard for long-term exterior application; shielding flakeboard from the effects of weathering appears more promising than attempts to greatly improve its resistance. Performance standards for sheathing and for combination subfloor and underlayment (see sec. 24-2) recognize two

Figure 24-17.—5,000 cubic-foot-capacity storage bin for dry flakes. (Top) Side view of bin; flakes enter the top of the bin at the left end and are deposited on a moving-chain floor which conveys them to the left against four picker rolls arranged to rotate against (up) the inclined face of the pile to meter flakes into the resin blender; flakes are discharged downward at extreme left end. (Bottom) View of bin interior showing the several strands of conveyor chain on the floor, the four picker rolls at the discharge end of the bin, and the top rakeback conveyor which pulls excess flakes to the rear of the bin (toward the viewer) and away from the top entry hopper. (Photos from Precision Service and Engineering Ltd.)

exposure ratings, neither of which qualify products for unprotected exterior application.

With few exceptions, the hardwood structural flakeboard industry uses phenol-formaldehyde resins as binders. One company has manufactured waferboard from a spray-dried mixture of co-reacted kraft black liquor and a phenolic resol (Dolenko and Clarke 1978), and much research has been aimed at binding aspen waferboards with spent sulfite liquor powder (Shen 1974, 1977a; Shen and Fung 1979). Polyisocyanates, in a variety of formulations, also show considerable promise for hardwoods (Hse 1978; 1981; Steiner et al. 1980). To reduce dependence on petroleum-based adhesives, researchers throughout the world are vigorously studying bark tannins as partial replacements for phenol, e.g., see Madle and Molnar (1980).

This book does not delve deeply into resin technology. Readers interested in the technology will find useful the treatise being prepared on the subject by C.-Y. Hse of the Southern Forest Experiment Station, Pineville, La. Texts on the subject already in print include Martin (1956), Megson (1957), and Lloyd (1981). Some knowledge is needed, however for appreciation of manufacturing procedures and panel performances.

PHENOL-FORMALDEHYDE RESOL AND NOVOLAC RESINS

Resol resins.—Phenol formaldehyde resins can be prepared by two methods. For **resol** resin, phenol is reacted with excess formaldehyde in the presence of an alkali catalyst. Mole ratios of formaldehyde to phenol of 1.8:1 to 2.2:1 are employed. Curing to produce a rigid thermoset resin is activated by increased temperature. Resol-type resins may be purchased either as a liquid or as a spray-dried powder which has to be mixed with water.

Novolac resins.—Reacting excess phenol with formaldehyde in the presence of an acid catalyst produces a hard resin known as **novolac**. Mole ratios of 0.8:1 to 1:1 are used. The novolac is ground into a fine powder to which is added about 15 percent of hexamethylene tetramine. When heated in a hot press, the powder forms ammonia, which acts as a catalyst, and formaldehyde—which reacts with the heat-liquified novolac—to produce a thermosetting resin. Novolac resins are more stable than the resols, but must be kept dry.

Powdered resins.—In the production of aspen waferboard, the primary adhesive type used is spray-dried phenolic resol powder which requires only about 150°C to thermoset, some 10° to 30°C lower than novolacs. Spray-dried resols also yield board properties superior to novolacs (Hickson 1980).

Powdered resin is easily applied to flakes of certain species (e.g., aspen) with simple equipment. Distribution is good because the resin tends to cling in a uniform monolayer over all surfaces, thus minimizing over-application, and affording high resin efficiency. Because of the added manufacturing operations of spray drying and grinding, however, powdered resins are usually more expensive than liquid. For optimum flow, they also require 10 to 20°C higher press temperatures than those needed for liquid resins, and they sometimes create an annoying dust problem (Hse 1975a).

While effective on aspen flakes, powdered resins have been much less successful when applied to southern hardwoods such as oaks, hickories, and sweetgum. By the early 1980's, therefore, liquid resin was preferred by those with most experience in fabricating structural panels from southern hardwood flakes.

Powdered resin probably fails on southern hardwoods because these species are less compacted than aspen in flakeboard pressing, and their cure times are short. Powdered resins applied to flakeboards comprised of 60 percent oaks and 40 percent low density southern hardwoods require high compaction ratios, or long cure time, or both, as follows:

Resin and press time	Panel density based on OD weight and volume at test	Internal bond strength
Minutes	*Pounds/cu ft*	*Psi*
Liquid		
5.5	42	80.0
Powder		
5.5	42	30.4
5.5	50	64.9
8.0	42	67.0
8.0	46	79.9

Liquid resins.—Numerous liquid resins of the resol type were prepared and tested by Hse (1975b, 1978) in a search for an economical formulation effective in gluing flakeboards of mixed southern hardwoods. Of those evaluated, the phenol-formaldehyde resin that performed best was formulated as follows (fig. 24-18).

Statistic	Value
Reaction concentration, percent by weight	47.5
Molar ratio of sodium hydroxide to phenol	0.45
Molar ratio of formaldehyde to phenol (first addition of formaldehyde)	1.5:1
Molar ratio of formaldehyde to phenol (in second addition after 2.5 hours of reaction time)	0.3:1
Reaction temperature	95°C

This resin yielded satisfactory bonds in laboratory panels made of mixed southern hardwoods with:

- A minimum resin-solids content of 4 percent of weight of ovendry flakes
- A maximum mat moisture content of 14 percent
- A hot press temperature of 325°F
- A minimum hot press time (closed) of 4 minutes

Subsequently Hse (1975c), using a very similar resin, evaluated the internal bond strength and stability of 1/2-inch-thick panels of nine species of southern hardwoods pressed to three densities. Within the range of the experiment, all species—except white oak and post oak—yielded panels of acceptable internal bond strength and dimensional stability at panel density, ovendry-weight basis, of 44.5 pounds per cubic foot or less (table 24-9). The flakes used in this experiment were identical to those shown in figure 18-264.

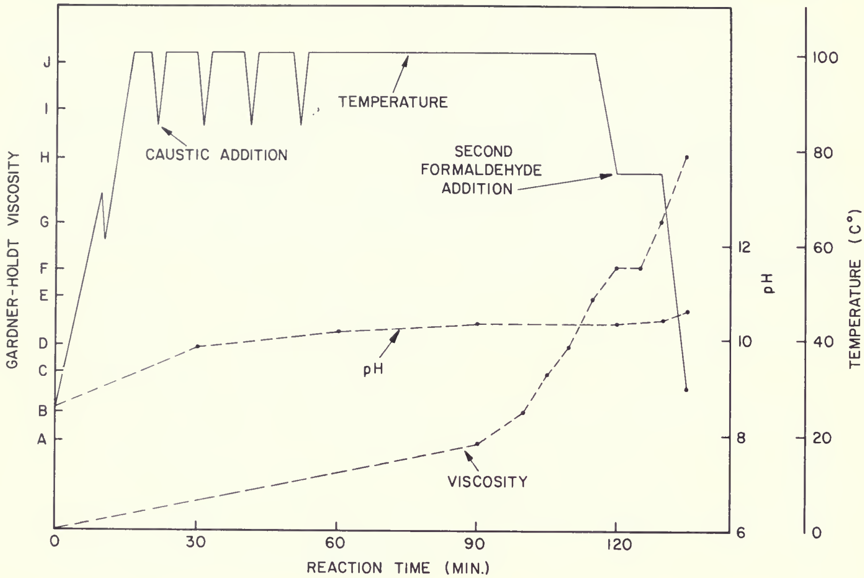

Figure 24-18.—Viscosity, pH, and reaction temperature as related to reaction time during preparation of phenol-formaldehyde resin. (Drawing after Hse 1975b.)

IMPROVED PHENOLIC LIQUID RESINS

Resorcinol-modified liquid phenolic resin.—Although resorcinol adhesives have outstanding durability under severe test conditions, Hse (1981) found that a resorcinol-modified phenolic system gave little improvement in dimensional stability of hardwood flakeboard.

Alloy of liquid phenol-formaldehyde resin and polyisocyanate.—Hse (1981) found that an alloy of two types of liquid resin could bond flakeboards of high-density hardwoods (white and southern red oak) so that they had acceptable stability (table 24-10). In this alloying process, minor amounts of polyisocyanate are applied to the flakes before application of major amounts of phenol-formaldehyde resin. The combined adhesive reacts in situ to obtain an improved thermosetting adhesive resin. Performance of the new phenolic alloy is superior to that of phenolic resin under conditions of high flake moisture content, low resin content, and low panel density. The process produced internal bond strength in all the white oak and southern red oak panels about 500 percent greater than in those with phenol-formaldehyde resin alone. This increased internal bond strength should permit reduction of panel density to improve dimensional stability. The alloyed resin, is, however, more expensive and presents more hazard to health during panel fabrication than conventional liquid phenol-formaldehyde resin.

TABLE 24-9.—*Internal-bond strength and dimensional stability, by three tests, of 1/2-inch flakeboard of nine species and three densities, bonded with liquid phenol-formaldehyde resin* (Hse, 1975c)[1,2]

Species	Board weight	Internal bond	Vacuum-pressure-soak[3] Thickness swelling	Vacuum-pressure-soak[3] Linear expansion	5-hour-boil Thickness swelling	5-hour-boil Linear expansion	50-90% RH Thickness swelling	50-90% RH Linear expansion
	Lb/cu ft	*Psi*	*Percent*					
Sweetbay	39.5	109	27.8	0.127	36.9	0.067	20.3	0.094
	44.5	260	29.3	.047	37.8	.061	16.4	.088
	49.5	236	30.1	.214	47.1	.168	21.1	.153
Red maple	39.5	97	20.3	.134	20.5	.145	13.3	.156
	44.5	284	27.1	.027	31.5	.053	13.9	.090
	49.5	315	27.8	.144	47.6	.146	20.8	.176
Sweetgum	39.5	81	23.6	.059	32.0	.095	21.6	.068
	44.5	171	31.9	.093	47.1	.045	20.8	.083
	49.5	196	42.6	.126	58.2	.164	31.8	.195
Black tupelo	39.5	113	22.3	.130	24.2	.128	15.4	.154
	44.5	239	23.4	.222	31.2	.177	14.6	.219
	49.5	385	25.7	.225	39.2	.199	21.6	.252
White ash	39.5	83	21.2	.198	23.3	.194	13.7	.204
	44.5	148	21.4	.149	28.1	.181	13.5	.174
	49.5	273	24.6	.227	40.0	.204	22.2	.259
Southern red oak	44.5	55	20.7	.171	26.4	.173	14.9	.169
	49.5	146	27.4	.253	51.5	.175	23.2	.251
Hickory	44.5	65	22.1	.245	27.3	.238	15.7	.212
	49.5	107	23.0	.171	33.5	.213	16.0	.172

Table continued on following page.

TABLE 24-9.—*Internal-bond strength and dimensional stability, by three tests, of 1/2-inch flakeboard of nine species and three densities, bonded with liquid phenol-formaldehyde resin* (Hse, 1975c)[1,2]—Continued

Species	Board weight	Internal bond	Vacuum-pressure-soak[3]		5-hour-boil		50-90% RH	
			Thickness swelling	Linear expansion	Thickness swelling	Linear expansion	Thickness swelling	Linear expansion
	Lb/cu ft	*Psi*	*Percent*					
Post oak	44.5	58	27.5	.296	63.7	.241	14.6	.270
	49.5	119	28.0	.306	65.2	.189	18.0	.268
White oak	44.5	51	48.5	.379	80.1	.314	20.1	.296
	49.5	88	56.8	.480	112.3	.443	25.6	.351

[1]Veneer flakes were rotary peeled 0.015 inch thick and clipped to 3-inch length and 3/8-inch width.

[2]Pressing conditions were as follows:
Flake moisture content 3 percent; resin-solids content was 4 percent based on ovendry weight of flakes; hot-press temperature was 325°F; hot-press time (closed) was 5 minutes.

[3]The vacuum-pressure-soak test (VPS) consisted of soaking 3- by 9-inch specimens under vacuum (25 inches Hg) for 30 minutes and then under 65 psi pressure (at room temperature) for 24 hours.

TABLE 24-10.—*Effect of application of polyisocyanate to flakes before addition of liquid phenol-formaldehyde resin on internal bond strength and stability of 1/2-inch-thick flakeboard panels of southern red oak and white oak* (Hse 1981)[1,2,3]

Wood species and resin	Internal bond strength	Thickness swelling [4]	Linear expansion [4]
	Psi	----------*Percent*----------	
Southern red oak			
Straight phenol-formaldehyde resin	29	26.0	0.358
Half phenolic and half polyisocyanate	147	27.2	.370
Three-fourths phenolic and one-fourth polyisocyanate	158	28.0	.343
White oak			
Straight phenol-formaldehyde resin	30	41.4	.528
Half phenolic and half polyisocyanate	176	31.8	.329
Three-fourths phenolic and one-fourth polyisocyanate	149	30.8	.375

[1]The phenolic resin had molar ratio of formaldehyde to phenol of 1.9, reaction concentration was 47.5 percent, and molar ratio of sodium hydroxide to phenol was 0.45; the commercially available polyphenol isocyanate had functionality of 2.7, and viscosity of 200 to 275 cps at 25°C; resin content of all panels was 5 percent of the ovendry weight of the flakes.

[2]Panels were homogenous with randomly oriented flakes cut 3 inches long, 0.015 inch thick, and random width on a shaping-lathe headrig. The flakes were conditioned to 7 percent moisture content before resin application.

[3]Panels were pressed at 335°F with 45-second press closing time and 5-minute closed-press time, to a density of 45 pounds per cubic foot (basis of ovendry weight and volume at test).

[4]After ovendry-vacuum-pressure-soak cycle.

APPLICATION OF RESIN

Unlike the waferboard plants of Canada which need contend only with aspen, the manufacturer of hardwood structural flakeboard in the southern pine region must tailor processes to suit a number of species with diverse anatomical characteristics. Southwide, the most plentiful pine-site hardwoods are sweetgum (13.2 percent), white oak (12.3 percent), hickory sp. (8.5 percent), and southern red oak (8.1 percent). Flakes from each of these species are distinctive (figs. 18-102 and 18-274ABC). Sweetgum flakes tend to be wide—some will be folded, hickory frequently yields tubular flakes, and the two oaks form strands. Because white oak has prominent tyloses in the vessels (figs. 5-13 top and 5-22) that inhibit flake separation at vessels, strands of white oak are usually wider than those of the red oaks that lack tyloses in vessels.

For reasons not entirely clear, probably related to compaction ratios and press times used—but possibly to surface texture of flakes (fig. 24-19)—powdered resins have been successfully applied to aspen flakes but not to flakes of pine-site hardwoods.

Failing to obtain good results with powdered resin, researchers have favored liquid resins for southern hardwood structural flakeboards. In most laboratories, the flakes are tumbled in a rotating drum (14 rpm) perhaps 3 to 4 feet in diameter

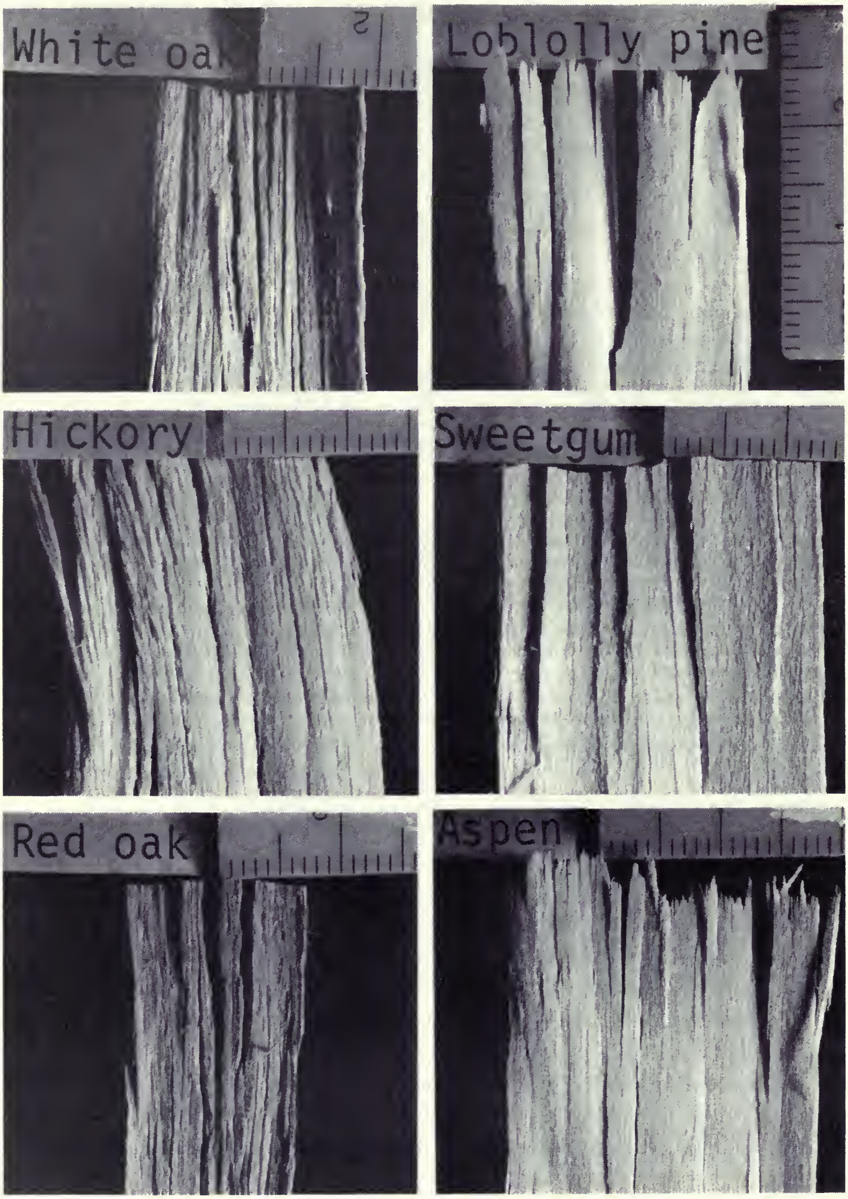

Figure 24-19.—Surface texture of flakes cut from six species with shaping-lathe headrig. Scale marks are 1/10-inch apart. (Photo from files of C.-Y. Hse.)

for long periods (7 to 10 minutes) while intermittently placed spray nozzles disperse a fog of resin comprised of the finest possible droplets. Liquid resin is usually applied to southern hardwood flakes at rates of 4 to 7 percent, resin solids basis, of the ovendry weight of the flakes. Figure 24-2 (top) depicts a panel made of flakes on which resin has been uniformly applied in desired small droplets.

In 1980 the literature contained no in-depth studies of the technology of applying liquid resins to flakes of the southern hardwoods on an industrial scale. It is likely that industrial plants will incorporate 1.0 to 1.5 percent of water-emulsified **slack wax** (based on ovendry weight of flakes) with the liquid resin. This wax, a byproduct of oil refining, provides some short-term resistance to water penetration into fabricated panels, and also may ease flake handling and mat forming problems by lowering friction coefficients of flake surfaces.

Liquid resin and its additives can be introduced into industrial blenders by air spray, airless spray, or centrifugal distribution from spinning disks or tubes. Airless sprays, operated at 600 to 800 psi, introduce less air into a blender than air sprays, but have smaller nozzles which may clog and afford less turbulence than air sprays.

Long-retention-time blenders.—Long-retention-time blenders for liquid resin are continuous-feed machines that approach the action of laboratory blenders of the drum type. Flakes must be tumbled gently to minimize breakup and production of fines, and must mix efficiently so all surfaces are exposed to resin fog in a short time. Blender capacity of 5 to 8 tons per hour enables most flakeboard mills to meet production requirements with three to five blenders. The resin atomization system should avoid small-diameter orifices prone to plug. In a blender designed by Nyberg and Beattie[5], liquid resin is fogged centrifugally within the blender from one or more 11-inch-diameter disks driven hydraulically at speeds up to 5,000 rpm (fig. 24-20). The 8- to 10-foot-diameter drum, with anti-slip internal ribs, is continuously loaded with flakes to a depth of 1 or 2 inches and rotated at a speed at which the flakes cling to the surface of the drum, but drop when near the top to repeat the cycle. Drum length is about 24 feet.

Short-retention-time blenders.—Short-retention-time blenders which require only seconds, instead of minutes, to apply resin take little space, can be adjusted quickly, and can be readily cleaned, have gained favor in the United States. These blenders (fig. 24-21) feature a small-diameter short tube in which a paddle agitator revolves at 500 to 700 rpm. Spray nozzles at the inlet end apply resin to only a portion of the flakes, uniform distribution being accomplished mainly by violent tumbling action during flake transit from inlet to outlet. The blender illustrated in figure 24-21 (bottom) is 42 inches in diameter, 108 inches in axial length, and is powered by a 75-hp motor. About 40 tons per hour (ovendry basis) of flakes can be blended with resin and wax. Wilson and Hill (1978) suggest that multiple short-retention-time blenders arranged in series achieve better resin application than single blenders.

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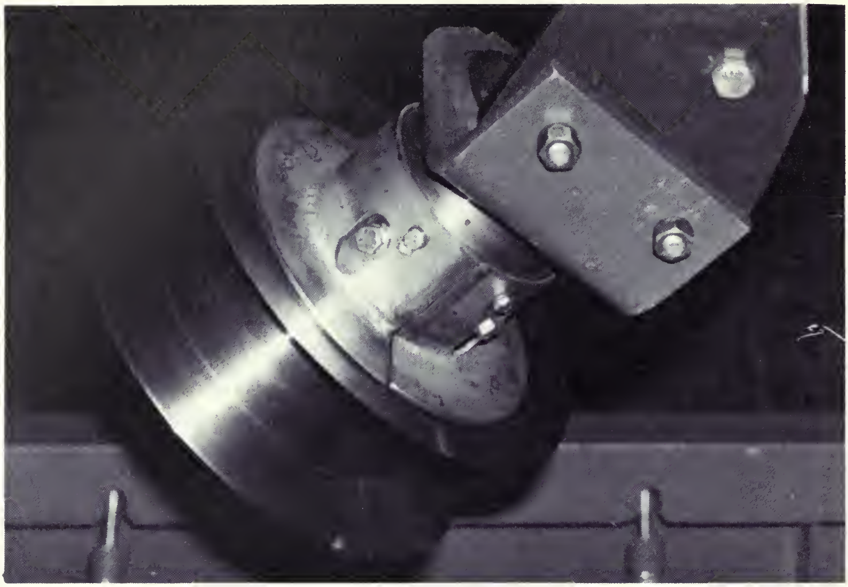
[5]Nyberg, D. W., and N. W. Beattie. 1980. Improved blending capabilities for waferboard. Paper given at Canadian Waferboard Symposium, November 18-20, 1980, Ottawa, Canada.



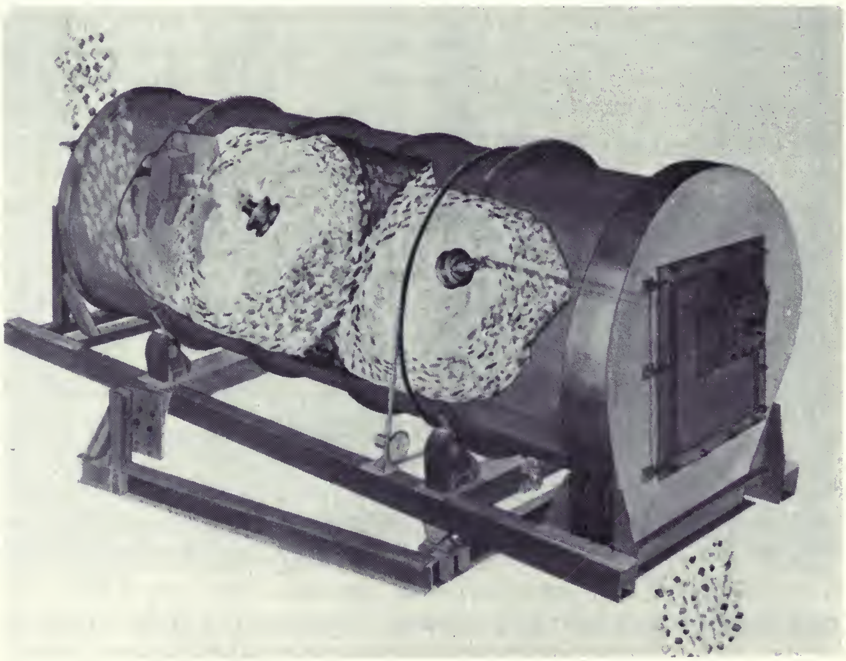
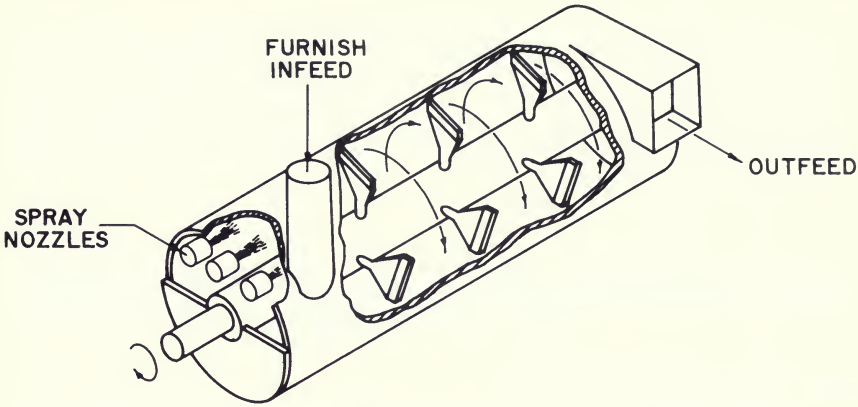


Figure 24-20.—A long-retention-time blender in which liquid resin is fogged centrifugally from rapidly rotating disks (top) mounted angularly within, and at both ends of, the 8- to 10-foot, 24-foot-long, rotating drum (bottom). Flakes enter at the left end through an inclined chute and are discharged from the bottom of the right end. (Photos from Canadian Car Division, Hawker Siddeley Canada, Inc.)



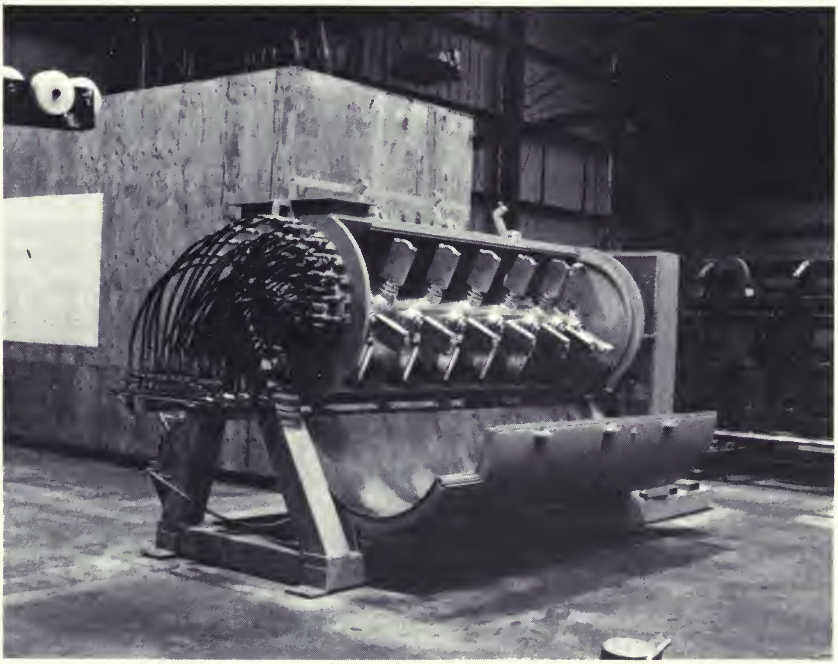


Figure 24-21.—Paddle-type, short-retention-time blender equipped with spray nozzles. (Top) Cut-away view showing inlet and outlet ports for flakes. (Drawing after Maloney 1977.) (Bottom) Photo of production blender with 42-inch-diameter tube opened to expose paddle agitators; resin nozzles are at inlet end on left. (Photo from Con-Vey/Keystone International.)

For other blender designs, see Maloney (1977, p. 438-457). Efficient resin application will be a key to successful manufacture of panels from southern hardwoods, and more research on the subject is needed. Kasper and Chow (1980) described a method of using X-ray spectrometry to determine resin distribution in flakeboard that should be useful during the conduct of such research.

24-6 MAT MOISTURE CONTENT, CONSTRUCTION, AND FORMATION

MAT MOISTURE CONTENT

Amount and distribution of moisture through the thickness of a formed mat significantly affect properties of pressed panels. By increasing moisture content in face layers, and decreasing it in the core layer, surfaces can be densified during pressing, thereby increasing panel modulus of elasticity and modulus of rupture. Below mat moisture levels at which boards blow apart when the hot press is opened, manipulation of mat moisture content can considerably alter board properties.

Laboratory trials with mats of species mixtures of southern hardwood flakes blended with liquid phenol-formaldehyde resin, indicate that for press temperatures in the range from 290°F to 345°F and compaction ratios from 1.1 to 1.2 mat moisture content for 1/2-inch-thick panels should average about 10 percent; an average moisture content of 12 percent should not be exceeded if panel blows are to be avoided.

With the alloy of isocyanate and phenol-formaldehyde resin described in table 24-10, mat moisture content for 1/2-inch-thick panels may be as high as 14 percent without delamination at press opening.

SPECIES COMPOSITION

About 47 percent of pine-site hardwood volume is oak, and hickory comprises a significant portion (8.5 percent).Single-species flakeboards of dense southern hardwoods tend to be excessively heavy when fabricated to have acceptable mechanical properties (table 24-11). Flakes of these, and other dense woods, must therefore be mixed in controlled proportions with those of less-dense woods such as sweetbay, red maple, yellow-poplar, and sweetgum, which as a group comprise about 25 percent of the total volume of pine-site hardwoods. Laboratory attempts to concentrate dense oak and hickory flakes in core layers and to place low-density sweetgum, red maple, yellow-poplar, and red maple on faces of 1/2-inch-thick sheathing panels have not been particularly successful.

Researchers experienced in constructing sheathing panels from southern hardwoods conclude that the same species mix (recipe) should be used uniformly throughout all board layers, and that the species mix should be controlled. This can be accomplished by separating incoming logs—and their flakes—into two species classes, with low-density wood in one and high-density wood in another. The two classes should be about equal in volume. For small (6-inch dbh) stemwood of all pine-site hardwoods, this division point will be at a density of about 0.569 (based on green volume and ovendry weight) or a weight per cubic foot of 35.5 pounds (ovendry basis). Larger stemwood will have slightly lower density.

Because species composition varies, each procurement area will have a different species mix, and therefore a different dividing point between the high- and low-density classes. Some typical panel properties for a number of particular mixes are given in section 24-16.

TABLE 24-11.—*Single-species flakeboard densities*[1,2] *at which target specifications*[3] *for mechanical properties and dimensional stability can be met* (Data from Hse 1975c)

Species	Minimum for 4,500 psi MOR (95 percent tolerance limit)	Minimum for 800,000 psi MOE	Minimum for 70 psi IB	Maximum, beyond which 0.25 percent linear[4] expansion is exceeded
	Lb/cu ft			
Sweetbay	35.9	37.2	30.4	49.5
Red maple	40.0	41.6	33.9	49.5
Sweetgum	40.9	42.3	34.5	49.5
Black tupelo	38.8	>49.5[5]	32.7	44.5
White ash	48.3	50.0	40.8	49.5
Southern red oak	49.9	51.6	42.1	44.5
Hickory	52.5	54.3	44.3	49.5
Post oak	54.8	56.7	46.3	<44.5[6]
White oak	57.1	59.0	48.1	<44.5[6]

[1]Flakeboards from which these values were derived were 0.5 inch thick made from 3-inch-long, 0.015-inch-thick, 3/8-inch-wide veneer flakes.

[2]Based on volume and weight at equilibrium at 80°F and 50 percent RH (i.e., at an MC of about 5.9 percent).

[3]Goals of the Forest Service Task Force on Panel Specifications.

[4]In 30-90 percent RH exposure test.

[5]Indicates undetermined value larger than 49.5.

[6]Indicates undetermined value smaller than 44.5.

BOARD LAYERING

Experienced researchers agree that face flakes of structural panels containing dense woods such as the oaks and hickories should be thin (e.g., 0.015 inch) and core flakes should be thicker (e.g., 0.025 inch). To accomplish this construction, the mat must be formed in three layers—a core and two faces. In 1/2-inch panels, the core layer may be about 1/4-inch thick and each face layer about 1/8-inch thick. Flakes in all layers can be randomly placed, producing panels with uniform properties in all directions which can be cut into smaller panels without regard to major or minor panel axes. This can be advantageous, especially when panels are pressed to 8- by 16- or 8- by 24-foot size. Also, delamination stresses between panel layers are probably less in panels with random flake placement than where flakes in face layers are aligned at 90 degrees to those in the core (fig. 24-2).

FLAKE ALIGNMENT

Fabrication of oriented-strand boards (fig. 24-2 bottom) requires a method of aligning flakes or strands in face layers parallel to the major panel axis, and at right angles to this direction in core layers. Maximum-strength panels are fabricated from long flakes—e.g., 3 inches in length. Sweetgum face flakes may be nearly square, hickory flakes tube-shaped, and oak flakes splintery and incompletely separated into strands (figs. 18-102 and 18-274ABC). Processing flakes of all these species through a flake splitter makes them more uniform in width, but substantial variation will remain. Oak flakes in particular retain characteristic incomplete separation so that individual strands may be semi-attached to one another. This lack of discreteness combined with 3-inch length makes alignment difficult on some equipment.

Mechanical alignment.—Laboratory- and industrial-scale equipment is available that aligns flakes by means of vibrating parallel plates (fig. 24-22A top). Readers interested in the degree of alignment attainable with vibrating parallel plates are referred to Geimer (1976). Finned rolls (figs. 24-22A bottom and 24-22B) also effectively align flakes, are in service in several plants, and are mechanically simple devices.

Electrical alignment.—Maloney (1980) reported that equipment based on Talbot's (1974) concept, and now available to the industy, can effectively align and cross-align most flakes (fig. 24-23). Industrial-scale demonstration on 3-inch-long white and red oak flakes had not been reported in the literature by early 1981. Earlier demonstrations in some southern laboratories indicated additional development was needed.

FORMING MACHINES

The alignment mechanisms just described, if incorporated in the production line, are part of the forming equipment. It seems likely that most structural flakeboard plants built to utilize southern hardwoods will have multi-opening presses with perhaps 16 openings and platens measuring 8 by 16 feet or 8 by 24 feet. Forming machines for such presses are essentially wide-belt distribution bins designed to discharge a uniform volume of material to the orientation devices (fig. 24-22B). Forming machines typically consist of one bottom-face forming head, two core heads, and one top-face forming head.

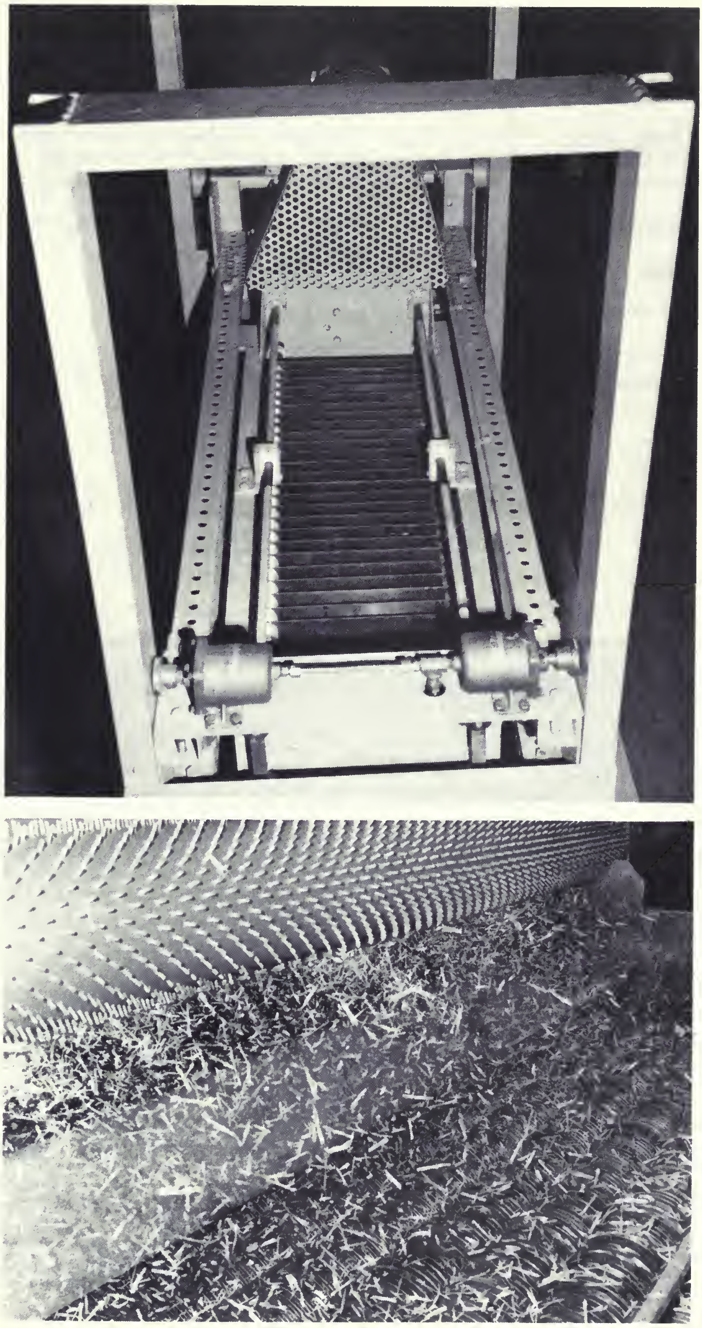


Figure 24-22A.—Mechanical devices to align flakes. (Top) Top view of laboratory-scale parallel vibrating plates; flakes are admitted to the plates from an overhead distribution chute, not shown, and as they pass through the plates are aligned parallel to them. (Photo from U.S. Forest Products Laboratory.) (Bottom) Finned rolls; strand-like flakes are shown dropping at the left and travelling over and through the power-driven finned rolls to form an aligned mat; see also figure 24-22B. (Photo from Siempelkamp Corporation.)

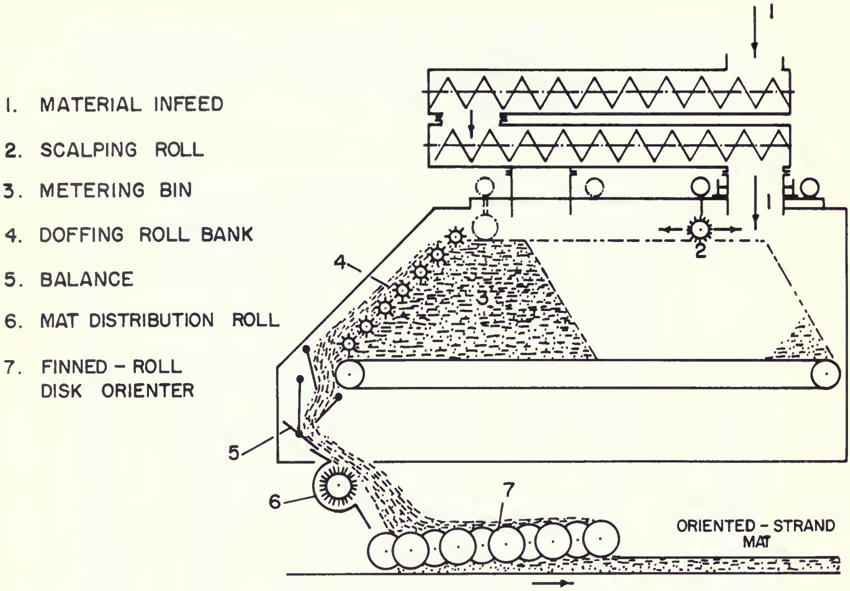


Figure 24-22B.—Oriented-strand board mat formation. (Top) Side elevation of forming head and finned rolls which orient the strands; since most structural flakeboards have three layers, three or four heads are required to form the complete mat. (Bottom) Mat of oriented strands emerging from the former. (Drawing and photo from Siempelkamp Corporation.)

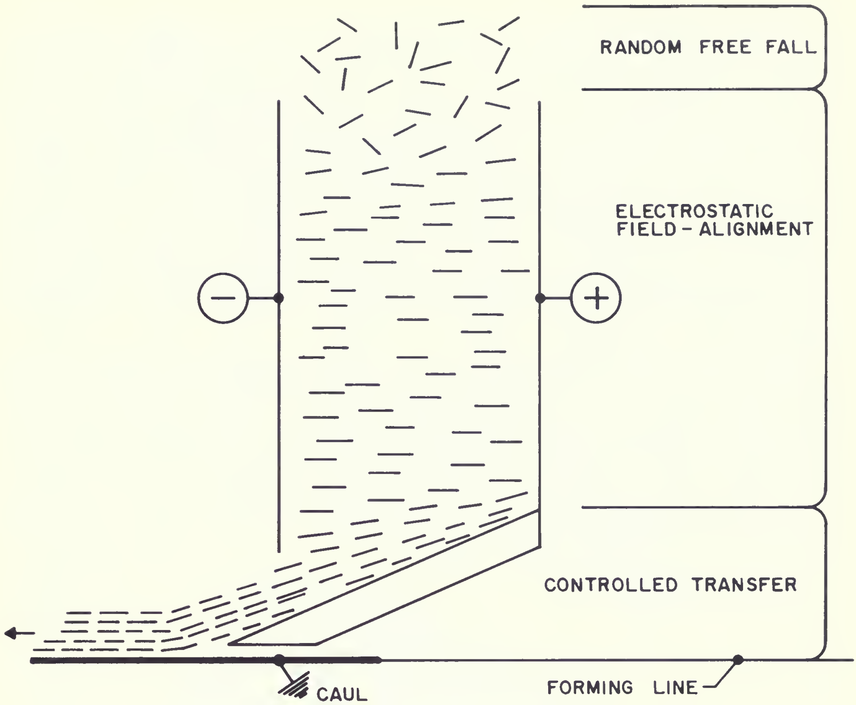


Figure 24-23.—Schematic diagram of electrical alignment of flakes. (Drawing after Maloney 1980.)

24-7 PRESSING

Platen-type hot presses convert the formed mat of flakes into a bonded panel of desired thickness by densifying it to develop adequate contact between flakes, and by heating it to glue-line temperatures at which the binder cures rapidly. In a typical flakeboard pressed to 0.5-inch thickness the mat would be about 25 flakes thick if the flakes were deposited with no voids and not compressed from their original average thickness of 0.020 inch. Because voids are present in mats of flakes, mats must be compressed to reduce the void volume and increase contact between individual flakes (fig. 24-26). Variation in flake thickness increases void volume and the need for compression. Generally, compression required to achieve adequate bonding between thin flakes of dense hardwoods may be about 20 percent, i.e., the density of the pressed panel may be about 20 percent greater than the density of the flakes from which the panel is made. The degree of compression is usually expressed as **compaction ratio**—1.20 in the example cited. Because wood of the most dense species (e.g., white oak or hickory) has about twice the compression strength of the least-dense species (e.g., yellow-poplar), the degree of compression of individual flakes varies significantly in a panel with a mixture of species.

Multiple-opening hot presses capable of delivering the high pressures required when pressing flakes of dense woods, are very expensive and plant capacity is usually determined by press output. This output increases as press cycle time is decreased. A 1/2-inch southern hardwood flakeboard might require a closed press time of 5-1/2 minutes at 350°F if bonded with liquid phenol-formaldehyde resin. Pressures available to close the press must be high (600-750 psi specific platen pressure) to achieve closure to desired thickness in 30 to 60 seconds. A 16-opening press with platens measuring 8 by 24 feet (fig. 24-24) requires 800-1,200 hp to drive hydraulic pumps and pistons adequate to close the press in 30 to 60 seconds on dense hardwood mats that will yield 1/2-inch-thick panels.

Platen temperatures are generally in the range from 340°F (liquid resin) to about 420°F (powdered resin). While it is quite possible to heat platens to this temperature with high-pressure steam, most plants use presses with oil-heated platens, the oil being heated with energy from combustion of wood residues. Typically, a wood-fired oil heater (fig. 24-25) might burn 2 tons per hour of green hardwood bark or sawdust to heat the press illustrated in figure 24-24 when pressing 7/16- or 1/2-inch panels.

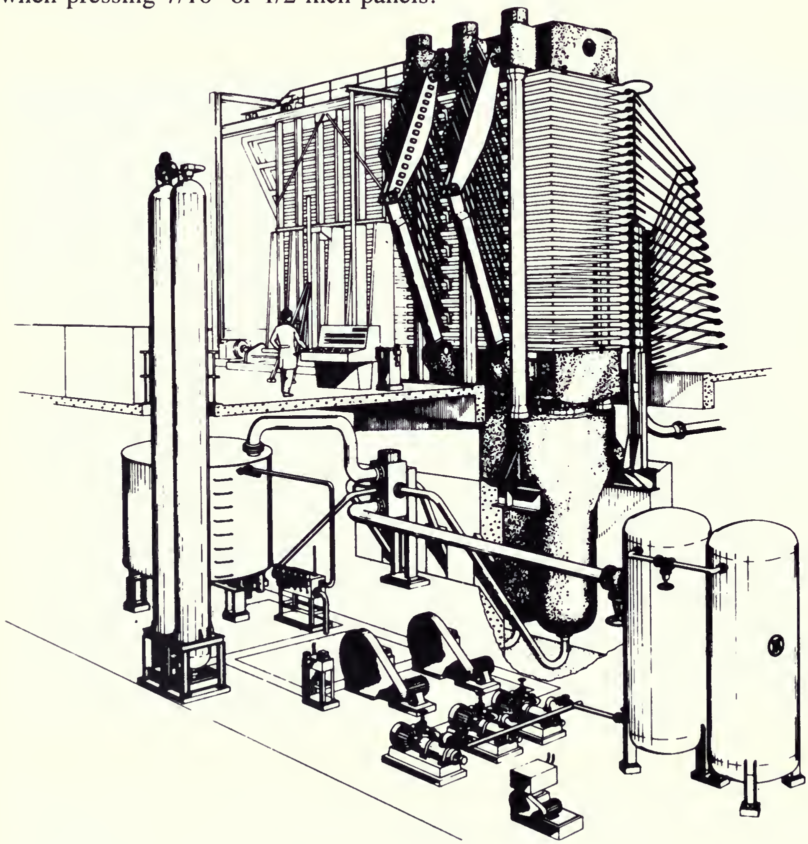


Figure 24-24.—Multi-opening, simultaneous-closing hot press. Hydraulic pumps and pressure accumulators are in foreground. (Drawing from A. B. Motalla Verkstad.)

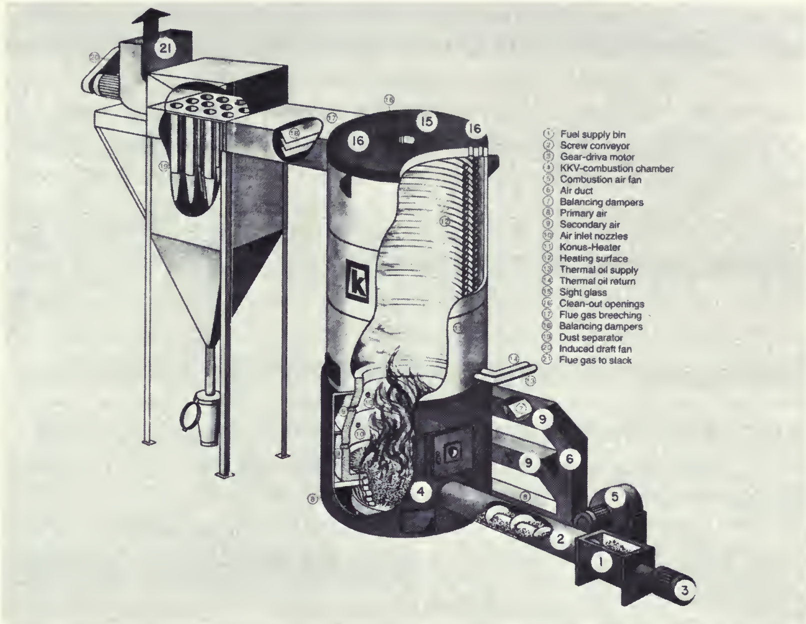


Figure 24-25.—This system to heat thermal oil for a multiple-opening hot press can be specified to burn either dry or wet bark and wood comminuted to particle size smaller than a 1-inch cube. (Drawing from Konus-Systems, Inc.)

Structural flakeboard is used primarily for floor decking and sheathing. For use as roof sheathing the panels may be pressed with a screen caul on one side to afford more secure footing to workmen.

The curing time of phenol-formaldehyde resins used in flakeboard fabrication decreases rapidly with increasing temperature; rapid temperature transfer to the center of the panel is therefore the key to short press time. With low moisture content in the mat, heat transfer occurs primarily by conduction, and short press time requires high platen temperature. Although heat conductivity of wood increases with increased moisture content, evaporation of water throughout moist mats retards temperature transfer, and longer press times are required to reduce moisture enough for adequate internal bond strength development. Mat moisture contents of 9 to 11 percent are probably optimum.

The density profile of a hot-pressed flakeboard varies according to distribution of moisture in the mat. Boards pressed from mats of uniform moisture content show lower density near the surface, an increase to maximum density within 3/32-inch of the surface, and a decline to lowest density at mid-thickness (fig. 24-28). If moisture content in the core of the mat is decreased to 5 percent moisture content and in face layers is increased to 15 percent, the contrast between density of face and core layers will be increased.

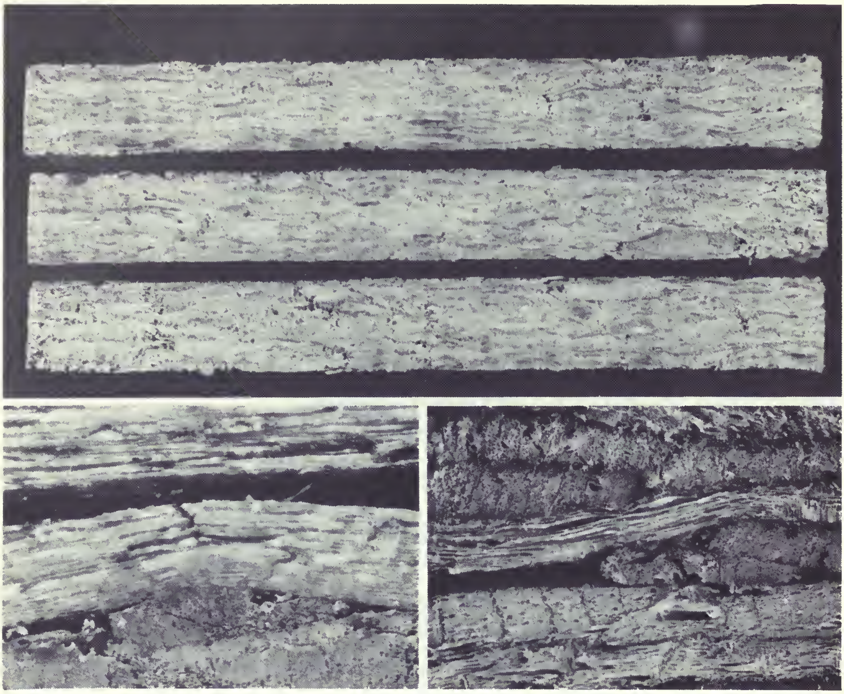


Figure 24-26.—(Top) Cross-sectional views of 1/2-inch-thick, three-layer, structural flakeboard comprised of 20 percent each of white oak, southern red oak, hickory, sweetgum, and southern pine pressed to a density of 45 pounds/cu ft , OD-weight basis. (Bottom left and right) Voids result from flake placement and variable compressibility of the species; flakes may fracture from deflections during pressing. Flakes are about 0.020-inch thick. (Photos from files of C.-Y. Hse and W. A. Côté; see text footnote[3].)

Press closing time also significantly alters the density profile of flakeboard panels. As closing time decreases, face density increases and core density decreases, resulting in higher bending strength but lower internal bond strength.

To summarize (fig. 24-27 and 24-28), hot pressing of 1/2-inch structural flakeboards bonded with liquid phenol-formaldehyde binder and fabricated with 50 percent or more of dense oak and hickory flakes calls for platen temperatures of about 350°F, closing time—with no hesitation or dwell—of 30 to 60 seconds, and mat moisture content in face layers of about 11 percent and in core layers of about 9 percent. This regime will yield densified face layers with resultant high bending strength and cores sufficiently densified for adequate internal bond strength. Readers interested in a more detailed analysis of factors controlling press time are referred to Heebink and Hefty (1972). Suchsland's (1967) explanation of behavior of a particleboard mat during the press cycle is also instructive.

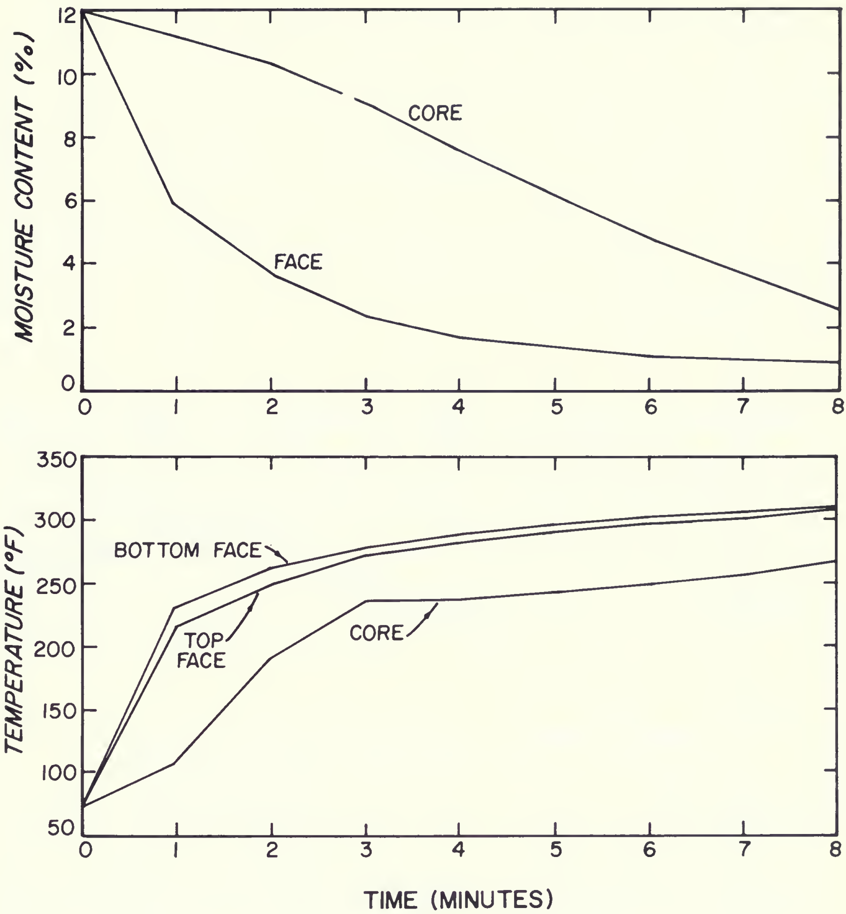


Figure 24-27.—Closed press time related to face and core moisture content (top), and temperature (bottom) of hardwood flakeboard being hot pressed. Platen temperature 350°F, closing time 45 seconds, panel thickness 1/2-inch. Face flakes 0.015-inch-thick and core flakes 0.025-inch-thick. Species mix comprised of 20 percent each of white oak, southern red oak, hickory, sweetgum, and southern pine. (Drawing from Study File FS-SO-3201-15, U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station, Pineville, La.)

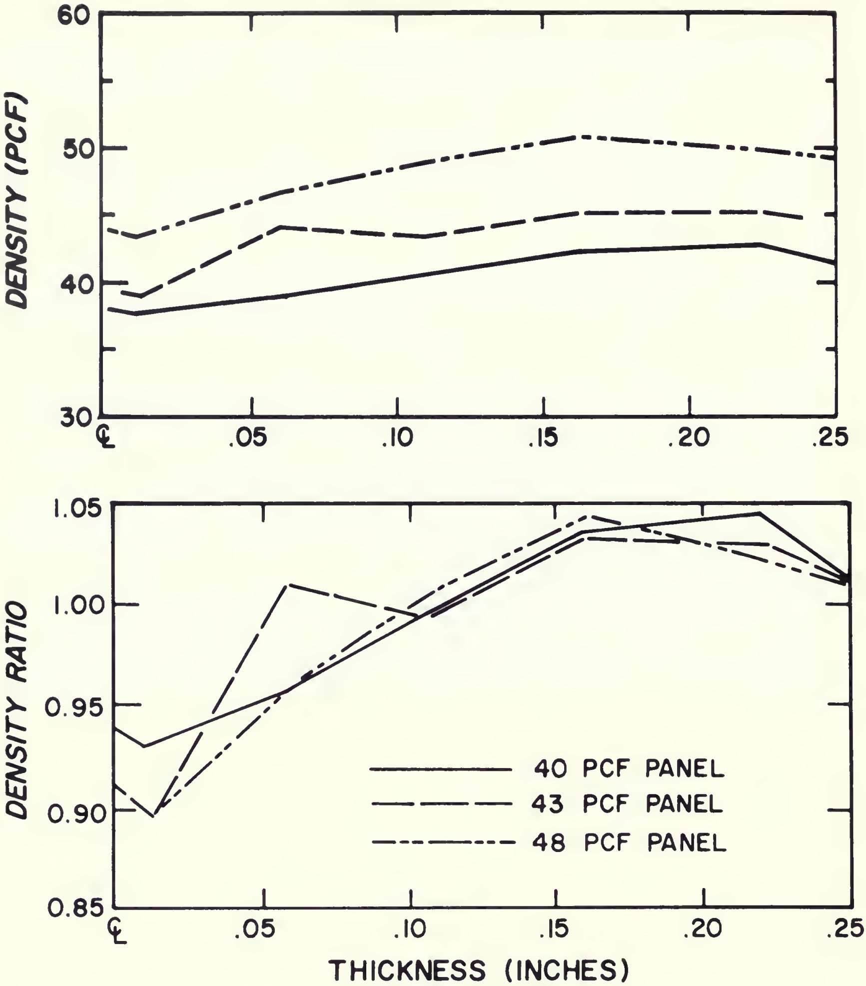


Figure 24-28.—(Top) Density profile in 1/2-inch-thick southern hardwood flakeboard of three densities, as described in caption of figure 24-27, from mid-thickness centerline to face. Densities based on ovendry weight and volume at 5 percent moisture content. (Bottom) Profile expressed as density ratio, i.e., the layer density divided by average panel density. (Drawings from Study File FS-SO-3201-15, U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station, Pineville, La.)

Maximum pressure on the mat, and closed press time varies with panel thickness. Some typical times and pressures for southern hardwood flakeboards pressed to about 45 pounds per cubic foot (ovendry weight basis) are as follows:

Panel thickness	Closed press times (after reaching stops)	Maximum pressure on mat
Inch	*Minutes*	*Psi*
3/8	3.5	600
7/16	4.5	650
1/2	5.0	700
5/8	6.0	700
3/4	8.0	750
7/8	10.0	750
1	12.0	750

Press cycles can be significantly shortened and panel stability increased by steam injection into the mat during hot pressing, but panel strength properties may be reduced by this procedure (Heebink and Hefty 1969; Shen 1973; and Thoman and Pearson 1976). Catalysts can also be added to some resins to speed press cycles, but results with phenol-formaldehyde resin formulations have not been promising (Lehmann et al. 1973). Application of radio-frequency energy to flakeboard hot presses is technically possible, but has not proven to be an economic way to speed press cycles.

24-8 POST-PRESSING OPERATIONS

Structural hardwood flakeboard for use as sheathing or floor decking is brushed to remove loose flakes as it emerges from the hot press, scanned by an ultrasonic device (see Albright and McCarthy's 1975 description of the technology) to detect internal delamination or blows, and then trimmed on panel sizing machines resembling two double-end tenoners coupled at 90° to each other so that large panels (8 by 24 feet, for example) can be reduced to smaller size (4 by 8 feet) in one pass. If the smaller panels are to be used as single-layer floor decking, edges and ends may be tongue and grooved on similar machines (see sec. 18-20). Dulling of saws and grooving heads may be a problem when sizing and edge machining flakeboard. Readers interested in information on the subject beyond that given in section 18-29 are referred to Davis (1957), Theien (1970), Neusser and Schall (1970), Bridges (1971), and Stevens and Fairbanks (1977).

Sanding is not usually necessary for sheathing panels, but may be required for accurate thickness control of single-layer floor decking. Figure 18-168 and accompanying text describe this technology.

24-9 MECHANICAL PROPERTIES

Performance of structural hardwood flakeboard as sheathing and floor decking is linked to its density, modulus of elasticity, modulus of rupture, internal bond strength, plate shear strength, and impact strength. These properties can be controlled and manipulated to considerable degree by controlling fabrication variables. In general, the fabricator's objective is attainment of acceptable mechanical properties at the lowest practical panel density.

Discussion that follows in this section is limited to data on structural flakeboard bonded with phenol-formaldehyde resin and comprised of the principal hardwoods found on southern pine sites. Broader reviews of engineering and physical properties of particleboard, principally softwood, bonded with both urea and phenolic resins, have been provided by McNatt (1973) and Kelly (1977). Data on tropical hardwood flakeboards can be found in Haygreen and French (1971) and Vital et al. (1974).

DENSITY

Densities of structural flakeboard of southern hardwoods for sheathing and floor decking generally are in the range from 42 to 50 pounds per cubic foot (ovendry basis) depending on the percentage of oak and hickory they contain and on the mechanical properties required. Inclusion of significant proportions of the dense woods, and/or requirement of high strength, result in dense panels. Density profile across panel thickness varies with pressing cycle (figs. 24-27 and 24-28). The relationships between panel density and seven mechanical properties are discussed in the following sub-sections.

MODULUS OF ELASTICITY

Structural flakeboard panels must support, without undue deflection, loads incurred in service—such as snow loads on roofs and concentrated loads on floor decking—and also loads imposed during construction, e.g., workmen carrying bundles of shingles. Panel stiffness is a function of modulus of elasticity (MOE) as well as panel thickness. Section 24-2 noted that modulus of elasticity (MOE) in bending of construction exterior grade plywood in the United States is about 1,200,000 psi along the grain of face veneers and 500,000 psi across the grain. For 2-MW waferboard and 2-MF flakeboard, the National Particleboard Association (1980) requires an MOE of at least 450,000 and 500,000 psi, respectively (see table 24-2). Deflection specifications for APA RATED STURDI-FLOOR panels are given in table 24-3 and related discussion; those for APA RATED SHEATHING in table 24-5 and related discussion.

MOE of flakeboard panels is affected by a number of variables including wood species, flake dimensions, flake orientation, resin content, mat moisture profile, pressing procedure, and density profile. Hse et al. (1975) examined these relationships as they relate to phenol-formaldehyde-bonded flakeboard made from pine-site hardwoods; their conclusions and other pertinent literature are summarized in the following paragraphs.

Flake orientation.—Price (1974) provided basic information that confirmed results of other workers and showed that MOE and ultimate tensile strength of

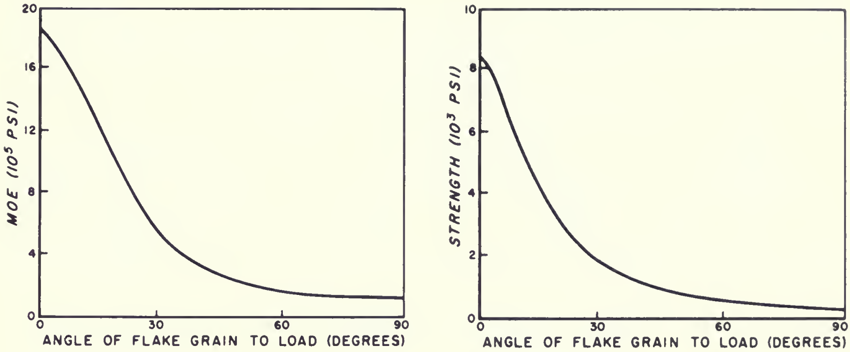


Figure 24-29.—(Left) Relationship between MOE and orientation of flakes in tensile specimens cut from 42-pound, 1/2-inch flakeboard of sweetgum veneer flakes 0.015-inch-thick, 3 inches long, and 3/8-inch wide. Resin content 5 percent. (Right) Relationship between ultimate tensile strength and orientation of flakes in tensile specimens cut from this flakeboard. (Drawing after Price 1974.)

1/2-inch sweetgum board could be very substantially increased by aligning flakes so that their grain angle was within 15° of alignment with direction of load application. With perfectly formed, 0.015-inch-thick, 3-inch-long flakes perfectly aligned with the direction of tension loading, it was possible to obtain an MOE of over 1,800,000 psi and an ultimate tensile strength of over 8,000 psi (fig. 24-29). These values were attained at a panel density of only 42 lb/cu ft.

The flakes used by Price were cut from 0.015-inch-thick veneer to precise length (3 inches) and then clipped to precise width (3/8-inch) to yield extremely uniform flakes (fig. 18-264). In subsequent discussion these perfect flakes will be termed **veneer** flakes.

In another comparison of MOE of panels with aligned flakes and random flakes, Price (1978) used mixed-species flakes cut on a shaping lathe (fig. 18-274abc)—hereafter referred to as **lathe** flakes—and found alignment yielded an MOE of about 1 million psi along the major panel axis, whereas panels with random flakes averaged about two-thirds that value (table 24-12).

Wood density and species.—Hse (1975c) made panels 0.5 inch thick from 3-inch-long, 0.015-inch-thick, 3/8-inch-wide veneer flakes of nine species of hardwoods commonly found on southern pine sites. He found that the main effects of species were related to variation in wood density. Low-density species compacted readily when pressed, and the resulting good flake contact improved bonding and gave boards of high strength. With species having specific gravity above 0.6, it was difficult to form stiff boards without increasing panel density unduly (table 24-11).

The typically cross-grained flakes of black tupelo yielded panels of exceptionally low MOE, even though wood specific gravity was below 0.6. Sweetbay yielded flakeboards with highest MOE. Only minor differences in MOE were noticed among sweetgum, red maple, white ash, hickory, and southern red oak. Both post oak and white oak yielded flakeboards of substantially lower MOE.

TABLE 24-12.—*Modulus of elasticity and modulus of rupture of 4- by 8-foot flakeboard made from a mixture of southern woods with flakes aligned and randomly oriented*[1] (Data from Price 1978)

Panel thickness (inch)	Face flakes aligned in 8-foot direction, core flakes in 4-foot direction		All flakes randomly placed; values averaged over both 8- and 4-foot directions
	8-foot direction	4-foot direction	
	psi		
	MODULUS OF ELASTICITY		
1/2	967,020	377,380	632,260
5/8	1,026,070	341,260	681,380
	MODULUS OF RUPTURE		
1/2	5,412	3,346	4,624
5/8	5,735	2,992	4,778

[1]Panels were a mix of 20 percent each by weight of hickory, white oak, southern red oak, sweetgum, and southern pine. Flakes were cut 3 inches long from heated wood on a shaping lathe. Face flakes were 0.015 inch thick and core flakes 0.025 inch thick. Flake moisture content, before addition of 6 percent of phenol-formaldehyde resin and 1 percent of wax, was 3 to 4 percent; mat faces were sprayed with 4.32 g of water/ft^2 surface area. Mats were constructed with each face having one-fourth of total weight. Pressed panels had a density of 46 lb/cu ft based on ovendry weight and volume at 65 percent RH. They were tested after equilibrating at 65 percent RH.

MOE proved to be significantly related to compaction ratio. Figure 24-30 shows the relationship (black tupelo omitted). Each small increase in compaction ratio yields a significant increase in MOE.

Efforts to layer flakeboard according to species, e.g., placing white oak in the core layer and sweetgum in face layers, have not been particularly successful. Best success has been attained by mixing flakes of the species to be used in controlled proportions, and then using this mixture for all layers. Price (1974) demonstrated the strong effect of species mix on MOE. Using lathe flakes of white oak (a very dense wood) and sweetgum (a low-density wood) Price found that if panel density was fixed, MOE was correlated with the species mix (fig. 24-31). This effect was also observed by Hse et al. (1975) when veneer flakes of sweetgum and white oak were mixed in varying proportions, with results as follows for flakeboard of constant density:

Proportion of flakes by species		
Sweetgum	White oak	MOE
percent		*psi*
100	0	825,000
75	25	761,000
50	50	734,000
25	75	699,000
0	100	677,000

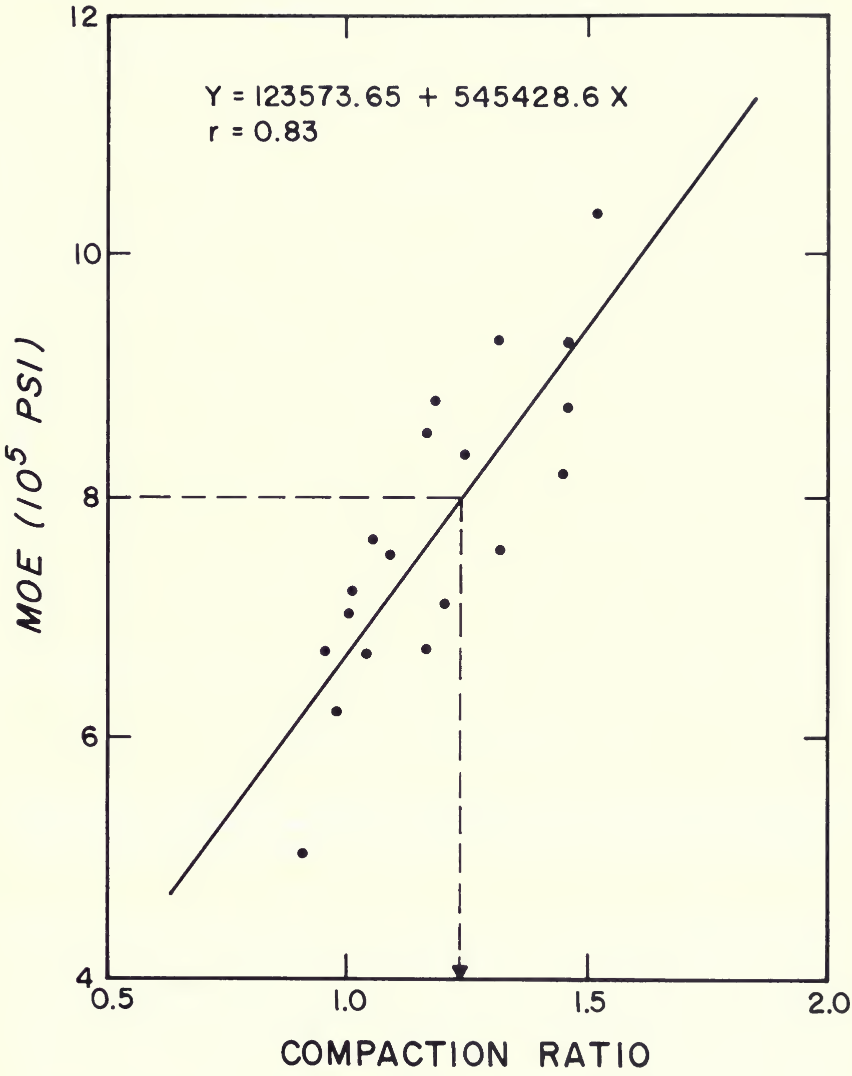


Figure 24-30.—Relation of compaction ratio to flakeboard modulus of elasticity. Data points represent single-species panels of sweetgum, hickory, southern red oak, post oak, white oak, sweetbay, white ash, and red maple veneer flakes. Dashed lines indicate the compaction ratio corresponding to an attained average of 800,000 psi MOE. Black tupelo did not follow this correlation. (Drawing after Hse 1975c.)

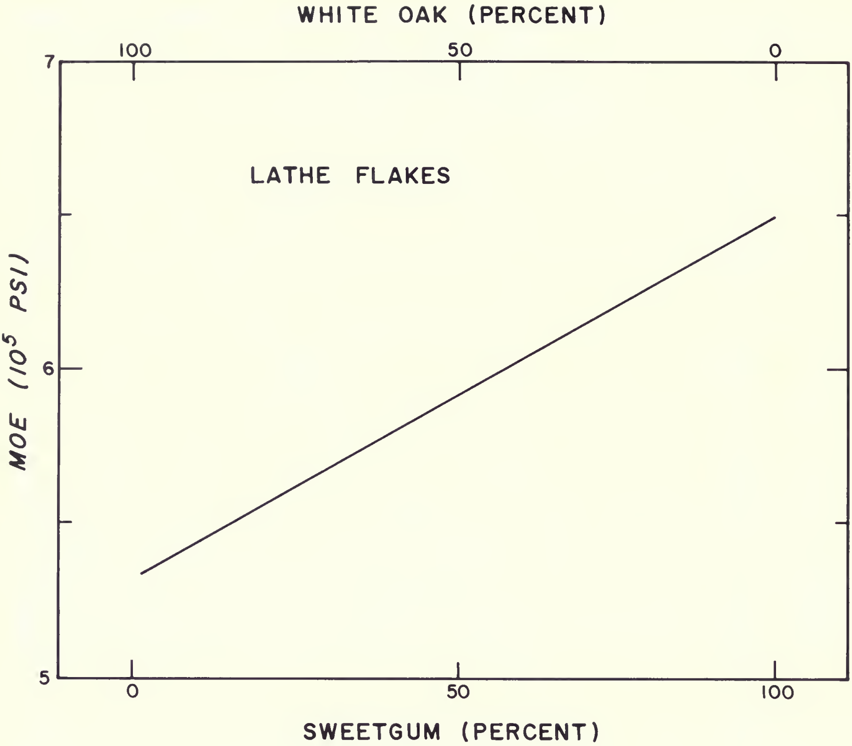


Figure 24-31.—Relationship of modulus of elasticity to proportion of white oak and sweetgum lathe flakes in 1/2-inch flakeboard; all boards pressed to a density of 42 pounds/cu ft, ovendry-weight basis. (Drawing after Hse et al. 1975, from Price 1974.)

Flake quality.—Price (1974) demonstrated the major dependence of MOE on flake quality. Flakes cut on the shaping-lathe headrig (fig. 18-102 and 18-274ABC) are of good industrial quality, though substantially less uniform in thickness and width than veneer flakes (fig. 18-264). Price showed that lathe flakes made boards of substantially lower MOE than did veneer flakes, and that MOE values are correlated with proportions of the two flake types (fig. 24-32).

Among major types of industrial flakers (drum, disk, shaping lathe, and ring) evaluated by Price and Lehmann (1978), the shaping-lathe produced oak and hickory flakes (fig. 18-274 bc) that yielded boards with highest MOE (fig. 24-5).

As noted in section 24-4, slope of grain in flakes reduces flake MOE significantly, e.g., a 10-degree slope of grain can reduce flake MOE by 16 percent, and a 20-degree slope by 33 percent. Incorporation of cross grain flakes in a panel therefore lowers panel MOE.

Flake length/thickness ratio.—Flakeboard MOE increases as the ratio of flake length to thickness increases in face layers. The rate of increase is substantial at ratios below 200, but slows at higher ratios. While flakes 6 inches long and longer have been used experimentally, most existing flakeboard plants limit

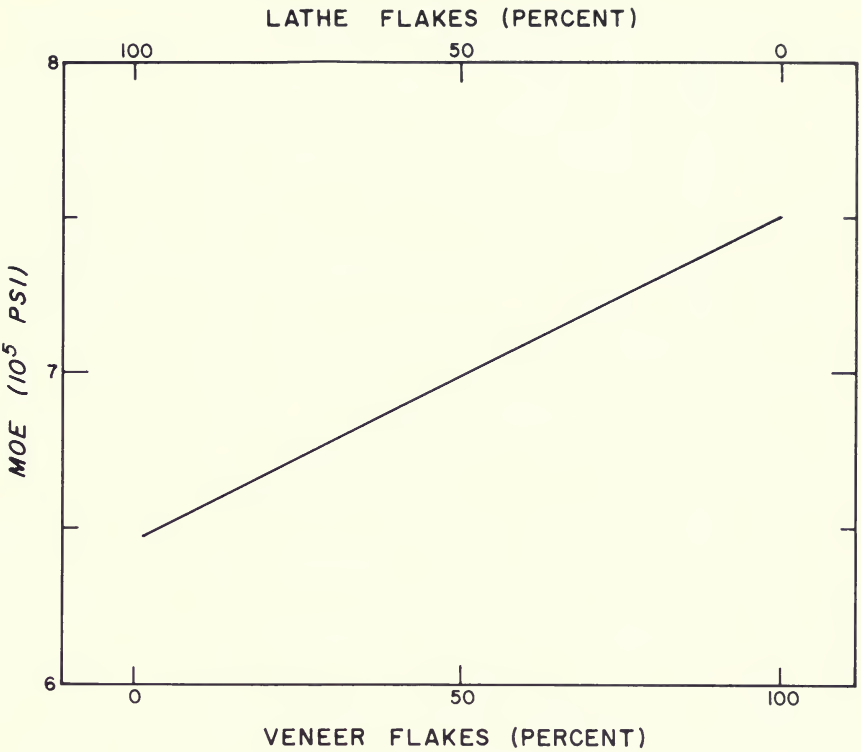


Figure 24-32.—Relationship of modulus of elasticity to proportions of veneer and lathe flakes in 1/2-inch sweetgum flakeboard with density of 42 pounds per cubic foot. (Drawing after Price 1974.)

flake length to the range from 1 to 3 inches to ease flake handling problems. At the Pineville, La. laboratory of the Southern Forest Experiment Station, researchers repeatedly have shown the superiority in face layers of 3-inch-long flakes cut 0.015 inch thick (length-to-thickness ratio of 200); 3-inch-long core flakes cut 0.025 inch thick also contribute more to panel stiffness than 1.5-inch flakes of this thickness (fig. 24-33 top). It is difficult to cut flakes thinner than 0.015 inch on industrial flaking equipment; an L/T ratio of 3/0.015 = 200 therefore seems near the practical maximum for face-layer flakes.

McMillin and Koch[6], in a study of flakeboards made from mixed-species, 3-inch-long lathe flakes of sweetgum, hickory, and southern red oak, showed that MOE was maximum with flakes 0.015 inch thick (fig. 24-34), but that internal bond strength was maximum with 0.025-inch-thick flakes. In boards made of each of these species, and also of loblolly pine, the same relationship prevailed. A three-layer board having 0.015-inch-thick face flakes and 0.025-inch-thick core flakes should achieve near optimum MOR and MOE, with acceptable IB.

[6]McMillin, C. W., and P. Koch. 1974. Properties of homogeneous exterior structural boards made from southern hardwood and loblolly pine flakes cut on a Koch lathe. U.S. Dep. Agric., For. Serv., South. For. Exp. Stn., Alexandria, La., Fin. Rep. FS-SO-3201-2.67, dated Aug. 26, 1974.

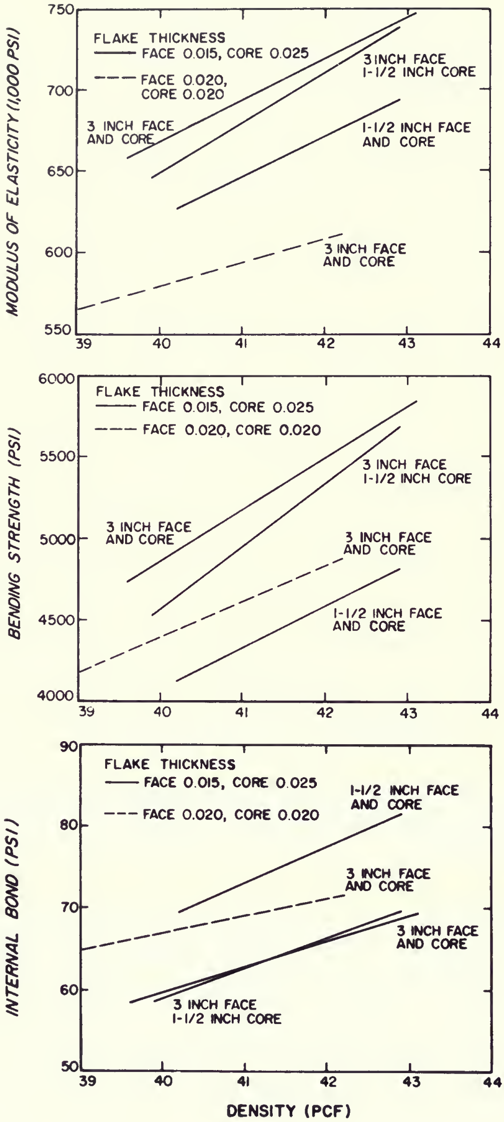


Figure 24-33.—Effect of flake length and thickness in faces and core, and panel density (ovendry weight and volume at test) on modulus of elasticity (top), modulus of rupture (center), and internal bond strength (bottom) of 7/16-inch-thick, phenol-formaldehyde-bonded, three-layer flakeboard with random orientation of flakes. All flakes were cut on a shaping-lathe. Panels, with 5-1/2-percent resin content (applied as a liquid) were tested at 72°F and 50-percent RH. Face layers were each one-fourth of panel thickness. Species mix was uniform throughout the board as follows: 32 percent sweetgum, 18 percent hackberry, 5 percent elms, 14 percent red oaks, 17 percent ashes, 5 percent white oaks, and 9 percent pecan. (Drawing after Price and Hse; see text footnote[9].)

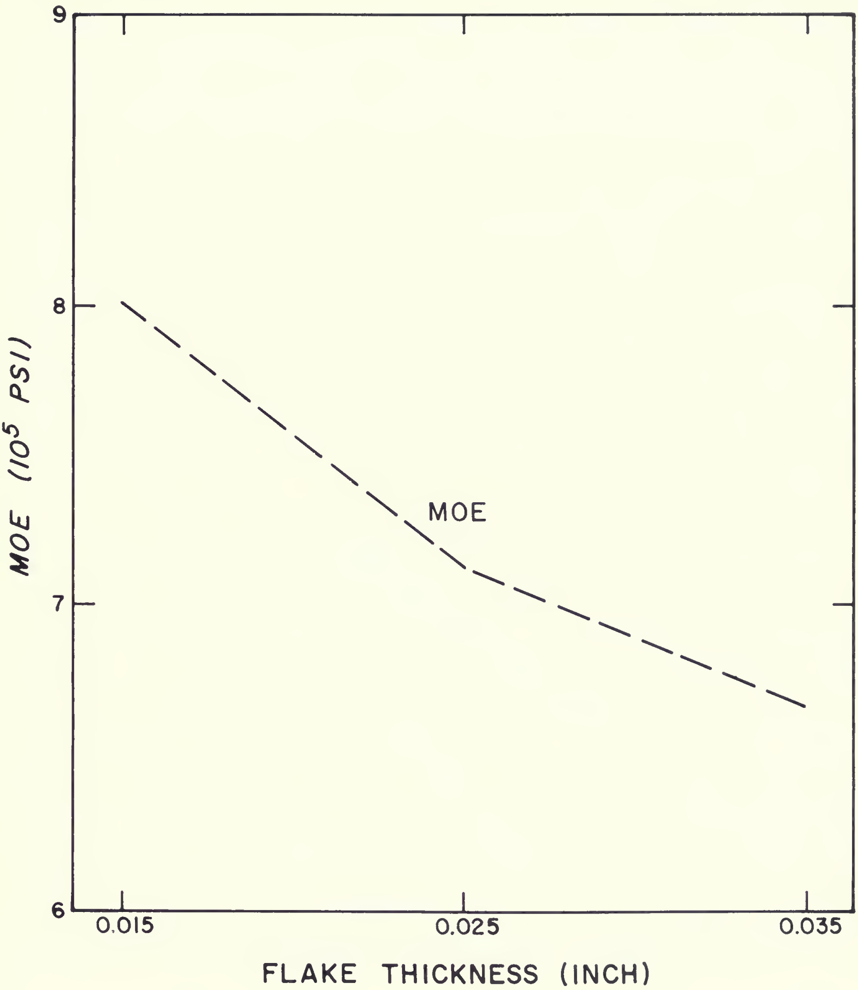


Figure 24-34.—Relationship of flake thickness to modulus of elasticity of mixed-species boards made from lathe flakes. Boards were 25 percent sweetgum, 25 percent hickory, and 50 percent southern red oak. Flakes were 3 inches long. (Drawing after Hse et al. 1975, from McMillin and Koch[6].)

Flake width.—Further data from the McMillin-Koch experiment[6] showed that internal bond strength is significantly improved if lathe flakes of certain species (e.g., sweetgum, hickory, and loblolly pine) are reduced in width after they are formed on the shaping-lathe headrig. This eliminates very wide flakes that fold (sweetgum and pine) or roll (hickory), causing poor resin distribution. Horizontal density distribution is also generally improved by reduction of flake width.

Reduction of flake width did not improve MOE, however. These observations suggest a three-layer board with random flake orientation in which core flakes are narrow and face flakes are wider. In boards with oriented flakes in face layers, narrow flakes (strands) are easier to align than wide flakes (wafers).

Moisture content of mat.—The McMillin-Koch experiment[6], and ancillary work in connection with it, showed that flake moisture content before addition of binder should be near 4 percent to maximize internal bond strength, but that moisture content of mat surface layers should be considerably higher to maximize MOE.

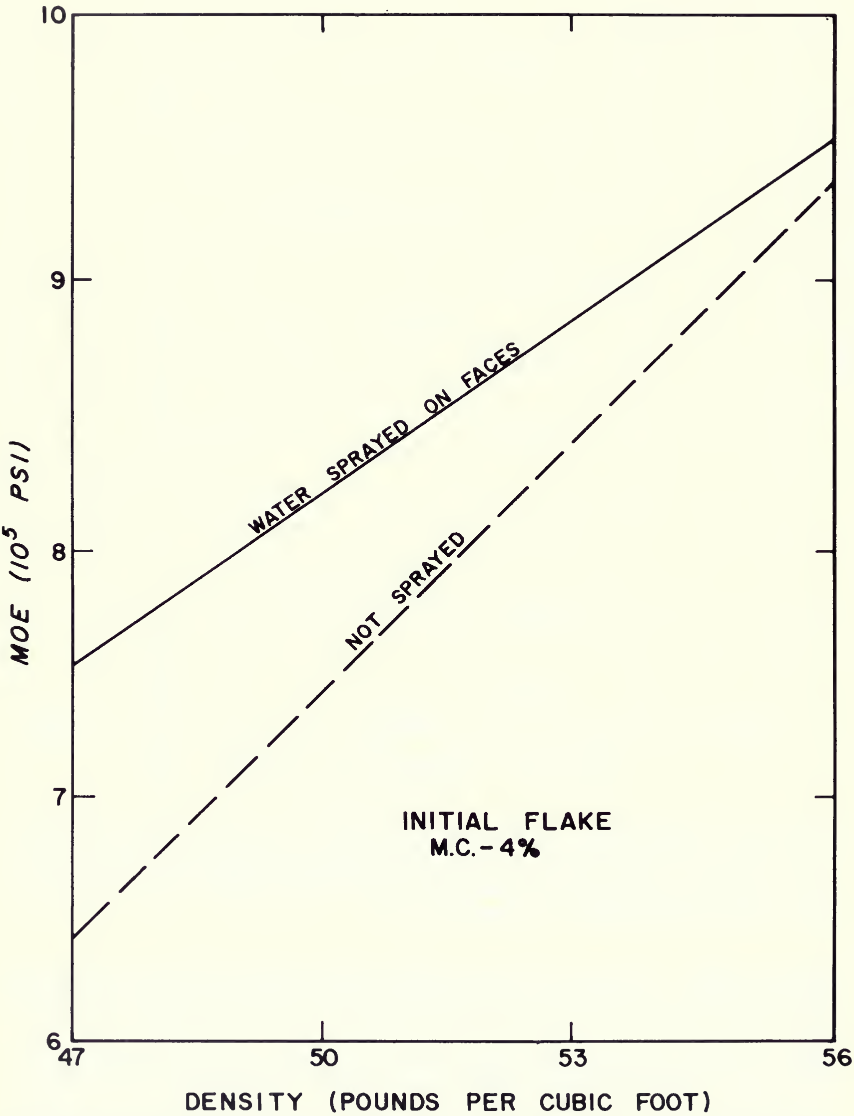


Figure 24-35.—Effect on modulus of elasticity of water-spraying top and bottom mat surfaces just prior to hot-pressing three-layer board made of cold-cut lathe flakes 3 inches long and randomly oriented. Flake thickness was 0.025 inch in the core and 0.015 inch in the faces. Boards contained 25 percent each of sweetgum, hickory, southern red oak, and white oak. Resin content was 5 percent and press time 5 minutes. (Drawing after Hse et al. 1975, from Hse and Koch[7].)

Hse and Koch[7] amplified this observation in a sub-experiment in which both surfaces of a mat were sprayed with water (10 grams to each face of a 20- by 20-inch mat) just prior to hot pressing. When a three-layer mixture of hardwood flakes was pressed to stops in 45 seconds to yield a panel density of 50 lb/cu ft, this water spray raised MOE about 100,000 psi (fig. 24-35). The increase in MOE was mainly attributable to densification of surfaces; density profiles were not quantitatively evaluated, however. Similar observations have been made by Klauditz and Rackwitz (1952), Strickler (1959), and others.

Inclusion of southern pine in the furnish.—The McMillin-Koch experiment[6] included observations of boards made of loblolly pine as well as those made of mixed hardwoods (25 percent sweetgum, 50 percent red oak, and 25 percent hickory). It was abundantly evident that the pine yielded boards of greater MOE than did the mixed hardwoods. Moreover, while the pine board showed positive correlation between MOE and panel specific gravity, the slope of the regression line was less steep than that for the mixed hardwood board (fig. 24-36).

From these observations and from figure 24-38, it was concluded that a small proportion of pine would substantially improve MOE, internal bond strength, and modulus of rupture at panel densities below 50 lb/cu ft.

Inclusion of baldcypress in the furnish.—On the coastal plain of the Southeastern States, baldcypress (*Taxodium distichum* var. *distichum*) is an important component of forests. It has lower specific gravity than any of the major species of hardwoods that grow among southern pines, except for yellow-poplar. Mechanical properties of baldcypress are not greatly different from those of yellow-poplar. Baldcypress is somewhat denser, stronger, and stiffer than aspen (*Populus tremuloides* Michx.). Flakeboards comprised of one-third baldcypress and two-thirds mixed southern hardwoods have modulus of elasticity at 41 to 43 pounds/cu ft panel density of about 700,000 psi (table 24-13).[8]

Seven-species mix of bottomland hardwoods.—Figure 24-33 summarizes the relationship between panel density and modulus of elasticity of 7/16-inch flakeboard comprised of hardwood species typically found in south-central Louisiana. With 3-inch-long flakes in face and core layers arranged so that face flakes were 0.015-inch thick and core flakes 0.025 inch thick, modulus of elasticity exceeded 700,000 psi at board densities above 41 pounds/cu ft.[9]

This seven-species mixture, bonded with liquid resin and comprised as described above of flakes cut from hot wet wood on a shaping lathe, had mechanical properties generally superior to boards made of other mixes of Louisiana hardwood species, other flake types and dimensions, or with powdered resin (table 24-14).[9]

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[7]Hse, C.-Y. and P. Koch. 1974. Properties of hardwood exterior flakeboard made from flakes prepared on a veneer lathe and on the Koch lathe. U.S. Dep. Agric., For. Serv., South. For. Exp. Stn., Alexandria, La., Fin. Rep. FS-SO-3201-2.66, dated Dec. 31, 1974.

[8]Hse, C.-Y., and E. W. Price. 1982. Technical feasibility of structural flakeboard made with north Florida hardwoods and cypress. U.S. Dep. Agric., For. Serv., South. For. Exp. Stn., Alexandria, La., Fin. Rep. FS-SO-3201-24.

[9]Price, E. W., and C.-Y. Hse. 1982. Technical feasibility of a structural flakeboard made with south-central Louisiana hardwoods. U.S. Dep. Agric., For. Serv., South. For. Exp. Stn., Alexandria, La., Fin. Rep. FS-SO-3201-20. See also: Price, E.W. and C.-Y. Hse. 1983. Bottomland Hardwoods for structural flakeboards. For. Prod. J. 33 (11/12): 33-40.

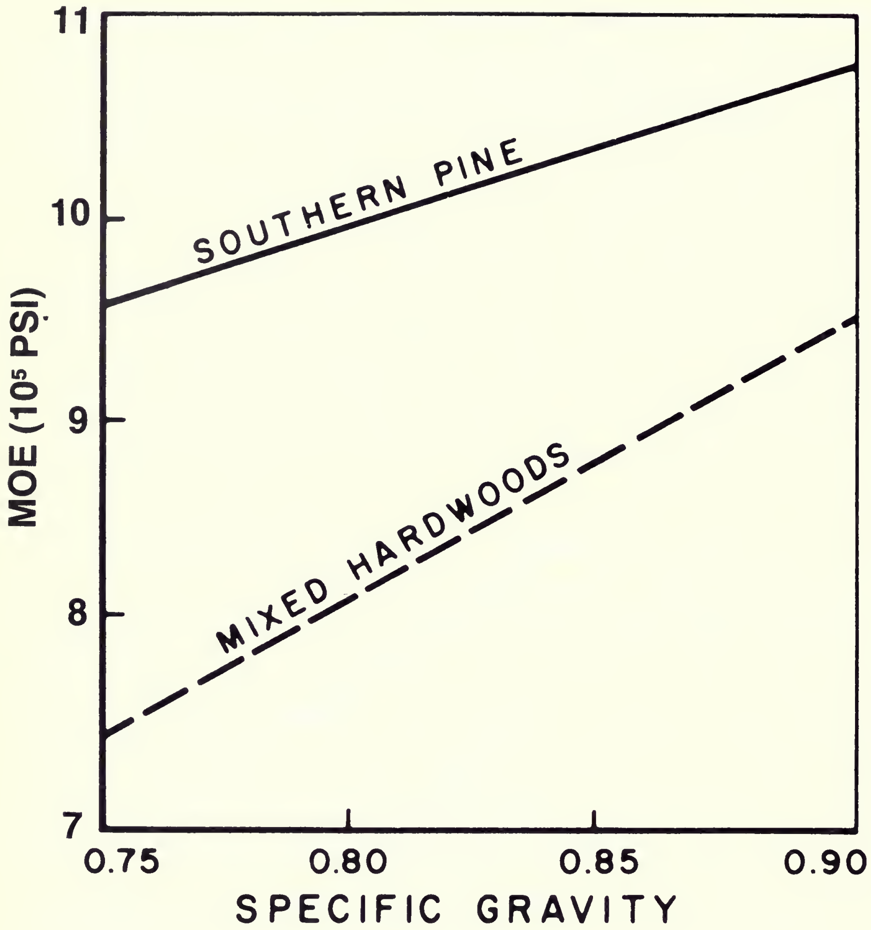

Figure 24-36.—Relationship between modulus of elasticity and specific gravity of 1/2-inch board made from randomly oriented 0.015-inch lathe flakes of southern pine and of a mixture of 25 percent sweetgum, 25 percent hickory, and 50 percent southern red oak. (Drawing after Hse et al. 1975, from McMillin and Koch[6].)

TABLE 24-13.—*Mechanical and physical properties of 1/2-inch-thick flakeboard comprised of one-third baldcypress and two-thirds mixed southern hardwoods from the coastal plains of the southeastern United States* (Hse and Price, text footnote[8])[1,2,3]

Property	Board density, pounds/cu ft[4]	
	40.7	42.7
Modulus of elasticity, thousand psi	670	720
Modulus of rupture, psi	5,300	5,630
Internal bond strength, psi	64	73
Linear expansion, percent[5]	0.116	0.113
Thickness swell, percent[5]	28	27
Internal bond strength after OD-VPS treatment, psi	32	37

[1]Species mix was: 35.4 percent baldcypress; 31.4 percent soft hardwoods; 17.1 percent oak sp.; 14.7 percent other hard hardwoods; 1.4 percent minor species.

[2]The three-layer board had face flakes 0.015-inch thick and core flakes 0.025 inch thick; all flakes were 3 inches long and cut on a shaping-lathe headrig.

[3]Resin content was 5.5 percent of ovendry weight.

[4]Basis of ovendry weight and volume at test moisture content of about 5 percent.

[5]After ovendry-vacuum-pressure-soak treatment.

Resin content.—Increases in resin content increase modulus of rupture and internal bond strength moderately, but affect MOE of hardwood flakeboards to a lesser degree. In fabricating scarlet oak panels from veneer flakes randomly oriented, Post (1961) found that urea-formaldehyde resin content was a much less potent factor determining MOE than was flake length-to-thickness ratio. Rice and Carey (1978) found that MOE of yellow-poplar and sweetgum flakeboards was less affected by increased content of phenol-formaldehyde resin than were internal bond strength and modulus of rupture (fig. 24-37).

Optimization of MOE with retention of acceptable internal bond strength.—On the basis of the literature and their prior experiments, Hse and Koch[7] fabricated a series of flakeboards as follows:

- Fixed factors
  - Panel thickness, 1/2-inch
  - Species mix: 20 percent each of hickory, white oak, southern red oak, sweetgum, and southern pine
  - Flake type: Shaping-lathe headrig; i.e., lathe flakes
  - Flake length: 3 inches
  - Flake moisture content: 3 to 4 percent
  - Specific pressure on mat: 575 psi
  - Press temperature: 335°F

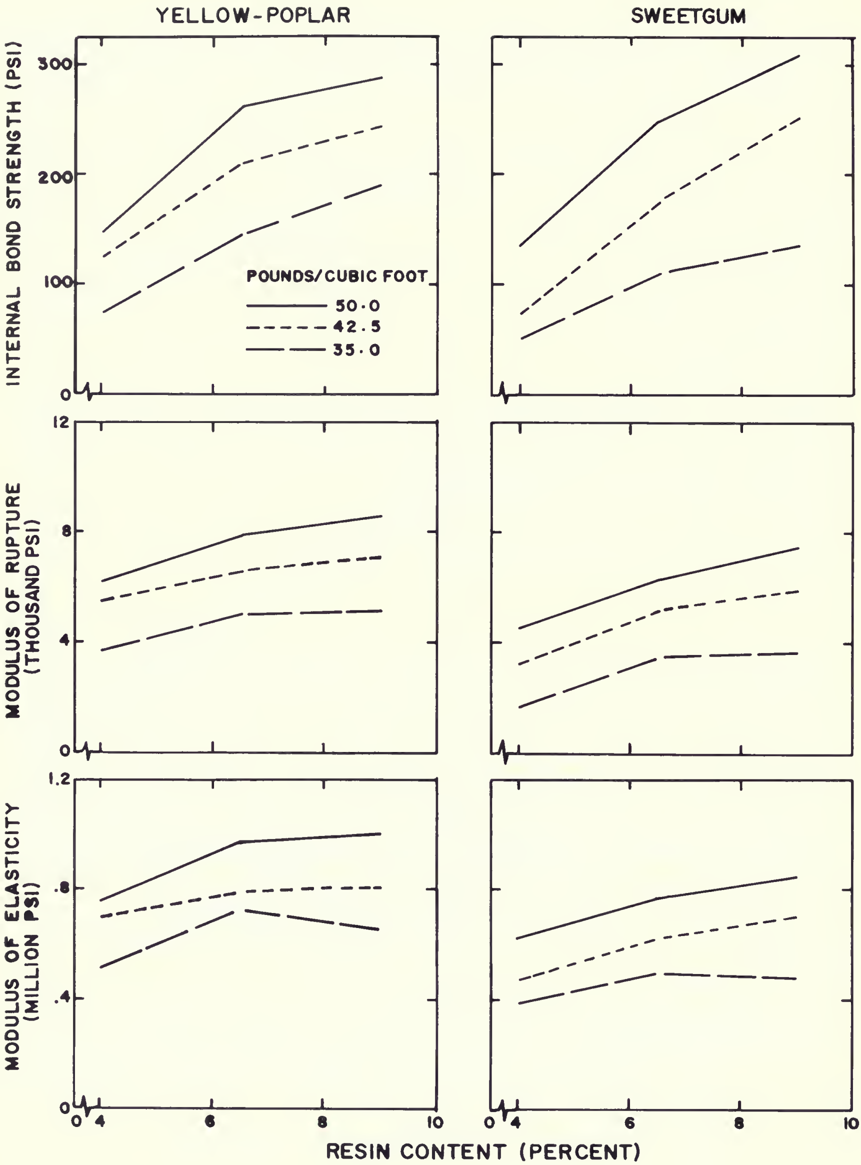

Figure 24-37.—Relationship between content of phenol-formaldehyde resin solids (applied as liquid spray) in yellow-poplar and sweetgum flakeboards and internal bond strength, modulus of rupture, and modulus of elasticity at three panel densities. Flakes were 1/2 to 1 inch long and 0.015 inch thick. Panels were pressed 15 minutes at 350°F with 400 psi specific pressure and equilibrated before test to 8.5 percent moisture content. (Drawing after Rice and Carey 1978.)

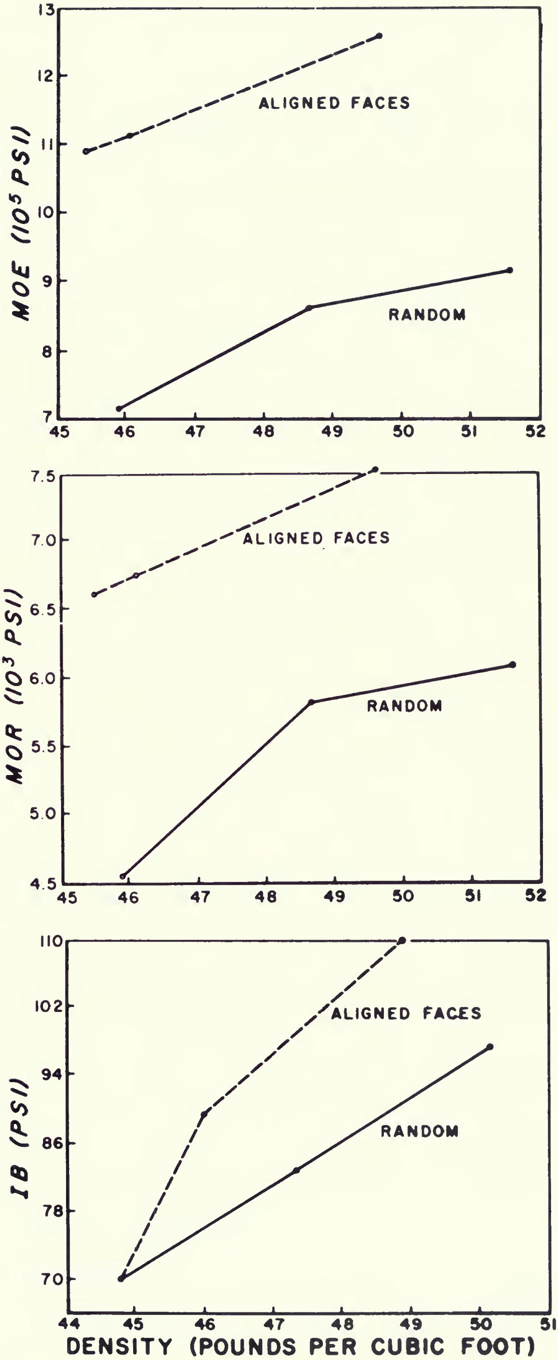

Figure 24-38.—Relationship of modulus of elasticity (top), modulus of rupture (center), and internal bond strength (bottom) to panel density in three-layer, 1/2-inch boards made of lathe flakes, with random cores and either aligned or random faces. Cores and faces contained 20 percent each of white oak, hickory, southern red oak, sweetgum, and southern pine. (Drawing after Hse et al. 1975, from Hse and Koch[7].)

TABLE 24-14.—*Properties of several types of flakeboard fabricated at 42 pounds/cu ft density based on ovendry weight* (Price and Hse, see text footnote[9])

Species mixture[1]	Flake type	Resin[2]	Bending strength	Modulus of elasticity	Internal bond	Linear expansion[3]
			psi	*1000 psi*	*psi*	*%*
7 species	Lathe 0.015 face 0.025 core Hot	L - 5½	5,500	716	66	.16
7 species	Lathe 0.020 Hot	L - 5½	4,840	610	71	.19
SG (55), RO (20), A (25)	Lathe 0.020 Hot	L - 5½	4,080	640	98	.22
HA (55), PE (45)	Lathe 0.020 Hot	L - 5½	3,990	600	112	.21
HA (55), OC (45)	Lathe 0.020 Hot	L - 5½	3,810	541	113	.30
SG (58), HA (33), E (9)	Lathe 0.020 Hot	L - 5½	3,870	574	79	.08
RO (31), A (38), OC (11), PE (20)	Lathe 0.020 Hot	L - 5½	3,500	568	110	.33
7 species	Disk 0.020 Hot	L - 5½	4,850	691	87	.20
7 species	Disk 0.020 Cold	L - 5½	4,350	624	103	.25
7 species	Disk 0.020 Cold	L - 4½	3,300	560	69	.27
7 species	Disk 0.020 Cold	P - 3	2,550	560	72	.42
7 species	Disk 0.020 Cold	P - 2¼	2,125	498	62	.47

[1]The 7 species and percentages are sweetgum (SG)-32, hackberry (HA)-18, elm (E)-5, red oak (RO)-14, ash (A)-17, overcup oak (OC)-5, and pecan (PE)-9.

[2]The letter abbreviation indicates liquid (L) or powder (P) phenolic resin. The number gives the percent based on OD weight of panel.

[3]Ovendry to vacuum-pressure soak test method P-1 of the American Plywood Association.

Press time: 5 minutes (including closing time of 45 to 60 sec)
Resin content: 5-1/2 percent
Core flakes: Random orientation, 0.025 inch thick, width-reduced, with special attention to sweetgum and hickory
Face flakes: 0.015-inch thick, mat water-sprayed on both sides just prior to pressing

- Variable factors

  Panel density at 50 percent RH: 45, 47, and 49 lb/cu ft
  Face flakes
  (1) Random orientation; not width reduced
  (2) Aligned; sweetgum, hickory, and southern pine flakes reduced in width for ease of feeding through the aligning mechanism

  Replications of boards: 3

This three-layer design met target goals suggested by the Forest Service Task Force on Panel Specifications for modulus of elasticity, modulus of rupture, and internal bond strength at densities below 50 lb/cu ft:

	Face flake orientation	
Panel property at 50 percent RH	Random	Aligned
Density (lb/cu ft)	47.5	45.5
IB (psi)	83	82
MOE (psi)	800,000	1,090,000
MOR (psi)	5,300	6,625

Relationships of these properties to panel density are plotted in figure 24-38 (from which the foregoing tabulation was constructed). The target IB of 70 psi was attained in both aligned and random boards at a panel density of 44.7 lb/cu ft. Target MOE of 800,000 psi required a random panel density of 47.5 lb/cu ft, however, at which density IB was 83 psi. The board with aligned faces had an MOE of 1,090,000 at density of 45.5 lb/cu ft, at which density IB was 82 psi. At all densities, MOR of the aligned board was well above that of the random board.

The flakes for the panels just described were cut with sharp knives from wood heated in water to 160°F. Subsequent experimentation showed a loss of a few percentage points in MOR and IB in panels made from the same mix of flakes cut from wood at 72°F. Another slight loss in values was discernible when knives were allowed to become substantially dull.

To evaluate the correlation between small- and large-panel properties, Price (1978) fabricated 4- by 8-foot flakeboards using the prescription of Hse and Koch[7]. At 46 lb/cu ft, MOE values were comparable (table 24-12) to those obtained by Hse and Koch; modulus of rupture and internal bond strengths were also comparable.

MODULUS OF RUPTURE

Structural flakeboards must support, without danger of failure in bending, loads anticipated in service and those imposed during construction. Modulus of rupture (MOR) is the measure of ultimate strength in bending. Section 24-2 noted that the MOR of construction exterior-grade plywood in the United States is about 8,000 psi along the grain of face veneers and 4,000 psi across the grain. For 2-MW waferboard and 2-MF flakeboard, the National Particleboard Association (1980) requires MOR of at least 2,500 and 3,000 psi, respectively (see table 24-2). Ultimate bending-load specifications for APA RATED STURDI-FLOOR panels are given in table 24-3 and related discussion, and those for APA RATED SHEATHING in table 24-5 and related discussion.

McNatt (1973) found that tensile strength of particleboards parallel to the surface is closely correlated with MOR ($R^2 = 0.90$) as follows (at 9-percent moisture content):

$$\text{Tensile strength, psi} = -221 + 0.523\,(\text{MOR, psi}) \qquad (24\text{-}1)$$

Factors and procedures that increase modulus of elasticity, also increase MOR, as summarized in the following paragraphs.

Flake orientation.—Ultimate tensile strength of flakeboards is closely related to orientation of flakes within the board (fig. 24-29 right); e.g., when flakes in a board are all aligned at 45 degrees to the axis of applied tension load, tensile strength of the board is only about one-tenth that of a board with flake grain perfectly aligned with tension load direction.

Price (1978) found that panels with aligned flakes had an MOR of about 5,574 psi along the major axis and 3,169 along the minor axis, whereas panels with random flakes averaged about 4,701 psi (table 24-12).

Price (1978) also applied concentrated and distributed loads to these panels. He found that the 5/8-inch panels—both with aligned and random flakes—were more than adequate for APA RATED STURDI-FLOOR, and that the 1/2-inch panels of both designs were more than adequate for APA RATED SHEATHING panels, as specified in tables 24-3, 24-4, and 24-5. He found that for 200- and 300-pound concentrated loads applied 2½ inches from the edge on 1- and 3-inch disks, respectively, oriented and random panels had similar deflection values. Failure loads applied on the disks, however, were higher for the random panels than for the oriented panels, and the random panels retained more strength after a 3-day water spray than the oriented panels. In general, the oriented panels deflected less than random panels in tests of distributed load over a 24-inch span. For a 16-inch span, dry-tested 5/8-inch random panels deflected less than oriented panels.

Wood density and species.—In flakeboards described by table 24-11, Hse (1975c) found that MOR ranged from 3,914 psi for white oak boards at 44.5 lb/cu ft panel density to 10,080 psi for sweetbay boards at 49.5 lb/cu ft. MOR increased with panel density; at constant density, values were highest for sweetbay, followed in decreasing order by red maple, black tupelo, sweetgum, white ash, southern red oak, hickory, post oak, and white oak. To achieve a MOR of 4,500 psi with randomly placed flakes, Hse found that flakeboard density varied

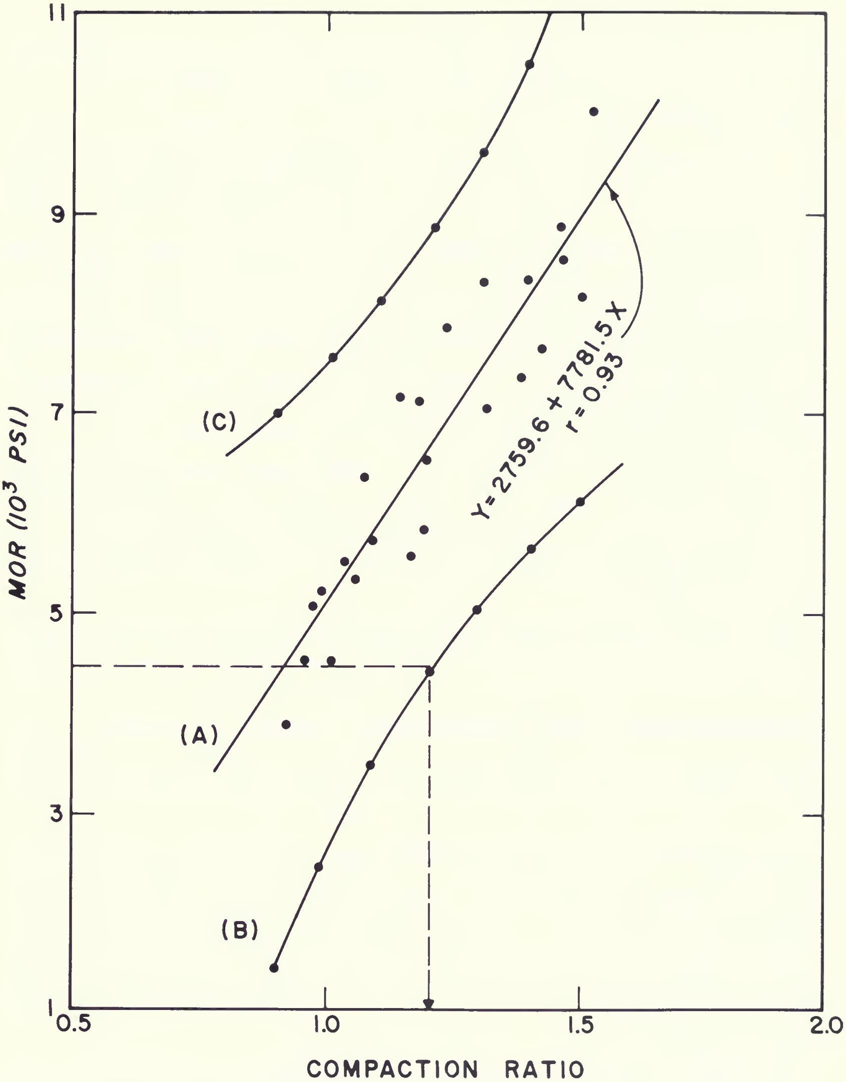

Figure 24-39.—Relationship of compaction ratio to modulus of rupture. Curved lines B and C show 95 percent tolerance limits. Dashed lines indicate the compaction ratio corresponding to an attainable minimum of 4,500 psi modulus of rupture. Data points represent single-species panels of sweetgum, black tupelo, hickory, southern red oak, post oak, white oak, sweetbay, white ash, and red maple veneer flakes. (Drawing after Hse 1975c.)

from a low of 35.9 lb/cu ft for sweetbay to a high of 57.1 lb/cu ft for white oak (table 24-11). He also found that bending strength increases proportionately as compaction ratio increases, with close correlation (fig. 24-39).

Flake quality.—Just as well-cut veneer flakes yield boards with superior MOE values compared to boards made from industrially-cut flakes (fig. 24-32), they also yield boards with superior MOR values. Among major types of industrial flakers (drum, disk, shaping-lathe, and ring) evaluated by Price and Lehmann (1978), the shaping-lathe produced oak and hickory flakes that yielded boards with highest MOR (fig. 24-4). With sweetgum, the disk flaker gave highest MOR values at compaction ratios above 1.3 (fig. 24-10).

As noted in section 24-4, slope of grain reduces flake tensile strength drastically, e.g., a 10-degree slope of grain can reduce flake tensile strength by 49 percent and a 20-degree slope by 97 percent.

Flake length/thickness ratio.—As with MOE, MOR of flakeboard increases with increasing flake length/thickness ratio, most of the increase being obtained at an L/T ratio of 200—for example, using 3-inch-long, 0.015-inch-thick flakes in face layers. Three-inch-long core flakes cut 0.025-inch thick also contribute more to panel bending strength than core flakes 1.5 inches long of this thickness (fig. 24-33 center).

Flake width, moisture content of mat, and inclusion of southern pine in the furnish.—MOR increases with MOE, therefore refer to the paragraphs with these headings in the previous subsection and to figures 24-35 and 24-36.

Inclusion of baldcypress in the furnish.—Flakeboards comprised of one-third baldcypress and two-thirds mixed southern hardwoods have modulus of rupture, at 41-43 pounds/cu ft panel density, of about 5,300-5,630 psi (table 24-13).

Seven-species mix of bottomland hardwoods.—At 42 pounds/cu ft density, optimally fabricated flakeboards of seven hardwood species typical of south-central Louisiana had modulus of rupture of 5,500 psi (table 24-14, fig. 24-33).

Resin content.—Rice and Carey (1978) found that an increase in resin content significantly increased MOR of yellow-poplar and sweetgum flakeboards, particularly for resin contents between 4 and 6 percent and at board densities greater than 42 pounds/cu ft (fig. 24-37).

Hse (1975b) found that in southern hardwood flakeboards, all strength properties increased substantially as resin content increased from 2 to 8 percent; with increase from 8 to 10 percent, however, modulus of rupture and modulus of elasticity increased only slightly and internal bond strength decreased because excess moisture, introduced by the additional liquid resin, resulted in less than optimum gluing conditions. The lower limit of resin content (applied as a liquid) to yield adequate bond strength was about 4 percent.

Optimization of MOR.—Text related to figure 24-38 in the previous subsection on MOE, described a near-optimum fabrication procedure for flakeboard comprised of 20 percent each of hickory, white oak, southern red oak, sweetgum, and southern pine. Small flakeboards of this design had MOR of 6,625 psi when flakes were aligned at board density of 45.5 lb/cu ft, and 5,300 psi with random-flake placement at a board density of 47.5 lb/cu ft (fig. 24-38 center).

Table 24-12 shows MOR values obtained by Price (1978) from 4- by 8-foot panels of this near-optimum design; these larger panels had slightly lower MOR values than the small panels described in figure 24-38.

INTERNAL BOND STRENGTH

Internal bond strength (IB) is tensile strength perpendicular to panel faces. It is a measure of the cohesiveness of flake-to-flake bonds, and is evaluated at board equilibrium moisture content at 72°F and 50 percent RH. Section 24-2 noted that for 2-MW waferboard and 2-MF flakeboard, the National Particleboard Association requires an IB of at least 50 psi. Performance specifications of the American Plywood Association for APA RATED STURDI-FLOOR and APA RATED SHEATHING panels are discussed in section 24-2 under the paragraph heading *Bond durability*.

Flake orientation, which has a strong effect on MOE and MOR, has only minor effect on IB (Price 1978). The remaining factors that were shown to influence MOE and MOR, also influence IB in flakeboards made of southern hardwoods. Lei and Wilson (1980) concluded that internal bond strength of flakeboards can be increased by eliminating or reducing the size of voids—a concept not easy to achieve in practice.

There is some evidence, from work by W.E. Johns and W.L. Plagemann at Washington State University in 1983, that temperatures at which flakes are dried influence IB strengths of boards made from the flakes; a moderate dryer temperature (e.g. 150°C) appears to promote higher IB strengths in southern hardwood flakeboards than higher (350°C) or lower (20°C) temperatures.

Wood density and species.—Hse (1975c) made panels 0.5-inch thick from 3-inch-long, 0.015-inch-thick, 3/8-inch-wide veneer flakes of 9 species of hardwoods commonly found on southern pine sites. Low-density species compacted readily when pressed; resulting good flake contact yielded panels with high IB at acceptable panel density (tables 24-9 and 24-11). He found that IB was linearly related to compaction ratio (fig. 24-40). Average IB strengths ranged from 51 psi for white oak at board density of 44.5 lb/cu ft to 385 psi for black tupelo at 49.5 lb/cu ft (table 24-9). IB strength increased with panel density for all species except sweetbay. IB strength for the four densest species (i.e., hickory and the oaks) was significantly lower than for the other species, even though their resin coverage was greater. At 44.5 lb/cu ft all four species yielded panels with IB values less than the target value of 70 psi. At panel density of 49.5 lb/cu ft, however, satisfactory bond strength was obtained. Table 24-11 summarizes Hse's findings in terms of minimum board densities at which a target IB strength of 70 psi can be met.

On average, for the 44.5- and 49.5 lb/cu ft boards, black tupelo flakeboards had the highest IB strengths (312 psi) and were followed in decreasing order by red maple (299 psi), sweetbay (248 psi), white ash (209 psi), sweetgum (183 psi), southern red oak (100 psi), post oak (89 psi), hickory (87 psi), and white oak (69 psi).

It is likely that industry will make structural flakeboards from mixtures of southern hardwoods, rather than from single species. Price (1974) and Hse et al. (1975) demonstrated the strong effect of species mix on IB (table 24-15). Using lathe flakes of white oak (a very dense wood) and sweetgum (a low-density wood) Price found that if panel density was fixed, IB was correlated with the proportions of the species mix. Hse's findings were similar; he used veneer flakes with fixed panel density of 46 pounds/cu ft (table 24-15). Results with mixtures of white oak with other low-density southern hardwoods are similar to those for sweetgum (table 24-16).

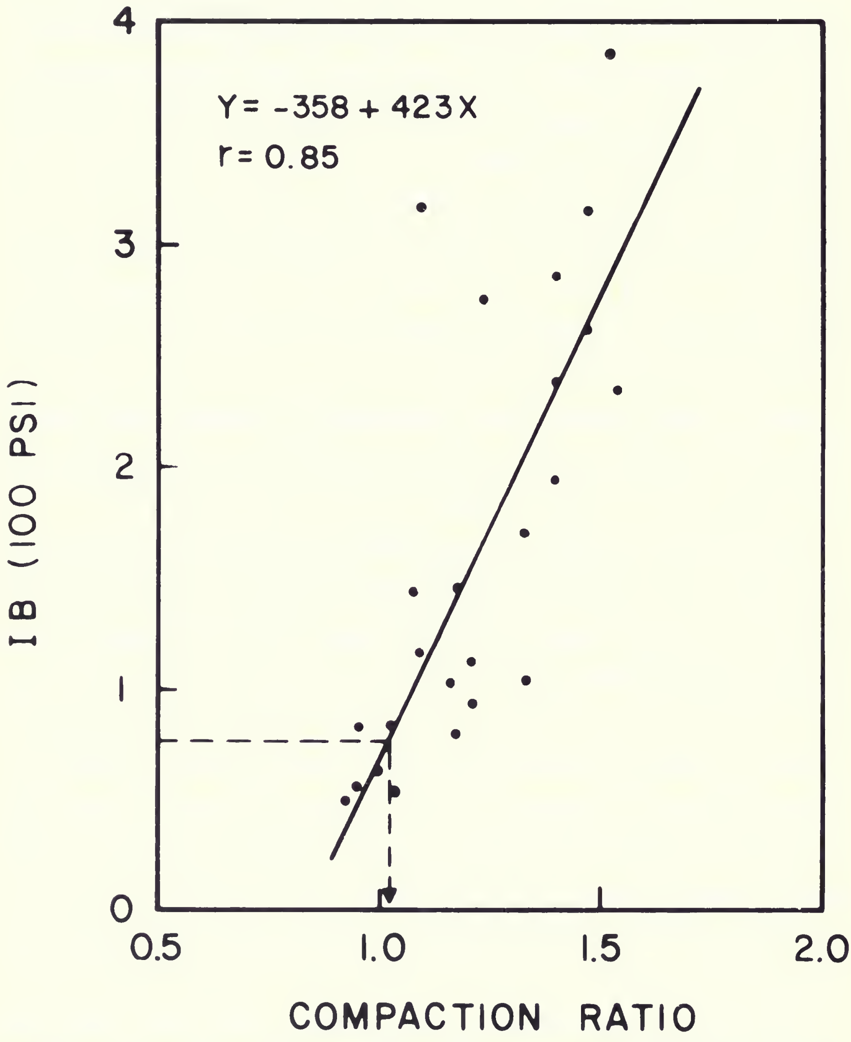

Figure 24-40.—Relationship of compaction ratio to internal bond strength. Data points represent single-species panels of sweetbay, red maple, sweetgum, black tupelo, white ash, southern red oak, hickory, post oak, and white oak. Dashed lines indicate the compaction ratio corresponding to an attainble average of 70 psi IB. (Drawing after Hse 1975c.)

TABLE 24-15.—*Internal bond strength of flakeboard as related to proportions of sweetgum and white oak in the board*

Proportions of flakes by species			
Sweetgum	White oak	Price (1974)[1]	Hse et al. (1975)[2]
		psi	
100	0	57	196
75	25	53	162
50	50	55	133
25	75	47	128
0	100	35	88

[1]Lathe flakes; board density at test, 42 pounds/cu ft.
[2]Veneer flakes; board density at test, 46 pounds/cu ft.

TABLE 24-16.—*Internal bond strength of flakeboard related to proportions of five low-density southern hardwoods mixed with white oak*[1,2]

Low-density species	Ratios of low-density hardwood to white oak				
	100/0	75/25	50/50	25/75	0/100
	Psi				
PANEL DENSITY: 42 POUNDS/CU FT					
Sweetgum	169	150	73	64	51
Sweetbay	267	157	111	63	51
Black tupelo	242	163	107	59	51
Red maple	269	110	91	55	51
Ash sp.	144	109	84	70	51
PANEL DENSITY: 46 POUNDS/CU FT					
Sweetgum	196	162	133	128	88
Sweetbay	236	129	138	131	88
Black tupelo	385	150	141	147	88
Red maple	315	180	168	142	88
Ash sp.	273	184	134	148	88

[1]Unpublished data from files of C.-Y. Hse, Pineville, La.
[2]Veneer flakes; 4 percent phenolic binder, applied as a liquid.

Flake quality.—IB varies significantly among panels fabricated from flakes (fig. 18-274abc) cut on major types of industrial flakers, i.e., drum, disk, shaping-lathe, and ring flakers. Price and Lehmann (1978) found that for southern red oak and hickory panels at 52.6 lb/cu ft, the ring-flake panels had highest IB under all circumstances except for panels fabricated at 5-percent resin content and exposed to accelerated aging (figs. 24-6 and 24-7). At the low resin content after accelerated aging, the range among IB values for the four flakers was only 7 psi. The IB's of the disk, lathe, and drum panels were similar except for the lathe-flake panel at 8-percent resin content under initial conditions, which had higher IB.

Flake length/thickness ratio.—McMillin and Koch[6], in a study of 1/2-inch-thick boards made from 3-inch-long mixed lathe flakes of sweetgum, hickory, and southern red oak showed that IB was maximum with 0.025-inch thick flakes. In boards of these single species, and of loblolly pine, the same relationship prevailed. This observation provided strong evidence for using flakes 0.025-inch-thick in core layers.

Price and Hse[9] found that when lathe flakes 0.025-inch-thick were used in core layers, and 0.015-inch-thick in face layers, 3-inch-long flakes in both face and core yielded boards with as high or higher IB strength than core flakes 1.5 inches long combined with 3-inch-long face flakes (fig. 24-33 bottom).

Flake width.—As noted earlier, McMillin and Koch[6] found that IB is significantly improved if lathe flakes of certain species, e.g., sweetgum, hickory, and loblolly pine are reduced in width after they are formed on the shaping-lathe headrig. This improvement results from eliminating very wide flakes that fold (sweetgum and pine) or roll (hickory) in such a manner that resin distribution is poor.

Moisture content of mat.—The McMillin-Koch experiment[6] and ancillary work in connection with it showed that flake moisture content before addition of liquid phenol-formaldehyde resin binder should be near 4 percent to maximize IB; this corresponds to a mat moisture content of about 11 percent.

Hse (1978) found that higher mat moisture contents (e.g., 7 percent) could be tolerated if polyisocyanate resin was applied before addition of liquid formaldehyde resin (table 24-10).

Inclusion of southern pine in the furnish.—McMillin and Koch[6] included observations of flakeboards made of southern pine, and they found that addition of a small proportion of southern pine to the furnish would substantially increase IB at panel densities below 50 lb/cu ft.

Inclusion of baldcypress in the furnish.—Flakeboards comprised of one-third baldcypress and two-thirds mixed southern hardwoods had IB strength of 64 to 73 psi when bonded with 5.5 percent resin (liquid) at panel densities of 41 to 43 pounds/cu ft (table 24-13).

Seven-species mix of bottomland hardwoods.—Mixtures of flakes from hardwood species typical of south-central Louisiana yielded boards with IB strengths from 62 to 113 psi depending on procedures and species (table 24-14).

Resin content.—Price and Lehmann (1978) found that regardless of type of flake used, flakeboards made with 8 percent phenol-formaldehyde resin solids (applied as a liquid) had higher IB strength initially and after accelerated aging than those made with 5-percent resin content (fig. 24-7). Other researchers in the field agree that IB values are correlated with resin content within the range of resin contents normally used (see fig. 24-37 top).

Optimization of IB.—IB optimization is limited by economic constraints on permissible resin content, and by the need to maintain MOE and MOR at acceptable levels. Text related to figure 24-38 in the previous subsections on MOE and MOR described a near optimum fabrication procedure for flakeboard comprised of 20 percent each of hickory, white oak, southern red oak, sweetgum, and southern pine. Small flakeboards of this design had IB of 82 psi when flakes were aligned at board density of 45.5 lb/cu ft, and 83 psi with random flake placement at a board density of 47.5 lb/cu ft (fig. 24-38 bottom).

Price (1978) fabricated 4- by 8-foot mixed-species flakeboard panels with aligned faces and cores, and also with random flake placement, using procedures (see table 24-12) similar to the optimum suggested by Hse et al. (1975). He found that to obtain an IB of 70 psi, 1/2-inch-thick panels must exceed 43 lb/cu ft and 5/8-inch panels 47 lb/cu ft in density. As exposure induced weathering or as moisture increased, IB decreased (table 24-17). Increasing RH from 50 to 65 percent decreased IB an average of 7.6 psi because of moisture increase or density decrease or both. Modified aging and accelerated aging reduced IB strength drastically. The average modified aging strength (13.5 psi) was only 21 percent of the 65 percent RH average. Accelerated aging reduced the IB an additional 8 percent. For the mixed-species panels, only 10 percent of the 65 percent RH strength was retained after accelerated aging, but the single-species panels—which were made of low-density woods—retained 28 percent.

PLATE SHEAR STRENGTH

Price (1978) evaluated the plate shear strength of 17.5-inch-square specimens cut from the 4- by 8-foot panels described in the preceding paragraph and in table 24-17. These specimens were tested according to ASTM D 3044-72 of American Society for Testing and Materials (1976). This property is important when flakeboards are used as webs in I-beams or boxbeams—as they likely will be in fabricated joists of various designs.

Price found that at a density of 46 lb/cu ft, the shear modulus of the random panels (259,000 psi) was 35 percent higher than that of the oriented panels (192,000 psi). The regression slopes of panel density on shear modulus were statistically equivalent for both 5/8-inch panels and the 1/2-inch random panel (table 24-18). Since the slope applicable to the 1/2-inch oriented panel was not the same as that for the 1/2-inch random panel, at higher or lower densities, the 35-percent difference in shear modulus will not be maintained.

IMPACT STRENGTH

Structural panels for use as sheathing or decking in building construction must have acceptable impact strength to withstand loads imposed when offloading panels at the building site, during construction, and during use. Impact loads are probably most severe during construction when building materials or tools are dropped, or when carpenters jump from level to level.

Johnson and Haygreen's (1974) evaluation of the impact behavior of aspen, Douglas-fir, and southern pine phenolic-bonded and urea-bonded structural particleboards in comparison with Douglas-fir plywood will likely be of interest to readers needing background information. Readers needing a review of methods to evaluate impact behavior of sheathing material should refer to Superfesky (1975).

TABLE 24-17.—*Summary of internal bond properties for flakeboards*[1] *subjected to various exposures* (Data from Price 1978)

Panel types	50% RH		65% RH		Modified aging		Accelerated aging	
	Density[2]	IB	Density[3]	IB	Density[3]	IB	Density[3]	IB
	Lb/cu ft	*Psi*	*Lb/cu ft*	*Psi*	*Lb/cu ft*	*Psi*	*Lb/cu ft*	*Psi*
1/2-inch oriented mixed species	43.22	77.4	42.67	71.1	43.24	12.8	42.46	7.6
	46.75	95.0	47.54	86.8	47.16	19.5	46.43	11.6
1/2-inch random mixed species	46.59	88.7	43.63	72.8	44.21	13.0	42.78	6.6
	47.92	96.4	45.92	81.6	45.98	14.3	45.36	7.5
5/8-inch oriented mixed species	43.72	57.4	42.65	44.0	42.46	5.7	42.43	4.3
	47.56	85.4	45.99	70.0	46.70	7.6	45.49	5.5
5/8-inch random mixed species	42.19	52.6	39.25	41.3	38.99	6.6	38.56	4.9
	44.61	65.7	42.35	54.4	41.77	7.8	41.20	5.2
	48.42	90.7	45.63	71.1	46.21	10.4	45.50	6.4
1/2-inch random pine	43.38	71.5	39.40	59.7	40.22	24.9	39.54	17.1
1/2-inch random yellow-poplar	42.40	68.3	39.41	65.1	39.62	25.7	38.58	17.1
Average	45.16	77.2	43.21	65.3	43.33	13.5	47.57	8.5

[1]Four- by 8-foot panels made with 6-percent liquid phenol-formaldehyde resin and 1-percent wax emulsion, layered with each face 1/4 of total weight; core flakes milled for width reduction. Other fabrication procedures as discussed in text related to figure 24-38, which describes performance of small panels.

[2]Density based on OD weight and volume at 50-percent RH.

[3]Density based on OD weight and volume at 65-percent RH. The **modified aging** regime consisted of three complete cycles of (a) immersing in water at 120°F for 6 hours, and (b) heating in dry air at 210°F for 18 hours. Before testing panels were conditioned at 72°F and 65-percent RH. The six-cycle **accelerated aging** was performed according to ASTM D 1037-72a (American Society for Testing and Materials 1975a).

TABLE 24-18.—*Summary of shear modulus and regression equations for flakeboards made by the optimum procedures suggested by Hse et al (1975)* (Data from Price 1978)

Flakeboard panel type	No. of test speci-mens	Moisture content	Density[2] ρ	Shear modu-lus G	Linear regression, $G = a + b\rho$			
					a	b	R^2	$Sy \bullet \rho$
		Percent	*Lb/cu ft*	*Thousand psi*				
1/2-inch oriented mixed species	16	10.34	42.55	173.84	−90.157	6.131	0.840	8.395
	16	9.78	46.85	193.95				
1/2-inch random mixed species	16	10.24	46.31	261.57	−122.291	8.302	.670	13.213
	16	10.17	48.00	276.80				
5/8-inch oriented mixed species	16	10.02	41.09	155.41	−155.924	7.573	.861	9.855
	16	10.30	45.48	188.40				
5/8-inch random mixed species	16	10.01	42.60	235.94				
	16	9.99	45.46	252.52	−91.683	7.622	.777	12.601
	8	10.20	49.48	288.24				
1/2-inch random pine	16	10.66	41.95	266.89	N.S.			
1/2-inch random yellow-poplar	16	9.50	42.25	301.30	N.S.			

[1]The mixed-species flakeboards had 20 percent each by weight of white oak, southern red oak, hickory, sweetgum, and southern pine.
[2]Density based on OD weight and volume at test.

Discussion in this text will be limited to performance under impact loads of phenolic-bonded structural flakeboards made of southern hardwoods by the procedure suggested by Hse et al. (1975), and as described in the footnotes to table 24-12. The test procedure and results that follow are taken from Price (1978). The procedure is described in some detail so that results may be more readily interpreted. Both 1/2-inch and 5/8-inch panels satisfy impact requirements for APA RATED STURDI-FLOOR and APA RATED SHEATHING.

Procedure.—Six 4- by 8-foot flakeboard panels from each density group indicated in table 24-19 were used for impact evaluation. These were compared to 19 southern pine plywood panels of two thicknesses (1/2-inch with three plies and 5/8-inch with four plies) purchased from six building suppliers in central Louisiana. A 1/2-inch and 5/8-inch panel from each supplier was randomly selected for impact evaluation.

All 1/2-inch panels were cut into 4- by 4-foot sections; 5/8-inch panels were cut to obtain one 48- by 32-inch piece from each end. One section was used for dry test (50 percent RH condition). The other section was designated for a 3-day water spray applied to the top surface before evaluation.

All panels were nailed to nominal 2- by 8-inch, kiln-dried, No. 2 (or better) grade, southern pine framing; the 8-foot dimension of the panel spanned the framing members. Panels were attached with 8d common nails spaced about 6 inches on center and about 3/8-inch from the edge along outside framing members. Nails were 12 inches on center on the middle framing member. A nominal 1- by 4-inch board was nailed to the lower part of each end of the frame to prevent rotation of the structure.

All 1/2-inch panels were evaluated on 24-inch spans; the 5/8-inch panels were evaluated on 16-inch spans.

Impact locations were at mid-span 6 inches inward from the edge. A 200-pound load was applied to a 3-inch disk at the designated impact location before each drop of the impact load and after failure. The deflection resulting from the concentrated load was recorded relative to the joist. After removal of the concentrated load, a leather bag containing enough No. 9 lead shot to total 30 pounds was released by a remote-controlled solenoid-activated pair of jaws. The drop bag conformed to ASTM E 72-68 (American Society for Testing and Materials 1968a). The first drop height was 6 inches and height was increased in 6-inch increments until the panel would not support the 200-pound load or a failure was observed. The maximum drop height (MDH) was recorded, and the deflection caused by each drop was recorded relative to the joist.

Results.—Price (1978) found that southern pine plywood had greater average impact resistance than any of the flakeboard panels (table 24-19). However, yellow-poplar flakeboards that were wet tested had a higher impact resistance than plywood that was wet tested. Only the 1/2-inch oriented mixed species flakeboards had a deflection at maximum drop height that was less than that of plywood.

Considerable variation was observed in the impact resistance of different plywood panels and between locations on one panel. For instance, the 5/8-inch plywood that was dry-tested had an average MDH on the inside edge of 56 inches (range of 18 to 90 inches) and an average on the outside edge of 84 inches

TABLE 24-19.—*Average values for impact test and 200-pound concentrated load evaluation on southern hardwood and southern pine flakeboards compared to southern pine plywood panels* (Data from Price 1978)[1,2]

Panel Type	Moisture Content at Test		Maximum Drop Height		Deflection at Maximum Drop		Deflection with 200-Pound Concentrated Force: Initial		Deflection with 200-Pound Concentrated Force: Final	
	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet	Dry	Wet
	Percent		*Inch*							
24-INCH SPAN										
1/2-inch oriented mixed species . .	6.94	74.36	35	31	0.195	0.196	0.207	0.258	0.339	0.441
	(1.00)	(1.85)	(.55)	(.52)	(.90)	(.91)	(.96)	(.94)	(1.06)	(1.28)
1/2-inch random mixed species . . .	5.78	32.57	51	56	.220	.220	.210	.252	.326	.368
	(.83)	(.81)	(.80)	(.93)	(1.01)	(1.02)	(.98)	(.92)	(1.02)	(1.07)
1/2-inch pine plywood	6.94	40.12	64	60	.217	.215	.215	.274	.321	.344
1/2-inch random pine	6.65	61.94	52	55	.227	.215	.193	.240	.332	.384
	(.96)	(1.54)	(.81)	(.92)	(1.05)	(1.00)	(.90)	(.88)	(1.03)	(1.12)
1/2-inch random yellow-poplar . . .	5.49	25.41	60	72	.224	.257	.180	.208	.311	.345
	(.79)	(.63)	(.94)	(1.20)	(1.03)	(1.20)	(.84)	(.75)	(.97)	(1.00)
16-INCH SPAN										
5/8-inch oriented mixed species . .	6.96	88.15	64	56	.171	.179	.057	.071	.106	.257
	(1.08)	(2.08)	(.91)	(.62)	(1.36)	(1.16)	(.91)	(.76)	(.91)	(1.65)
5/8-inch random mixed species . . .	6.08	28.95	58	77	.188	.187	.055	.067	.085	.112
	(.94)	(.68)	(.83)	(.86)	(1.49)	(1.21)	(.87)	(.71)	(.73)	(.72)
5/8-inch pine plywood	6.44	42.37	70	90	.126	.154	.063	.094	.117	.156

[1]See footnote of table 24-12 for flakeboard fabrication procedures.
[2]The ratio of flakeboard to plywood is inside the parentheses.

(range of 66 to 120 inches). The 1/2-inch plywood had a more consistent average MDH (64 inches for both edges), but the range was 36 to 78 inches for the outside edge and 12 to 102 inches for the inside edge.

Among flakeboards, yellow-poplar panels had the greatest and 1/2-inch oriented panels the least impact resistance. Results for random pine panels were similar to those for random mixed species panels. The 5/8-inch random flakeboard had a higher MDH than similar oriented flakeboard for the wet test but a lower MDH for the dry test. The difference may have occurred because of excessive thickness swell and water absorption by the oriented panels.

Except for yellow-poplar flakeboards, the impact resistance and deflection of 1/2-inch panels in the dry test were similar to those in the wet test. Among 5/8-inch panels, the random panels and plywood had more impact resistance when wet than when dry tested. Oriented panels and plywood deflected more when wet tested than when dry tested.

After impact failure, all panels supported the 200-pound concentrated load. Except for a few cases, the deflection ratio—final deflection/initial deflection—exceeded 1.50 but was greater than 1.86 only for the wet 5/8-inch oriented mixed species flakeboards. Among 1/2-inch panels, plywood had the lowest ratio for both wet and dry conditions. But the ratio for 5/8-inch random flakeboard was less than that for 5/8-inch plywood for the dry test and equal for the wet test.

The 200-pound concentrated load caused less initial deflection for all types of flakeboards than for plywood when equal thicknesses were compared. After failure, the plywood deflected slightly less than flakeboard of equal thickness except for the dry tested 1/2-inch yellow-poplar flakeboards and wet tested 5/8-inch oriented mixed species flakeboards.

INTERLAMINAR SHEAR STRENGTH AND STIFFNESS

Resistance to in-plane shear deformation is a significant mechanical-property requirement for materials in webs of composite beams and structural diaphragms. No data specific to flakeboards made of southern hardwoods are published, but data from other species give useful information probably applicable to southern hardwoods.

Interlaminar shear strength.—From evaluations of 10 particleboards at about 9-percent moisture content, McNatt (1973) found that internal bond strength is linearly correlated with interlaminar shear strength (fig. 24-41); at internal bond strength of 70 psi, his data indicate interlaminar shear strength of 252 psi.

In-plane shear modulus.—Hunt (1978) compared the change in shear moduli of sheathing-grade aspen waferboard with sanded Douglas-fir structural-I-grade Douglas-fir plywood over a range of relative humidities from 36 to 87 percent. He found that throughout this range, the flakeboard had in-plane shear moduli about 2½ times greater than that of the plywood. No comparable data are published describing flakeboards of southern hardwoods, nor are data available from systematic studies of the effects of weathering on this relationship.

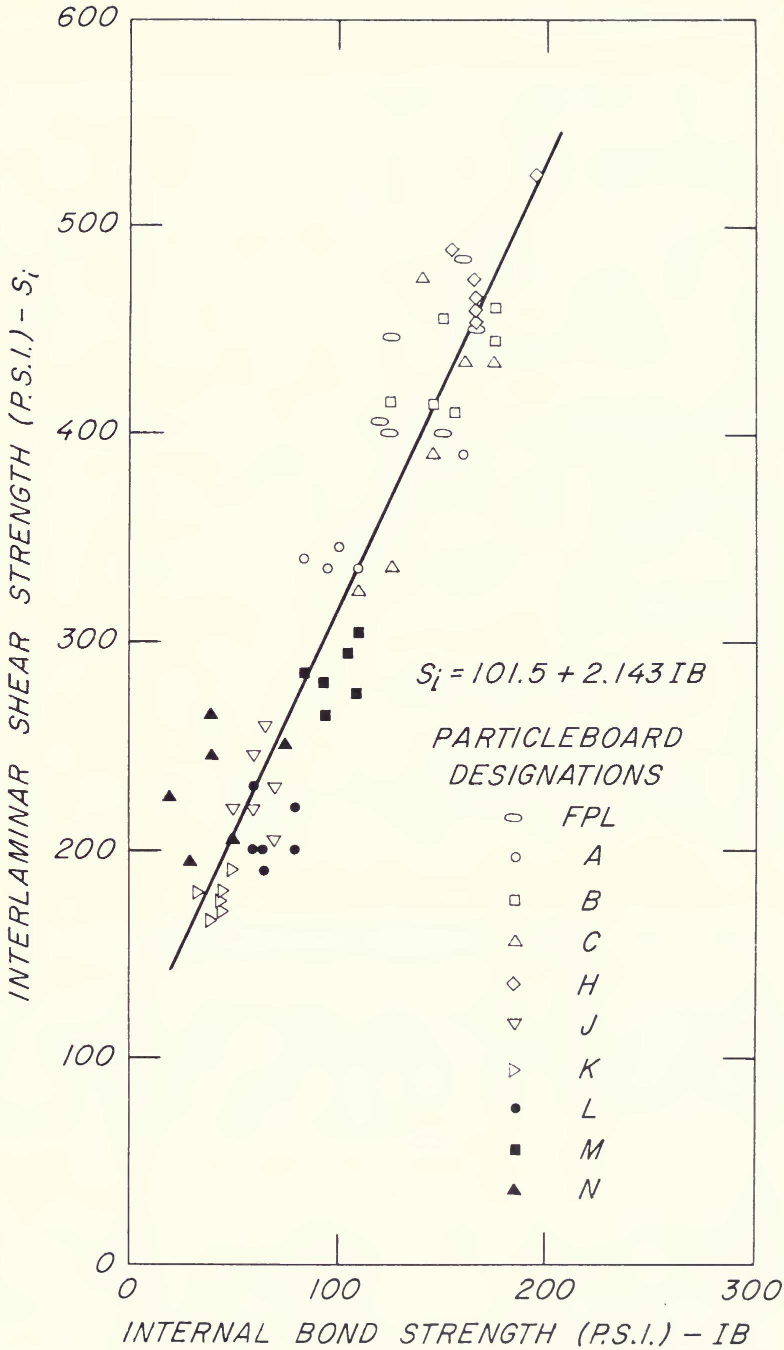

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Figure 24-41.—Relationship of interlaminar shear strength to internal bond strength of particleboard. The FPL flakeboard is of Douglas-fir; flakeboard M has southern pine faces and southern pine and mixed southern hardwoods in the core; flakeboard N is of aspen. The others are a variety of softwood particleboards. (Drawing after McNatt 1973.)

RACKING STRENGTH

One measure of adequacy of sheathing panels is the deflection and strength of walls sheathed with the panels, when the walls are subjected to in-plane shear, i.e., to racking loads. Price and Gromala (1980) compared racking behavior of flakeboards of high and low density and two thicknesses fabricated from 20 percent each of white oak, hickory, southern red oak, sweetgum, and southern pine (see table 24-12 for fabrication details), with 1/2-inch yellow-poplar flakeboard, southern pine flakeboard (both with random orientation of flakes), and with southern pine 3-ply, 1/2-inch-thick, CDX plywood. The racking loads were applied to full-size racking panels (8 by 8 feet) according to ASTM E 72 (American Society for Testing and Materials 1968a) and also to small panels measuring 2 by 2 feet.

Price and Gromala found that when subjected to a 1,600-pound racking load, 8- by 8-foot panels sheathed with flakeboards containing a mixture of hardwood and pine flakes were slightly stiffer than southern pine plywood (0.10-in. vs. 0.12-in. deflection). Yet, plywood sheathed panels provided slightly higher strengths for the full-size racking test (6,000 vs. 5,500 pounds). The highest average racking strength, 6,200 pounds, was obtained with the 1/2-inch yellow-poplar-sheathed panels.

After a 24-hour water soak, small-panel racking resistances and lateral nail strength decreased. The racking strength decrease ranged from 4 percent (5/8-in. oriented mixed high density) to 18 percent (1/2-in. oriented mixed low density). All panel types had racking strength reductions within limits allowed under current standards. The nail-strength decrease ranged from 9 percent (5/8-in. random mixed high-density flakeboard) to 27 percent (1/2-in. southern pine plywood).

24-10 LINEAR EXPANSION

Construction panels, particularly those used for roof sheathing and floor decking, usually are rain wetted at times during the construction period before roofing and walls are made weather tight. Also, all sheathing and decking material is subject to fluctuations in relative humidity during construction and during building life. Moisture pickup resulting from rain wetting or humidity changes causes flakeboard to expand (fig. 24-42). The sorption isotherm for the flakeboard described in figure 24-42 is depicted in figure 8-18. To guard against buckling, application specifications for sheathing and decking panels call for them to have end and edge spacing of 1/8 inch. This space is 0.26 percent of the 4-foot width and 0.13 percent of the 8-foot length of the usual 4- by 8-foot panel.

Kasper and Carroll (1979) found that phenolic-bonded structural particleboards exposed as floor decking during 6 weeks of winter weather in Vancouver, British Columbia—or under conditions simulating that weather—underwent less than half (38-percent) of the linear expansion of unrestrained board specimens subjected to an ovendry-vacuum-pressure-soak cycle. This diminution of

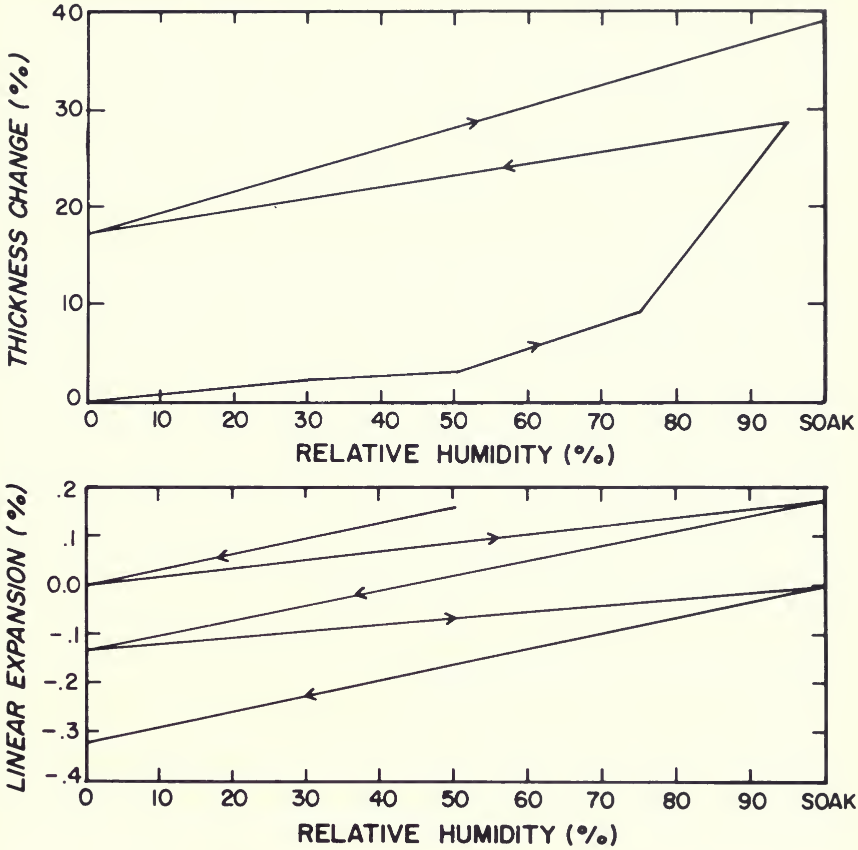

Figure 24-42.—(Top) Relationship between relative humidity and thickness swell in 1/2-inch-thick, phenolic-bonded, three-layer flakeboard made of randomly placed, 3-inch-long, shaping-lathe flakes of mixed southern woods fabricated as described in discussion related to figure 24-38, when pressed to a density of 44-48 pounds/cu ft, based on ovendry volume and weight; the lower curve depicts data as RH is increased from ovendry to 30, 50, 75, and 95 percent; the upper curves depict return to ovendry and ovendry to soak. (Bottom) Linear expansion in such flakeboard from 50 percent RH to ovendry, then during two cycles of ovendry-water soak-ovendry. (Drawings from Study File FS-SO-3201-15, U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station, Pineville, La.)

linear expansion was attributed to partial restraint offered by the framing to which the decking was nailed.

Section 24-2 noted that unrestrained linear expansion of CDX plywood between 30- and 90-percent relative humidity is about 0.10 percent along the major axis and 0.14 percent across the major axis. For 2-MW waferboard and 2-MF flakeboard, the National Particleboard Association (1980) specifies that linear expansion between 50- and 90-percent relative humidity shall be less than 0.20

percent. Linear stability of APA RATED STURDI-FLOOR and APA RATED SHEATHING panels must be such that they can satisfy one of three alternative specifications (see paragraph *Linear Expansion* in text related to table 24-3).

The optimum 1/2-inch-thick, small, phenolic-bonded flakeboards of mixed southern species described by Hse et al. (1975), and the 4- by 8-foot 1/2- and 5/8-inch-thick panels of mixed southern woods made by Price (1978) according to the procedure of Hse et al.—see table 24-12 for fabrication details—meet these specifications.

As noted by Kelly (1977) particleboards composed of flakes are most linearly stable; thin flakes (less than 0.012 to 0.015 inch) and flake lengths of 1 inch and longer favor linear stability. If resin content is sufficient for adequate internal bond strength, additional resin only slightly improves linear stability. Addition of wax to the furnish reduces dimensional changes under cyclic relative humidity conditions and short term liquid water exposure. The literature is not clear about the relationship between flakeboard density and linear expansion (Kelly 1977). Geimer (1982), however, concluded from research on Douglas-fir flakeboard that boards saturated by vacuum-pressure-soak treatment had linear expansion positively correlated with specific gravity, i.e., dense boards had greater linear expansion than less dense boards.

SINGLE-SPECIES FLAKEBOARDS

Boards made of veneer flakes.—Hse (1975c) made single-species flakeboards from 3-inch-long, 0.015-inch-thick, 3/8-inch wide veneer flakes of nine hardwoods commonly found where southern pines grow and measured their linear expansion under three exposure conditions (table 24-9). As panel density increased, percentage of water absorbed declined in all but two species (sweetbay and sweetgum) during the 5-hour boil test, and declined in all but one species (sweetbay) during the ovendry-vacuum-pressure-soak test (OD-VPS). Hse found that, on average, panels of high-density species (hickory, southern red oak, post oak, and white oak) absorbed a slightly lower weight percentage of water. In the 50-90 percent RH exposures, species and panel densities had no effect on moisture gain. Water absorption varied significantly with exposure, as follows:

50-90 percent RH	13-16 percent
5-hour boil	68-125 percent
OD-VPS	75-116 percent

Ranges for average linear expansions in the three exposure tests were:

50-90 percent RH	0.068-0.351 percent
5-hour boil	.045- .443 percent
OD-VPS	.027- .480 percent

On average, Hse found that the low-density species were slightly more stable than the high density ones; white oak panels were the least stable. All 49.5-lb/cu ft boards, except hickory and post oak, expanded more than either 44.5 or 39.5-lb/cu ft boards of the same species. Red maple, sweetbay, and sweetgum were the most stable among the 44.5-lb/cu ft boards. Among 39.5-lb/cu ft boards, sweetgum and sweetbay were the most stable.

Post (1961) found that scarlet oak flakeboard made from veneer flakes had least linear expansion if flakes were about 0.012 to 0.015 inch thick.

Comparison of single-species boards made from flakes cut on industrial flakers.—Price and Lehmann (1978) evaluated linear expansion of boards composed of flakes cut on ring, disk, drum, and shaping-lathe flakers. When exposed to the ovendry-vacuum-pressure-soak test, southern red oak, hickory, and sweetgum boards made with lathe flakes were most stable (figs. 24-8 and 24-12). Lathe flakes also made the most stable sweetgum boards as tested by a 24-hour water soak. When cycled between 30 and 90 percent RH, oak and hickory boards had most linear stability if made from lathe or drum flakes.

Heebink and Lehmann (1977) made flakeboards of yellow-poplar, red oak, and hickory from randomly oriented 1-inch-long flakes 0.015 inch thick cut in the 0-90 direction by cross-grain planing. Linear expansions they observed in the single-species boards of 40 lb/cu ft density bonded with phenol-formaldehyde resin (6 percent resin content) were as follows:

Condition	Yellow-poplar	Red oak	Hickory
	Percent		
0-90 percent RH	0.21	0.29	0.29
30-90 percent RH	.11	.17	.16
30-day water soak	.20	.36	.25
24-hour water soak	.12	.17	.17

In a study of phenolic-bonded 1/2-inch-thick flakeboard made from randomly oriented 0.020-inch-thick, 3-inch-long sweetgum flakes cut on a shaping lathe, R. C. Tang and E. W. Price found (Final Report FS-SO-3201-12, dated March 31, 1982, Pineville, La.) that linear expansion was at follows:

Relative humidity cycle	Linear expansion
Percent	
35 to 95	0.153
55 to 95	.118

These observations were made with an optical comparator.

Price (1978), using calipers to measure between pins fitted in grommeted holes, found that yellow-poplar and southern pine boards made with 3-inch-long, 0.015-inch-thick face flakes and 0.025-inch-thick core flakes cut on a shaping-lathe had linear expansion—averaged across 4-foot and 8-foot panel directions—after a 24-hour water soak, as follows (table 24-20):

Species	Linear expansion	Panel density
	Percent	*Lb/cu ft*
Yellow-poplar	0.030	39.4
Southern pine.............	.036	40.4

When northern red oak flakeboard was given OD-VPS treatment, Heebink and Lehmann (1977) found that linear expansion was 0.53 to 0.56 percent; these oak boards were made of cross-grain planed flakes 2 inches long and 0.015 inch thick. Ring-flakes 2 inches long and 0.020 inch thick yielded flakeboards with linear expansion after OD-VPS as follows:

American elm	0.28-0.33 percent
Maple sp.	0.38-0.40 percent

Hse (1981) found that linear expansion of a phenol-formaldehyde-bonded white oak flakeboard subjected to the OD-VPS cycle was particularly large (0.528 percent) compared to that of southern red oak flakeboard (0.358 percent), but was significantly reduced by applying polyisocyanate to the flakes before application of liquid phenol formaldehyde resin (table 24-10).

Heebink and Hann (1959) concluded that addition of 1 percent wax to northern red oak flakeboard made of 1-inch-long, 0.015-inch-thick, disk-cut flakes did not increase linear stability; their boards were bonded with urea-formaldehyde resin.

TABLE 24-20.—*Dimensional stability evaluated by 24-hour water soak of flakeboards of mixed species and single species of southern woods* (Data from Price 1978)[1]

Panel type and density (lb/cu ft)	Water absorption	Thickness swell		Linear expansion[2] 8-foot direction	4-foot direction
	Percent	*Percent*	*Percent/ percent MC*[3]	*------Percent------*	
1/2-in oriented mixed species					
43.63	30.0	20.8	0.338	0.085	0.030
48.30	36.4	17.8	.383	.079	.020
1/2-in random mixed species					
43.95	21.4	13.2	.454	.055	.090
45.68	21.0	13.2	.445	.062	.101
5/8-in oriented mixed species					
42.54	36.6	22.7	.463	.193	.143
47.16	27.8	19.0	.351	.190	.129
5/8-in random mixed species					
38.77	26.7	13.3	.342	.058	.116
42.03	22.5	12.0	.383	.028	.057
47.07	17.1	9.6	.428	.065	.085
1/2-in random pine					
40.37	27.3	12.9	.331	.020	.053
1/2-in random yellow-poplar					
39.42	20.5	9.9	.372	.025	.035

[1]See footnote of table 24-12 for flakeboard fabrication procedures.

[2]Calipers were used to measure the distance between pins set in grommeted holes.

Anthony and Moslemi (1969) found that hickory flakeboard bonded with urea-formaldehyde resin (8 percent) from 1-inch-long, 0.015-inch-thick, disk-cut flakes and pressed to a density of 46.2 lb/cu ft had linear expansion between 50- and 90-percent RH of 0.146 percent.

MIXED-SPECIES BOARDS FROM SHAPING-LATHE FLAKES

By use of mechanical micrometers and measuring between grommeted holes in panels, Price (1978) measured the linear expansion after 24-hour water soak of boards composed of 20 percent each of shaping-lathe-cut flakes from white oak, hickory, southern red oak, sweetgum, and southern pine fabricated in 4- by 8-foot panels. Boards were made in 1/2-inch and 5/8-inch thicknesses with flakes aligned and randomly placed. In no case did linear expansion exceed 0.20 percent (table 24-20).

Through use of microscopes arranged in an optical comparator, Price and Hse[9] measured linear expansion of flakeboard comprised of a mixture of shaping-lathe flakes of seven southern hardwood species or species groups (table 24-21). These flakeboards, if pressed to a density of 41 pounds/cu ft or more, were most stable linearly if both face flakes and core flakes were 3 inches long—rather than 1.5 inches long, and if face flakes were 0.015 inch thick and core flakes 0.025 inch thick (fig. 24-43). If so fabricated, linear expansion at board density of 42 pounds/cu ft was as follows:

Test	Linear expansion
	Percent
OD-VPS	0.16
30- to 90-percent RH	.04

Mechanical properties of these flakeboards are given in figure 24-33.

Because some parts of the coastal plains of the South and Southeast carry a large component of baldcypress, phenolic-bonded flakeboards comprised of shaping-lathe flakes with the following species mixture were evaluated by Hse and Price[8]: 35.4 percent baldcypress, 31.4 percent soft hardwoods, 17.1 percent oak sp., 14.7 percent other hard hardwoods, and 1.4 percent minor species. Both face and core flakes were 3 inches long; face flakes were 0.015 inch thick and core flakes 0.025 inch thick. These boards had linear expansion of 0.116 and 0.113 percent, at 40.7 and 42.7 pounds/cu ft panel density, after ovendry-vacuum-pressure-soak treatment (table 24-13).

24-11 THICKNESS SWELL

Rainwetting and moisture content increase attributable to increase in relative humidity (fig. 8-18) cause flakeboard to swell in thickness (fig. 24-42). Some of this swelling is irreversible.

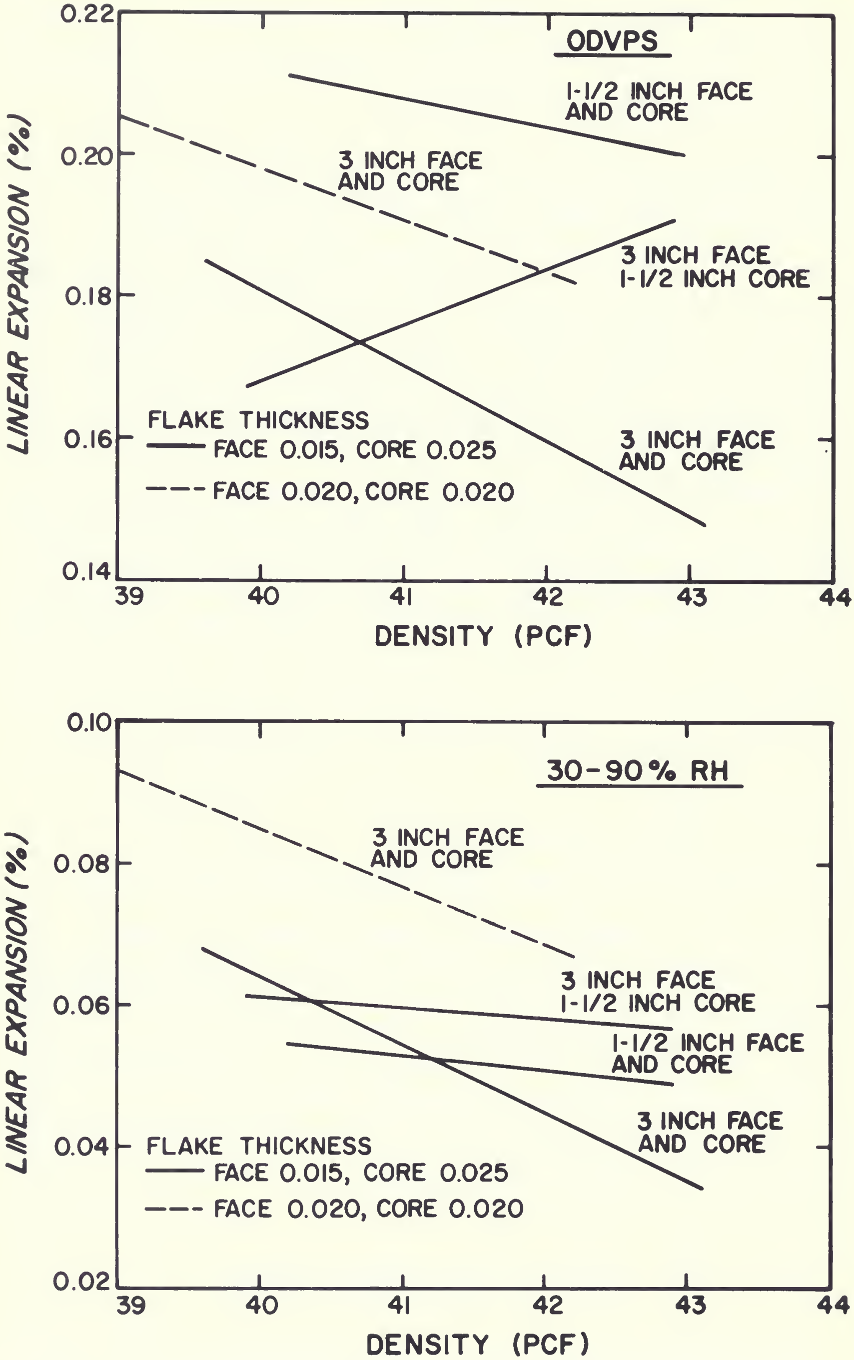

Figure 24-43.—Effect of flake length and thickness in faces and cores and panel density (ovendry weight and volume at 50-percent RH) on linear expansion of southern hardwood flakeboard during the ovendry-vacuum-pressure-soak test (top) and cycling from 30- to 90-percent relative humidity (bottom). See table 24-21 (footnote[1]) for species mix and fabrication procedure. (Data from Price and Hse, text footnote[9].)

TABLE 24-21.—*Linear expansion and thickness swell of flakeboards made with shaping-lathe flakes of a seven-species mixture of bottomland hardwoods*[1]
(Data from Price and Hse, text footnote[9])

Flake length (inch)			ODVPS[3]				30 to 90% RH			
			Moisture content				Moisture content			
Face	Core	Density[2]	Initial	Final	LE	TS	Initial	Final	LE	TS
		pcf	*Percent*							
Panels made with 0.015-inch face flakes, 0.025-inch core flakes, and 5½% liquid phenolic resin										
1½	1½	40.2	0	124.9	.211	27.9	7.06	19.0	.055	14.9
		(39.8-40.7)		(119.3-129.6)	(.185-.231)	(26.0-29.5)	(7.00-7.19)	(19.0-19.1)	(.020-.114)	(13.5-16.6)
1½	1½	42.9	0	114.0	.205	29.1	7.04	18.5	.049	14.6
		(42.4-43.8)		(107.4-119.8)	(.170-.256)	(25.9-33.0)	(7.01-7.07)	(18.0-19.0)	(.025-.090)	(13.3-17.1)
3	1½	39.9	0	125.2	.167	26.2	7.07	18.5	.061	13.8
		(39.3-40.6)		(120.3-132.0)	(.125-.191)	(23.0-28.6)	(7.00-7.25)	(18.0-18.8)	(.030-.106)	(12.8-14.5)
3	1½	42.9	0	115.0	.191	27.5	7.06	18.4	.057	14.1
		(42.7-43.1)		(108.2-124-3)	(.166-.221)	(24.0-30.4)	(7.02-7.18)	(18.1-19.0)	(.040-.075)	(12.9-16.5)
3	3	39.6	0	128.6	.185	28.0	7.08	18.8	.068	14.6
		(38.6-40.7)		(115.3-139.3)	(.161-.216)	(23.6-33.6)	(7.00-7.20)	(18.4-19.2)	(.040-.110)	(13.0-19.6)
3	3	43.1	0	117.8	.148	28.6	7.05	18.8	.034	16.2
		(41.7-44.7)		(108.7-123.5)	(.110-.171)	(23.8-31.6)	(7.03-7.10)	(18.3-19.4)	(.010-.070)	(14.0-19.5)
Panels made with 0.020-inch flakes and 5½% liquid resin										
3	3	39.0	0	132.6	.205	35.3	6.67	17.1	.093	12.8
		(38.6-39.2)		(110.6-150.4)	(.110-.320)	(30.4-40.4)	(6.50-7.04)	(16.7-17.7)	(.050-.120)	(10.4-14.4)
3	3	42.2	0	116.3	.182	34.4	6.82	16.9	.067	11.9
		(40.8-43.4)		(106.8-134.7)	(.111-.271)	(30.5-40.2)	(6.60-7.07)	(16.4-17.4)	(.040-.100)	(10.5-12.7)

[1]The seven species and percent of the total mixture; were sweetgum (32%), hackberry (18%), elm (5%); red oak (14%), ash (17%), overcup oak (5%), and pecan (9%). All panels were made at 7/16-inch thickness, flakes randomly oriented, and pressed for 5½ minutes. For panels with different face and core flake thicknesses, one quarter of the board weight was in each face and half of board weight was in the core. Panels with liquid resin consisted of a six-panel replication and a press temperature of 340°F. The range of values is given in the parentheses.

[2]Density based on ovendry weight and volume at test of the bending specimen.

[3]ODVPS = ovendry to vacuum-pressure soak test method P-1 of the American Plywood Association.

In roof and wall sheathing applications, a 1/2-inch flakeboard panel of mixed southern woods (42 to 46 pound/cu ft density) will increase in thickness about 10 to 12 percent as relative humidity increases from 50 to 90 percent. This will, of course, lift shingles or siding by this amount—but should cause no particular problems. Floor decking will similarly increase in thickness, uniformly lifting floor tile, rugs, or other floor covering.

If thoroughly wetted, as by a long-term plumbing leak, such a flakeboard originally pressed to 1/2- to 5/8-inch thickness may swell 25 percent. After such swelling, panel stiffness and load carrying capacity may be slightly diminished—but not excessively, as indicated by the following data on southern hardwood flakeboard from Price (1978, p. 114).

Panel thickness and type	Maximum load supportable on a 3-inch-diameter disk		Deflection under a 2,000-pound uniform load	
	Dry	Wet	Dry	Wet
	Pounds		*Inch*	
24-INCH SPAN: 2- BY 4-FOOT PANEL				
1/2-inch				
Oriented	573	388	0.189	.245
Random	672	575	.249	.334
5/8-inch				
Oriented	769	514	.115	.150
Random	938	740	.146	.188
16-INCH SPAN: 2- BY 2.67-FOOT PANEL				
1/2-inch				
Oriented	748	494	.039	.043
Random	850	612	.040	.062
5/8-inch				
Oriented	1,015	600	.032	.026
Random	1,173	861	.027	.032

Limits on thickness swell are not prescribed by the National Particleboard Association for 2-MW waferboard and 2-MF flakeboard. Neither has the American Plywood Association set a limit on thickness swell of APA RATED STURDI-FLOOR and APA RATED SHEATHING.

FACTORS AFFECTING THICKNESS SWELL

Flakeboards swell in thickness when their moisture contents increase because dry wood swells when wetted (fig. 8-28) and because individual flakes that have been compressed during mat compaction tend to revert to their original dimensions. Most of the thickness swell occurs at relative humidities above 70 percent. Since the heat and pressure of the pressing cycle cause some compression set, complete thickness regain is unlikely even after numerous cycles. Once water-swollen, most flakeboards do not return to their original pressed thickness. If flakeboard could be made with no compression of flakes and with no voids, maximum thickness change would be approximately equal to values for radial and tangential shrinkage of wood given in tables 8-9 and 8-10.

As seen from figures 24-30, 24-39, and 24-40, however, considerable compaction is required to develop acceptable MOE, MOR, and IB strength. Swelling of flakeboard could be minimized by achieving a uniform degree of compaction and density across panel width and length; visualize use of sponge-like caul plates that would not unduly compress those areas of the mat that contained too much wood substance. In practice, this concept is difficult to apply; also, such panels must be sanded to uniform thickness.

Use of uniformly thin flakes (e.g., 0.015 inch) favors thickness stability compared to non-uniform thick flakes. Flake length, in the range from 1 to 3 inches, does not strongly affect thickness swell if flakes are thin.

Increasing resin content of flakeboard increases thickness stability somewhat (fig. 24-9), but the increment of improvement diminishes as resin content increases above levels in normal industrial use (8 percent maximum for liquid phenolic resin). Inclusion of wax, usually about 1 percent by weight, moderates dimensional changes during humidity fluctuations and short-term wetting, but probably does not alter thickness stability during long-term changes in relative humidity.

Single-species flakeboards vary considerably in thickness stability; for example, white oak flakeboards have greater thickness swell than boards of most other major southern hardwoods (table 24-9).

To give the reader some appreciation of the magnitude of thickness swell under various conditions, the balance of this section presents experimental data pertinent to flakeboards made from hardwoods found on southern pine sites.

EXPERIMENTAL DATA

Single-species flakeboards made from veneer flakes.—Hse (1975c) measured thickness swell in boards of nine species (table 24-9), comprised of veneer flakes 3 inches long, 0.015 inch thick, and 3/8-inch wide bonded with 4-percent phenol-formaldehyde resin applied in liquid form. He found that ranges of average thickness swelling in three exposure tests were:

50-90 percent RH	13-32 percent
5-hour boil	20-112 percent
VPS	20-57 percent

The vacuum-pressure-soak test (VPS) consisted of soaking 3- by 9-inch specimens in water under vacuum (25 inches Hg) for 30 minutes and then under 65 psi pressure (at room temperature) for 24 hours.

Hse found that average thickness swelling varied from test to test. The 5-hour-boil consistently resulted in the greatest thickness swelling (average 43.7 percent), followed in order by the OD-VPS (average 28.4 percent), and 50 to 90 percent RH exposure test (average 18.7 percent).

In 5-hour-boil and OD-VPS tests, thickness swelling for all species increased with increasing panel density.

In the 50 to 90 percent RH test, there was little difference in thickness stability between panel densities of 39.5 and 44.5 lb/cu ft. Thickness swelling increased slightly as panel density increased to 49.5 lb/cu ft.

White oak panels swelled significantly more than those of other species, and they delaminated substantially between particles after the 5-hour boil. Hse (1975c) found no relationship, for any species, between initial IB and thickness stability.

Post (1961) made scarlet oak flakeboard from veneer flakes and found that thickness swell was least when flakes were very thin (0.006 or 0.012 inch). Jorgensen and Odell (1961), in an extension of Post's work, observed that high resin content favored thickness stability; thickness swell proceeded slowly with an increase in RH to 5 percent at 83 percent RH but increased to about 30 percent at 90 percent RH (see also fig. 24-42).

Single-species flakeboards made from non-veneer flakes.—Price and Lehmann (1978) evaluated thickness swell of boards composed of flakes cut on ring, disk, drum, and shaping-lathe flakers. When exposed to the OD-VPS test, southern red oak and mockernut hickory boards made of shaping-lathe flakes had least thickness swell (fig. 24-8). Between 30- and 90-percent RH, oak boards made with shaping-lathe flakes and hickory boards made with ring flakes had least thickness swell. In sweetgum panels, shaping-lathe flakes yielded least thickness swell (14.1, 9.9, and 28.2 percent in the 30-to-90-percent-RH, 24-hour-water-soak, and OD-VPS tests). Price and Lehmann found that, on average, the 30-to-90-percent-RH test caused least thickness swell, the 24-hour water soak caused the same or slightly more, and OD-VPS treatment caused about twice the thickness swell of the 30-to-90-percent-RH cycle. Sweetgum flakeboards, for example, had average thickness swell as follows (pooled data for all four types of flakers):

Treatment	Average thickness swell
	Percent
30-to-90-percent-RH	15
24-hour-water-soak	15
OD-VPS	31

They also found that increasing resin content from 5 to 8 percent decreased thickness swell by 2.7, 4.0, and 7.6 percentage points for the 30-to-90-percent-RH, 24-hour-water-soak, and OD-VPS tests (fig. 24-9).

Yellow-poplar flakeboards made similarly were found by Price (1978) to have thickness swell of 9.9 percent after a 24-hour water soak cycle (table 24-20)—about the same as for sweetgum boards of this design.

Hse (1981) found that thickness swell of phenol-formaldehyde-bonded white oak flakeboard subjected to the OD-VPS cycle was substantially greater (41.4 percent) than that of southern red oak flakeboard (26.0 percent), but was significantly reduced by applying polyisocyanate to the flakes before addition of liquid phenol-formaldehyde resin (table 24-10).

Heebink and Lehmann (1977) made flakeboards of yellow-poplar, red oak, and hickory from randomly oriented 1-inch-long flakes 0.015 inch thick cut in the 0-90 direction by cross-grain planing. Thickness swell in single-species boards of 40 lb/cu ft density bonded with phenol-formaldehyde resin (6-percent resin content) were as follows:

Condition	Yellow-poplar	Red oak	Hickory
	Percent		
0-to-90-percent RH	11	9	13
30-to-90-percent RH	10	8	11
30-day-water-soak	38	31	32
24-hour-water-soak	24	12	24

Heebink and Lehmann (1977) also found that American elm flakeboard made with 2-inch-long, 0.020-inch-thick ring flakes to 40-lb/cu ft density had thickness swell of 31.2 percent after an OD-VPS cycle.

Anthony and Moslemi (1969) found that hickory flakeboard bonded with urea formaldehyde (8 percent) from 1-inch-long, 0.015-inch-thick, disk-cut flakes and pressed to a density of 46.2 lb/cu ft had thickness swell between 50 and 90 percent RH of 7.5 percent.

Rice and Carey (1978) found that an increase in resin content significantly decreased thickness swell in yellow-poplar and sweetgum flakeboards pressed to densities of 35 to 50 lb/cu ft, and that thickness swell was least in the lowest density boards (fig. 24-44).

Mixed-species boards from shaping-lathe flakes.—Price (1978) measured thickness swell after 24-hour water soak of boards composed of 20 percent each of shaping-lathe flakes from white oak, hickory, southern red oak, sweetgum, and southern pine fabricated in 4- by 8-foot panels. Boards were made in 1/2-inch and 5/8-inch thicknesses with flakes aligned and randomly placed. In no case did thickness swell exceed 23 percent; dense boards had less percentage thickness swell than those of lower density (table 24-20).

In flakeboards made from mixed-species shaping-lathe flakes (face flakes 0.015 inch thick and core flakes 0.025 inch thick) of seven southern hardwood species (table 24-21), Price and Hse[9] found that after OD-VPS treatment thickness swell averaged about 28 percent and was not greatly affected by varying flake length from 1.5 to 3.0 inches. Between 30 and 90 percent RH, these flakeboards had average thickness swell of 15 percent; thickness swell was unaffected by flake length. If flake thickness in face and core was uniform at 0.020 inch, thickness swell after OD-VPS treatment was significantly greater, i.e., about 35 percent.

Hse and Price[8] evaluated thickness swell in flakeboards comprised of about one-third baldcypress and the balance mixed southeastern hardwoods. After ovendry-vacuum-pressure-soak treatment, thickness swell averaged 27 to 28 percent (table 24-13).

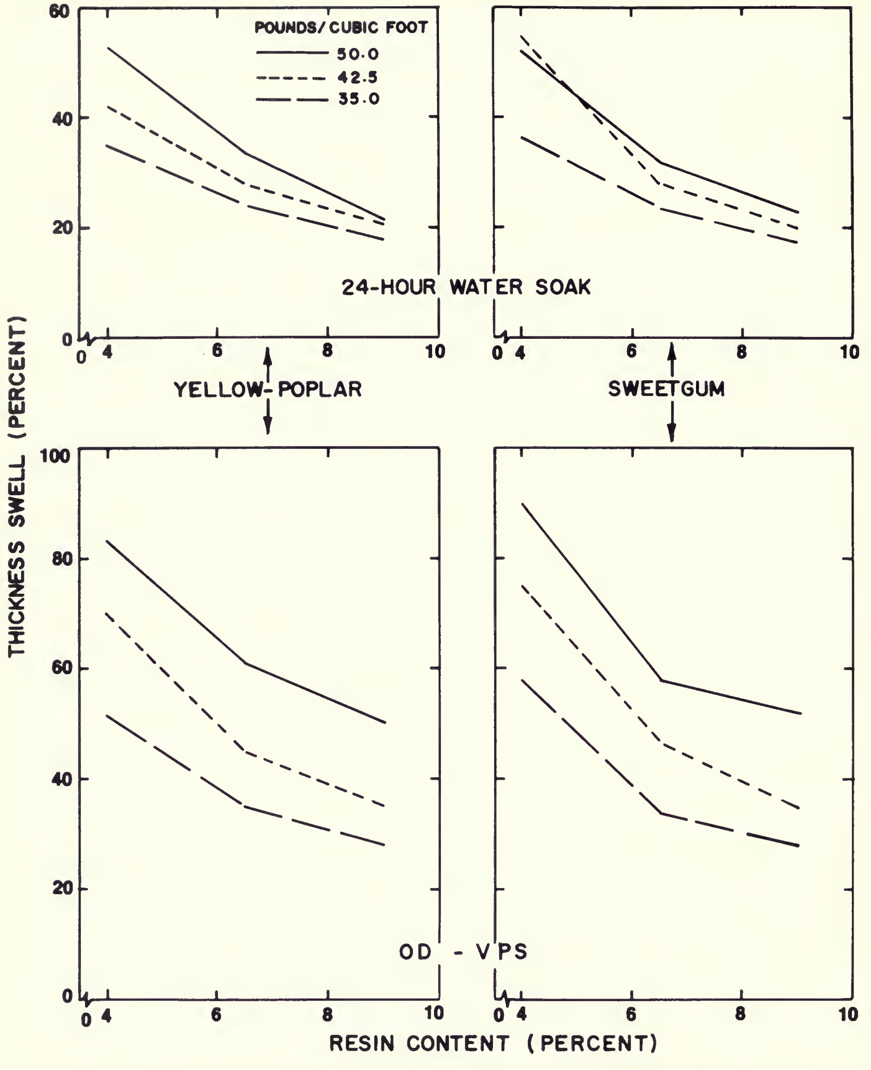

Figure 24-44.—Relationship between phenol-formaldehyde resin solids content (applied as liquid spray), in yellow-poplar and sweetgum flakeboard of three densities, and thickness swell after six cylces of ovendrying and water soaking. Flakes were 1/2-inch to 1 inch long, 0.015 inch thick, and 1/8- to 1/4-inch wide. Panels were pressed 15 minutes at 350°F with 400 psi specific pressure. (Drawing after Rice and Carey 1978.)

TREATMENTS TO REDUCE THICKNESS SWELL

Thickness swell of flakeboards can be reduced by pre-treatment of flakes (impregnating them with resin), by injecting steam into the mat during pressing, and by post-pressing exposure of panels to superheated steam, heated air, or hot oil.

Steam injection during pressing.—Shen (1973) found that injection of high-pressure steam into the mat during hot pressing can significantly reduce press time and thickness swell. For example, 1-inch-thick maple (*Acer saccharum* Marsh.) phenolic particleboard at 45-pounds/cu ft density was fully cured in 1 minute at a steam pressure of 300 psi. Thickness swell of this board after a 24-hour water soak was only about 10 percent, whereas conventionally hot-pressed board had thickness swell of about 33 percent.

Impregnation of flakes.—Brown et al. (1966) and Hujanen (1973) found that impregnating flakes with phenol-formaldehyde resin prior to board manufacture reduced both reversible and irreversible thickness swell. Between 50 and 90 percent RH, and in a 50-percent RH-VPS cycle, thickness swell was approximately halved compared to control boards without impregnation.

Steam post-treatment.—Hann (1965) and Heebink and Hefty (1968, 1969) found that flakeboards steamed at 360°F for 10 minutes in a stack with ventilated cauls between boards, and without restraint, had significantly reduced thickness swell. After water soaking for several days to equilibrium, thickness swell of steamed softwood flakeboards was about 10 percent, while that of unsteamed flakeboards was about 20 percent. MOR was reduced by the treatment, however.

Hujanen (1973) found that hardwood flakeboards (*Populus balsamifera* L.) similarly steamed also had reduced post-treatment thickness swell, but density and MOR of steamed boards were significantly reduced; moreoever, steaming produced irregular surfaces, excessive edge swelling, and board thickness increased 16 percent during the steam treatment.

Heat treatment.—Suchsland and Enlow (1968) found that phenolic-bonded flakeboard ovenheated in air for 2 hours at 425°F had only about 60 percent of the thickness swell of untreated controls when both were exposed to 90-percent RH. This heat treatment slightly reduced MOE, but increased internal bond strength slightly. The face layers of their flakeboard were of *Pinus banksiana* Lamb. with 12-1/2-percent resin content; the core was *Populus tremuloides* Michx. with 7 percent resin content.

Oil tempering.—Hall and Gertjejansen (1974) immersed *Populus tremuloides* Michx. waferboard in a blend of hydrocarbon drying oil and boiled linseed oil heated to 170°F and left it until they had retentions of 5 and 10 percent (ovendry-weight basis) of oil. The treatment effectively reduced irreversible thickness swelling and loss of MOR, MOE, and IB in samples subjected to accelerated aging. Tempering oil increased MOR and MOE of this waferboard, but had no effect on IB. Most of the benefits were obtained at 5-percent oil retention. Thickness swelling of the waferboard after OD-VPS exposure was reduced.

24-12 NAIL- AND SCREW-HOLDING CHARACTERISTICS

NAIL HOLDING

Sheathing and decking are usually secured to supporting rafters, wall studs, and joists by nails. Shingles and siding are nailed to sheathing, and hardwood flooring may be nailed to decking.

Nailing characteristics of interest are therefore driving resistance, withdrawal resistance, lateral resistance, and tendency of nails to "pop" or work loose.

Driving resistance.—Flakeboards made from southern hardwoods are more dense (44-46 lb/cu ft) than southern pine plywood (about 36 lb/cu ft) and therefore nails are somewhat more difficult to drive in the flakeboard. This is not perceived as a major obstacle to use because nailing guns, which work well on flakeboard, are much used to attach sheathing and decking to structural supporting members. Shingles, siding, and hardwood flooring being nailed to sheathing or decking give some support to nails permitting hammer driving without undue difficulty.

Withdrawal and lateral resistance of 6d nails.—Pages 1224 through 1270 of Koch (1972) describe in considerable detail factors affecting withdrawal and lateral resistance of nails in southern pine wood. Minimum lateral and withdrawal loads for 6d common nails with which APA RATED SHEATHING 1/2-inch and less in thickness is attached to supporting structure are specified in table 24-8. Minimum fastener performance for APA RATED STURDI-FLOOR is the same as the subfloor minimums shown in table 24-8. Data available suggest that flakeboard made from southern hardwoods readily meets these specifications (table 24-22).

TABLE 24-22.—*Ultimate withdrawal and lateral resistance of 6d common smooth-shanked nails driven through 1/2-inch-thick flakeboard and southern pine plywood*[1]

Statistic and exposure condition	*Flakeboard*[2]	*Plywood*[3]
	Pounds	
Withdrawal load		
Dry	158	81
Wet/redry[4]	75	52
Lateral load		
Dry	748	439
Wet/redry[4]	489	246

[1]Tested according to ASTM D1037-72 (American Society for Testing and Materials 1975a). Data from study files of FS-SO-3201, Southern Forest Experiment Station, Pineville, La.

[2]Three-layer, mixed-species flakeboard with randomly-oriented flakes fabricated according to optimum procedure of Hse et al. (1975); see footnote of table 24-12 for summary. Density, based on ovendry weight and volume, was 50 pounds/cu ft.

[3]Three-ply CDX southern pine plywood purchased in central Louisiana. Density based on ovendry weight and volume was 36 pounds/cu ft.

[4]Wet/redry is exposure to 24 hours of continuous soak followed by testing dry.

Lateral resistance of 8d nails.—Carpenters frequently use 8d nails to secure sheathing and decking to supporting structural framework. The American Plywood Association (1980) specifies that APA RATED SHEATHING roof panels, if more than 1/2-inch thick, should be fastened with 8d nails placed with minimum edge distance of 3/8-inch. Price and Gromala (1980) provided data relating lateral nail resistance of such nails at three edge distances, in dry and wet panels of 1/2- and 5/8-inch thickness and of various designs (table 24-23). They used a modified form of standard test ASTM D 1761-68 (American Society for Testing and Materials 1968b) to evaluate lateral nail resistance in single shear. Panel fabrication procedure was principally that described by Hse (1975c) and summarized in footnote 1 of table 24-12, except that some of the flakeboard panels were comprised solely of yellow-poplar, and others of southern pine.

Price and Gromala found that the flakeboards offered more lateral nail resistance when dry or wet than did southern pine plywood of equal thickness.

For all types of sheathing material, average nail resistance decreased after 24-hour water soak (table 24-23). Decreases ranged from 9 percent (5/8-in mixed random high-density flakeboard) to 27 percent (1/2-in southern pine plywood). Observed maximum lateral nail loads in both wet and dry tests generally increased with the distance of the nail from the edge.

For the flakeboards, dry lateral nail resistance did not consistently increase as density increased. Since the high-density flakeboard groups generally lost less lateral nail resistance after water soaking than low-density groups, wet lateral nail resistance increased as board density increased. Perhaps, the high-density specimens did not absorb as much moisture as low-density samples and thus maintained better particle bonding. If so, thickness swell and density change would influence the smaller decrease in lateral nail resistance for the high-density specimens. Lateral nail resistance also increased as board thickness increased for the mixed oriented flakeboards but not for the plywood or mixed random flakeboards.

Nail popping.—Flakeboard used for roof sheathing must be able to hold shingles in place. Failure of roofing nails to perform this function is manifested by nail ''pop''—the slow natural withdrawal of a nail due to shrinkage and swelling of the panel and shingles. Schaffer et al. (1980) studied the performance of 1-inch roofing nails that had been driven into and through commercial and experimental flakeboards. They found that such panels exposed to cyclic moisture conditions, including freeze-thaw, did not develop nail pop. Instead, the nailheads were observed to subside further into shingle and panel surfaces with increasing exposure. This subsidence was highly correlated to the thickness swell of the panels. They concluded that nail pop will not be a problem with nails driven through flakeboard.

SCREW HOLDING

Pages 1270 through 1281 of Koch (1972) describe load-carrying capacity of wood screws in southern pine. For additional discussion of wood screws applied to solid wood, see U.S. Department of Agriculture, Forest Service (1974, p. 7-9 through 7-12). No data specific to flakeboards made of southern hardwoods are

TABLE 24-23.—*Lateral nail resistance of 8d common nails spaced at three edge distances in flakeboards and plywood of two thicknesses when dry*[1] *and wet*[2] (Data from Price and Gromala 1980)

Sheathing material	Max. load					
	Dry			Wet		
	3/8 in.	1/2 in.	3/4 in.	3/8 in.	1/2 in.	3/4 in.
	Pounds					
Flakeboard						
Mixed, oriented (½ in.)[3]						
Low density	305[4]	343	383	229	259	286
	15.7	*11.2*	*18.1*	*21.0*	*15.8*	*10.9*
High density	338	335	352	271	302	326
	6.5	*16.9*	*20.1*	*18.7*	*19.6*	*14.4*
Mixed, oriented (5/8 in.)						
Low density	354	411	427	298	323	327
	8.5	*15.4*	*15.0*	*20.8*	*15.3*	*14.5*
High density	359	361	401	302	311	351
	12.0	*17.1*	*18.0*	*19.6*	*12.0*	*14.9*
Mixed, random (1/2 in.)						
Low density	319	341	381	258	309	304
	7.2	*13.7*	*8.9*	*13.4*	*23.7*	*14.8*
High density	314	338	386	294	273	316
	14.2	*11.1*	*10.4*	*14.1*	*11.2*	*11.6*
Mixed, random (5/8 in.)						
Low density	308	336	342	256	259	308
	11.7	*9.5*	*8.9*	*14.3*	*10.8*	*10.0*
High density	347	362	349	301	307	356
	8.8	*19.4*	*14.6*	*19.5*	*16.9*	*31.0*
Pine, random (1/2 in.)	314	385	388	257	288	290
	19.6	*24.7*	*12.2*	*16.6*	*23.4*	*24.2*
Yellow-poplar (1/2 in.)	351	370	406	301	290	337
	7.2	*13.9*	*23.7*	*15.3*	*15.8*	*13.9*
Plywood						
CDX southern pine						
(1/2 in.)	311	321	386	216	236	289
	10.5	*8.9*	*15.3*	*11.9*	*10.7*	*20.3*
(5/8 in.)	302	307	338	266	249	262
	9.6	*16.2*	*12.8*	*21.6*	*15.9*	*27.9*

[1]Tested at approximately 72°F and 50 percent RH.

[2]Tested after soaking 24 hours in water at 70°F.

[3]Mixed = white oak, southern red oak, hickory, sweetgum, and southern pine in equal proportions; see footnote 1 of table 24-12 for fabrication procedure. Oriented and random refer to flake alignment. Number in parentheses is nominal panel thickness.

[4]The first number per panel group is an average of nine tests, and the number in italics is the coefficient of variation.

published, but the following references provide background information on particleboards of other species:

Reference	Subject
National Particleboard Association (1968)	Screw holding of particleboard.
Whittington and Walters (1969)	Withdrawal loads of screws in soft maple and particleboard.
Carroll (1970, 1972)	Overdriving of screws in particleboard, and measuring screw withdrawal resistance with a torque wrench.
Didriksson et al. (1974)	Splitting of wood-base building boards caused by insertion of screws in panel edges.
Eckelman (1973, 1974, 1975)	Holding strength of screws in hardwoods, particleboards, and other wood-based materials.
Superfesky (1974)	Withdrawal resistance of sheet-metal screws from particleboard and medium-density hardboard.
Barnes and Lyon (1978a)	Withdrawal loads in weathered and unweathered particleboard decking.

24-13 FRICTION COEFFICIENT

Friction coefficients of steel on solid wood are given in section 9-4. The friction coefficient of interest during application of roof sheathing is not that of wood-to-steel, however, but rather that of sheathing-to-shoe sole. Since carpenters' shoes may be soled with leather, neoprene, or crepe rubber composition, all three are of interest.

These three shoe sole materials (all smooth, i.e., not textured) were evaluated (table 24-24) on four wet and dry sheathing materials: unsanded CDX southern pine sheathing plywood (across the face grain), and flakeboard of mixed southern hardwoods having randomly oriented 0.015-inch-thick face flakes and smooth surfaces (fig. 24-45 left), fine-screen textured surfaces, and coarse-screen textured surfaces (fig. 24-45 right).

For dry sheathing the highest average **static coefficient of friction** was obtained on coarse-screen flakeboard (.876). For wet sheathing, best average results were on plywood (.820). The best combination on dry sheathing was crepe soles on coarse-screen flakeboard (1.218). Crepe soles on wet coarse-screen flakeboard also did very well (0.938).

Szabo and Nanassy (1979) found from a study of aspen flakeboard and western softwood plywood that plywood and screen-back waferboard had similar coefficients of **kinetic friction** with common shoe sole materials when tested dry. They also found that neoprane and rubber are the safest sole materials for footwear of men working on wooden roof decks; piles of plywood or screen-back aspen waferboard can slip at slopes greater than about 20 degrees.

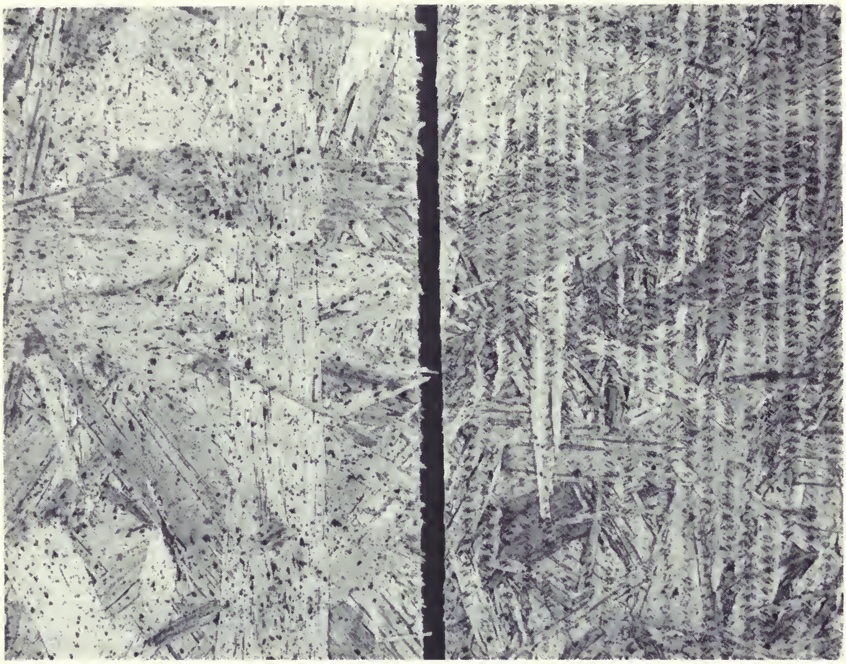

Figure 24-45.—Flakeboard of southern hardwoods pressed with a smooth caul (left) and a screen caul (right). (Photo from files of E. Price.)

TABLE 24-24.—*Static friction coefficients between shoe soles of three types and wet and dry unsanded southern pine CDX plywood*[1] *compared to that for wet and dry flakeboard sheathing made of randomly oriented flakes of mixed southern hardwoods*[2,3]

Shoe sole material	Flakeboard			Plywood
	Smooth	Fine screen	Coarse screen	
	Friction coefficient			
	DRY			
Leather	0.527	0.546	0.498	0.558
Neoprene	.566	.901	.911	.796
Crepe	.733	1.129	1.218	1.029
Average	.622	.859	.876	.791
	WET			
Leather	.994	.920	.907	.968
Neoprene	.547	.560	.544	.576
Crepe	.901	.889	.938	.916
Average	.781	.789	.793	.820

[1]Perpendicular to grain of face ply.

[2]Face flakes 3 inches long and 0.015 inch thick fabricated according to optimum procedure of Hse et al. (1975).

[3]Data from Final Report FS-SO-3201-52, dated April 8, 1982. U.S. Dep. Agric., For. Serv., South. For. Exp. Stn., Pineville, La.

24-14 CREEP[10]

When wood-based panels are loaded in bending, an immediate deflection occurs; this deflection increases with time, and the increase is called creep. Price[10] provided data specific to southern pine plywood, and flakeboards made of mixed species of southern woods according to the optimum procedures of Hse et al. (1975) as summarized in footnote 1 of table 24-12.

The oriented-strand flakeboards were made in 4- by 8-foot size at the Potlatch Corporation pilot plant in Lewiston, Idaho; the boards with random flake orientation were fabricated in 4- by 8-foot size at the pilot plant (20-foot, top-closing press) of the U.S. Forest Products Laboratory at Madison, Wis. Press closing speeds and platen pressures differed at the two pilot plants, as did the phenolic resin recipe, so surface densification profiles and bonding characteristics differed with pilot plant. Plywood for the study was three-ply southern pine CDX sheathing purchased in central Louisiana. Price's study included both 1/2- and 5/8-inch-thick panels, but for brevity only his data on 1/2-inch panels are presented here.

Loads were applied to panel specimens (fig. 24-46A) for 32 days, followed by 8 days with loads removed; during this 40 days, deflections were recorded as relative humidity (RH) in the test chamber was alternated from 50 to 85 percent at regular intervals in 4-, 8-, and 32-day cycles. On the 8-day cycle, for example, specimens were first held at 50 percent RH for 4 days, then at 85 percent RH for 4 days, and then returned to 50 percent RH for 4 days, and so on.

Specimens were loaded in two modes and at two load levels, as follows:

- Flexural specimens, which measured 18 inches long and 3 inches wide, were center-point loaded in bending (fig. 24-46A top) over a 15-inch span to yield bending stresses of 300 and 450 psi on specimens cut to represent the 4-foot panel direction, and 450 and 600 psi on those cut to represent the 8-foot direction.
- Concentrated loads, 200 pounds applied on a 1-inch-diameter disk and 300 pounds applied on a 3-inch disk (fig. 24-46A bottom), were located 2-1/2 inches from panel edge at midpoint of a 16-inch span; face-veneer grain and oriented strands of panels were arranged parallel to the span.

Mechanical properties of the 1/2-inch-thick panels evaluated by Price[10] were as follows:

[10]Text under this heading is condensed from: Price, E. W. 1982. Effect of time, load, and environment on ten designs of structural flakeboard composed of southern species. U.S. Dep. Agric., For. Serv., South. For. Exp. Stn., Alexandria, La., Fin. Rep. FS-SO-3201-3.16.

Property	Random flakeboard	Oriented flakeboard	Southern pine plywood
Density based on ovendry weight, and volume at about 6 percent, moisture content, pounds/cu ft	46.5	46.3	34.8
Internal bond strength, psi	68	57	95
Modulus of rupture, psi			
4-foot panel direction	4,200	3,400	1,900
8-foot panel direction	5,600	5,600	8,800
Modulus of elasticity, thousand psi			
4-foot panel direction	582	391	97
8-foot panel direction	768	967	1,430

These modulus of rupture and modulus of elasticity values were based on specimen dimensions at test, after completion of the creep cycling procedure, and after equilibration at 50 percent RH. Mechanical property values of stressed specimens did not differ from those of specimens on which no load was imposed. Some of the plywood flexure specimens failed when the load was initially applied, but none of the flakeboard specimens failed.

Price's[10] data suggest the following conclusions:

- There was substantial variation among plywood panels in creep deflection in flexure and under concentrated load; three of the plywood flexure specimens cut to represent the 4-foot panel direction failed when initially loaded. Less variability was observed among flakeboard specimens.
- Creep deflections of the panel types were not sufficiently different that one type could be selected as clearly superior to the others (fig. 24-46BCDE).
- Relative humidity cycles of 8 and 32 days caused greater creep deflection than 4-day cycles (figs. 24-46CE).
- Specimen deflections after 32 days of 8- and 32-day cycles between 50 and 85 percent relative humidity were about twice those when intially loaded (tables 24-25AB and figs. 24-46CE).

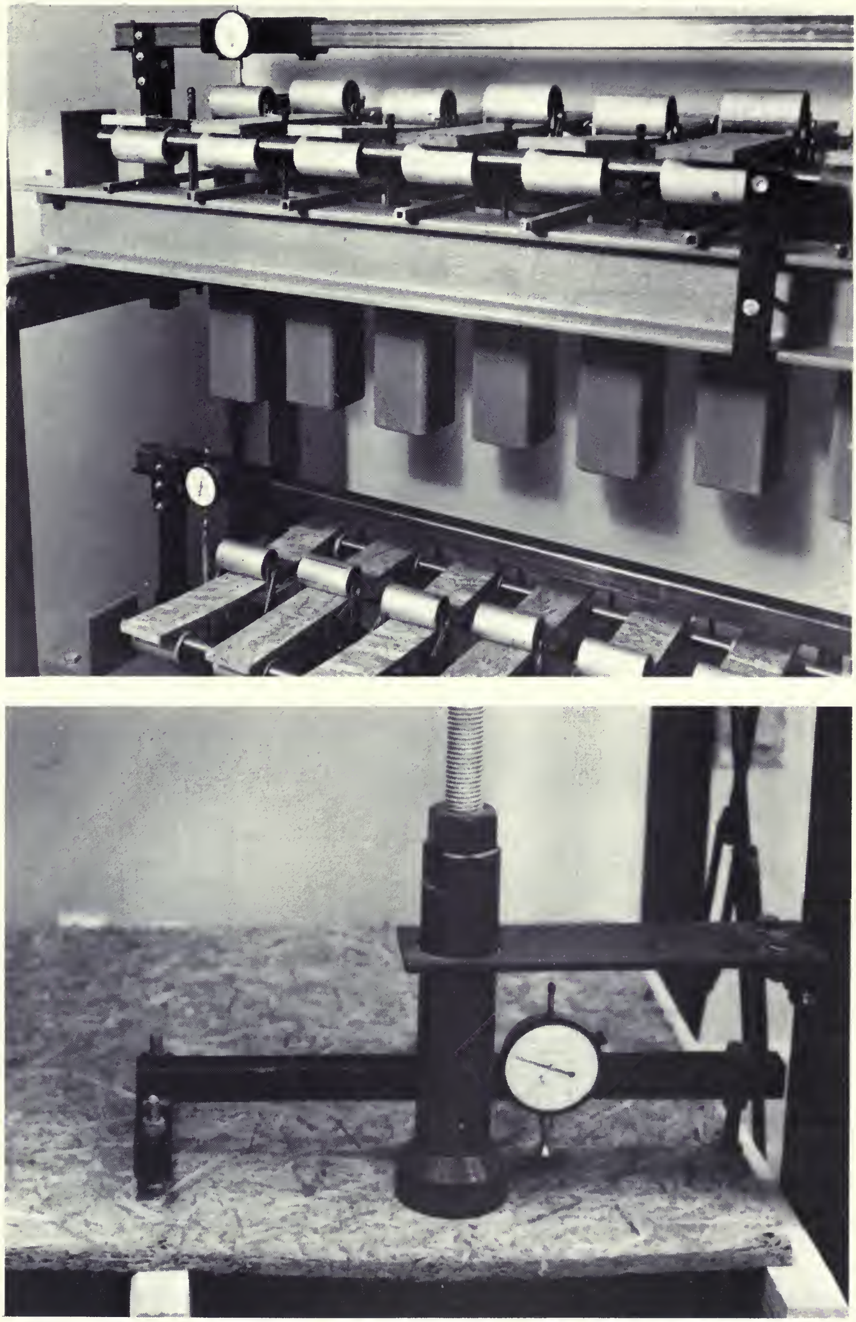

Figure 24-46A.—Creep loading and measuring devices. (Top) For flexure specimens cut to represent both 4- and 8-foot panel directions, mid-point loaded over a 15-inch span by suspended weights. (Bottom) Concentrated load applied on circular disk at midpoint of 16-inch panel span, 2-1/2 inches from panel edge. (Photos from Price, text footnote[10].)

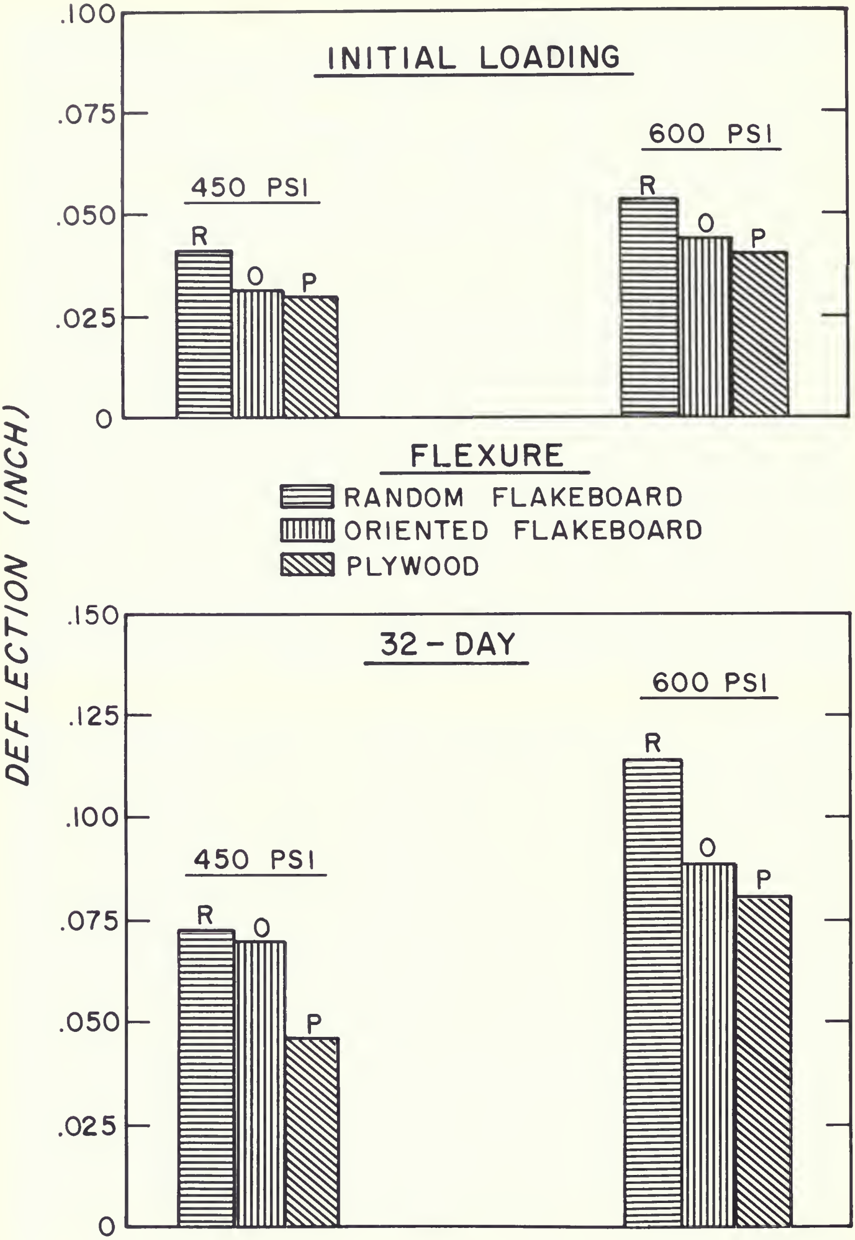

Figure 24-46B.—Deflection of 1/2-inch-thick flexure specimens of random flakeboard, oriented flakeboard, and southern pine three-ply CDX plywood, at two stress levels and with data from 4-, 8-, and 32-day relative humidity cycles pooled; specimens cut to evaluate 8-foot panel direction. (Top) When initially loaded. (Bottom) After 32 days cycling between 50 and 85 percent relative humidity. (Drawing after Price, text footnote.[10])

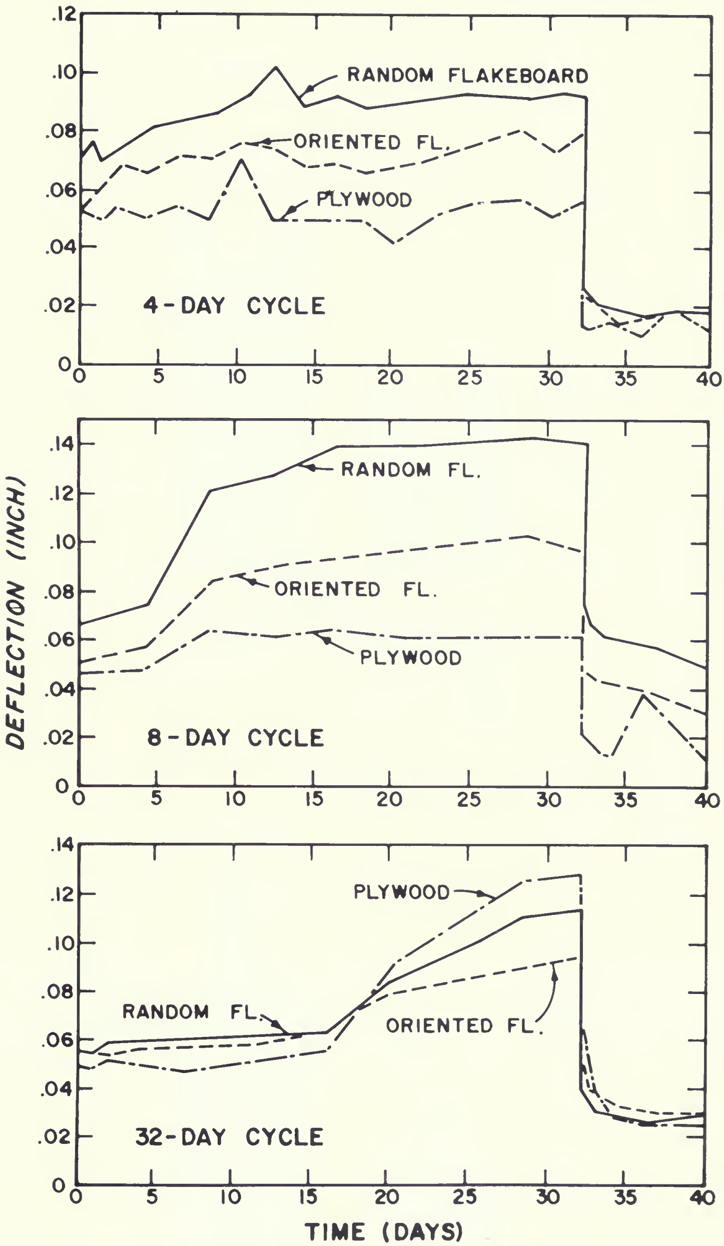

Figure 24-46C.—Deflection versus time for 1/2-inch-thick flexure specimens, cut to evaluate 8-foot panel direction, from random flakeboard, oriented flakeboard, and southern pine CDX plywood, subjected to 600 psi continuous stress for 32 days under 4-, 8-, and 32-days cycles between 50 and 85 percent relative humidity. (Drawing after Price, text footnote[10].)

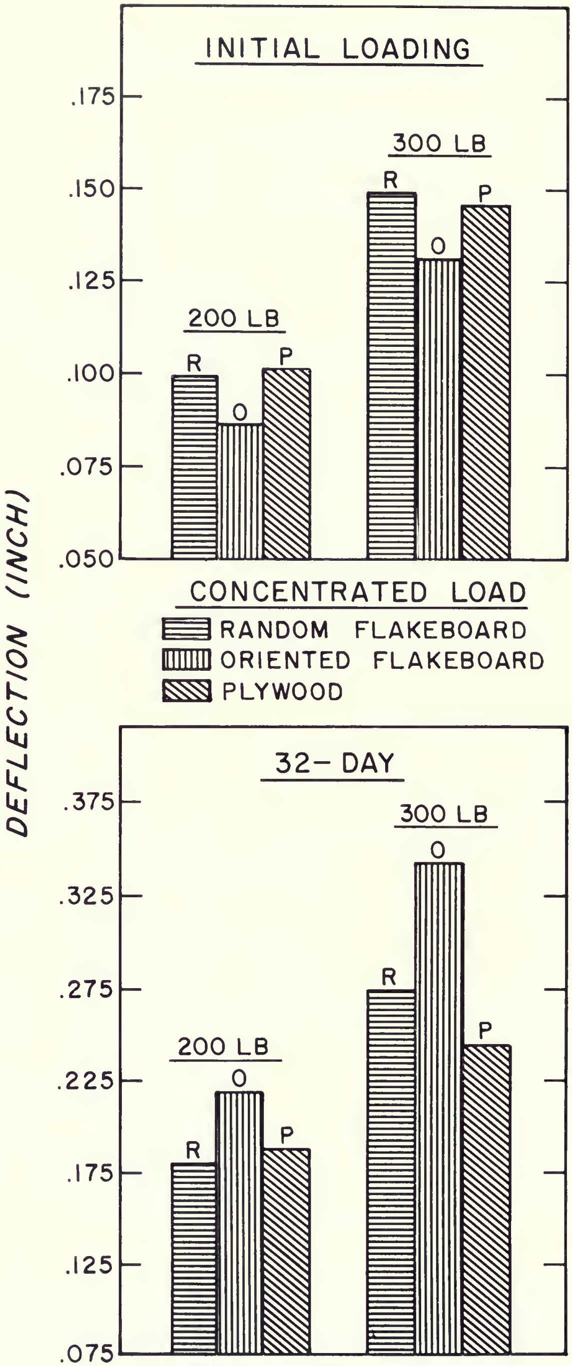

Figure 24-46D.—Deflection of 1/2-inch-thick panels of random flakeboard, oriented flakeboard, and southern pine three-ply CDX plywood under 200- and 300-pound concentrated loads (see fig. 24-46A bottom) with data from 4-, 8-, and 32-day cycles pooled. (Top) When initially loaded. (Bottom) After 32 days of cycling between 50 and 85 percent relative humidity. (Drawing after Price, text footnote[10].)

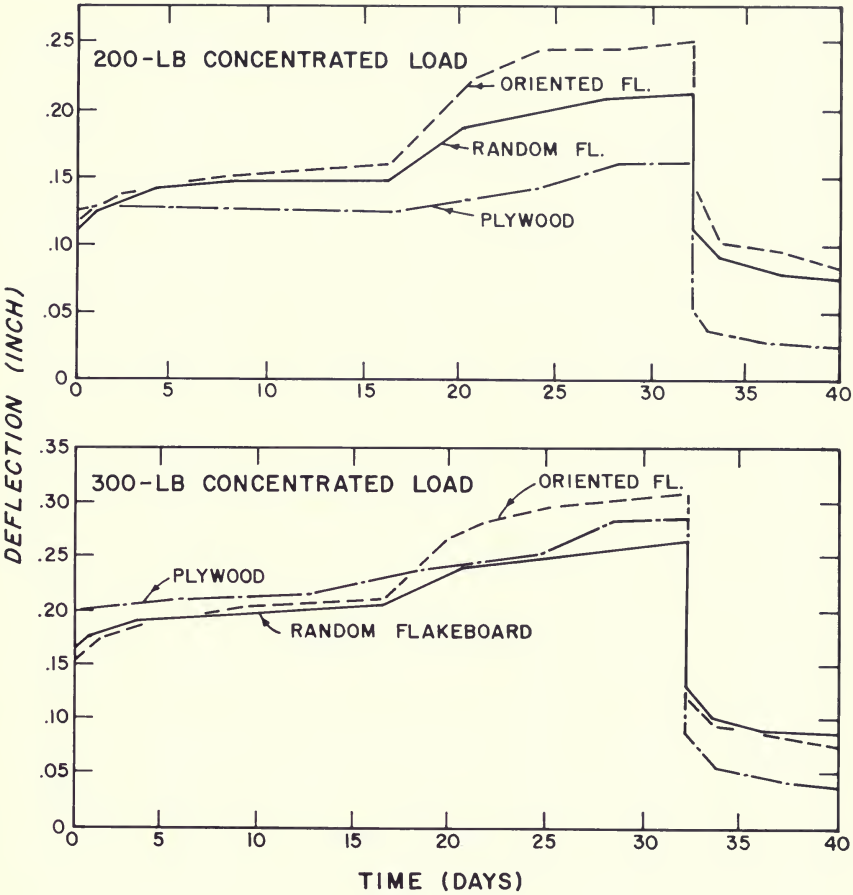

Figure 24-46E.—Deflection versus time of 1/2-inch-thick panels of random flakeboard, oriented flakeboard, and southern pine three-ply CDX plywood when subjected to 200-pound and 300-pound concentrated loads (see fig. 24-46A bottom), during 16 days of 50 percent relative humidity followed by 16 days of 85 percent relative humidity. (Drawing after Price; see text footnote[10].)

TABLE 24-25A.—*Initial, 16-day, and 32-day deflections at two stress levels and three relative humidity cycles of 1/2-inch-thick, 3-inch-wide flexure specimens, cut to represent 4- and 8-foot panel directions, from random flakeboard, oriented flakeboard, and 3-ply CDX southern pine plywood* (Data from Price[10])[1, 2]

Panel density[3] and relative humidity cycle (days)[4]	4-foot direction										8-foot direction									
	300 psi stress					450 psi stress					450 psi stress					600 psi stress				
	0 day	16 day	32 day	Recovery[5]	Relative creep[6]	0 day	16 day	32 day	Recovery	Relative creep	0 day	16 day	32 day	Recovery	Relative creep	0 day	16 day	32 day	Recovery	Relative creep
	--------*0.001 inch*-------					--------*0.001 inch*-------					--------*0.001 inch*-------					--------*0.001 inch*-------				
RANDOM FLAKEBOARD																				
45.6 pounds/cu ft																				
4	29	60	64	26	2.21	56	123	127	61	2.27	41	72	74	28	1.81	51	94	95	36	1.86
8	38	87	91	60	2.40	52	131	134	82	2.58	48	99	103	61	2.15	57	125	131	75	2.30
32	37	51	85	51	2.30	54	76	142	84	2.63	40	58	99	56	2.48	57	83	127	72	2.23
47.4 pounds/cu ft																				
4	43	77	81	36	1.88	50	92	94	36	1.88	27	50	60	10	2.22	52	92	92	33	1.77
8	32	72	76	40	2.38	44	107	112	60	2.55	39	80	82	47	2.10	60	139	141	90	2.35
32	28	41	62	27	2.21	45	68	125	70	2.78	42	56	80	42	1.91	46	63	113	59	2.46
ORIENTED FLAKEBOARD																				
44.9 pounds/cu ft																				
4	51	103	108	56	2.12	78	168	174	81	2.23	33	53	55	18	1.67	40	72	73	27	1.83
8	55	136	148	97	2.69	69	201	216	135	3.13	33	64	68	39	2.06	39	90	94	54	2.41
32	57	80	136	85	2.39	75	106	194	121	2.59	42	53	68	39	1.62	41	70	92	52	2.24
47.4 pounds/cu ft																				
4	53	100	105	49	1.98	71	157	163	77	2.30	36	60	63	21	1.75	42	70	80	21	1.91
8	51	118	128	81	2.51	77	181	196	117	2.55	34	73	75	45	2.21	44	93	97	58	2.21
32	54	77	147	95	2.72	75	118	194	113	2.59	26	39	60	24	2.31	46	63	93	48	2.02

TABLE 24-25A.—*Initial, 16-day, and 32-day deflections at two stress levels and three relative humidity cycles of 1/2-inch-thick, 3-inch-wide flexure specimens, cut to represent 4- and 8-foot panel directions, from random flakeboard, oriented flakeboard, and 3-ply CDX southern pine plywood* (Data from Price[10])[1, 2]—Continued

Panel density[3] and relative humidity cycle (days)[4]	4-foot direction										8-foot direction									
	300 psi stress					450 psi stress					450 psi stress					600 psi stress				
	0 day	16 day	32 day	Recovery[5]	Relative creep[6]	0 day	16 day	32 day	Recovery	Relative creep	0 day	16 day	32 day	Recovery	Relative creep	0 day	16 day	32 day	Recovery	Relative creep
	--------*0.001 inch*-------					--------*0.001 inch*-------					--------*0.001 inch*-------					--------*0.001 inch*-------				
SOUTHERN PINE PLYWOOD																				
34.8 pounds/cu ft																				
4	212	173	171	27	.81	219	356	364	127[7]	1.66	35	39	45	13	1.29	33	48	57	17	1.73
8	242	358	359	204	1.48[7]	217	456	511	268[7]	2.36	33	53	53	27	1.61	45	64	61	28	1.36
32	175	239	346	180	1.98	312	413	571	278	1.83	25	30	45	18	1.80	40	56	127	86	3.18

[1]Center-point loaded over 15-inch span; see figure 24-46A top.
[2]For species mix of flakeboard see footnote[1] of table 24-12.
[3]Based on ovendry weight and equilibrium volume at 50 percent relative humidity.
[4]Relative humidity in the test chamber was changed from 50 to 85 to 50 to 85 percent at regular intervals in 4-, 8-, and 32-day cycles; for example, the 32-day cycle had 16 days at 50 percent RH followed by 16 days at 85 percent RH.
[5]Deflection remaining 8 days after load was removed, RH cycle continued; i.e., observation made 40 days after test initiation at 50 percent RH.
[6]Relative creep = deflection at 32 days/initial deflection under load.
[7]Based on average of three specimens; all other values based on four specimens.

TABLE 24-25B.—*Deflections under concentrated loads of 1/2-inch-thick panels—initially, after 16 days, and after 32 days exposed to three relative humidity cycles* (data from Price[10])[1, 2]

Panel density[4] and relative humidity cycle (days)[5]	200-pound load[3]					300-pound load[3]				
	Initial	16 days	32 days	Recovery[6]	Relative creep[7]	Initial	16 days	32 days	Recovery[6]	Relative creep[7]
	Inch					Inch				
RANDOM FLAKEBOARD										
45.6 pounds/cu ft										
4	0.113	0.192	0.203	0.040	1.80	0.150	0.276	0.293	0.070	1.95
8	.105	.239	.260	.086	2.48	.120	.235	.251	.084	2.09
32	.105	.147	.210	.029	2.00	.154	.213	.266	.077	1.73
47.4 pounds/cu ft										
4	.107	.140	.145	.026	1.36	.156	.230	.246	.044	1.58
8[8]	.095	.161	.190	.051	2.00	.153	.262	.307	.081	2.01
32	.097	.148	.213	.075	2.20	.138	.203	.263	.088	1.91
ORIENTED FLAKEBOARD										
44.9 pounds/cu ft										
4	.091	.148	.154	.027	1.70	.142	.217	.226	.045	1.59
8[8]	.121	.284	.305	.141	2.52	.140	.290	.307	.141	2.19
32	.090	.127	.155	.034	1.72	.139	.218	.265	.078	1.91
47.6 pounds/cu ft										
4	.098	.237	.259	.099	2.64	.142	.378	.408	.166	2.87
8[8]	.063	.116	.137	.034	2.18	.140	.243	.295	.067	2.11
32	.097	.159	.251	.081	2.59	.116	.210	.307	.077	2.65

TABLE 24-25B.—*Deflections under concentrated loads of 1/2-inch-thick panels—initially, after 16 days, and after 32 days exposed to three relative humidity cycles* (data from Price[10])[1,2]—Continued

Panel density[4] and relative humidity cycle (days)[5]	200-pound load[3]					300-pound load[3]				
	Initial	16 days	32 days	Recovery[6]	Relative creep[7]	Initial	16 days	32 days	Recovery[6]	Relative creep[7]
	Inch					*Inch*				
SOUTHERN PINE PLYWOOD										
34.8 pounds/cu ft										
4	.093	.180	.188	.068	2.02	.116	.183	.192	.048	1.66
8[8]	.130	.186	.204	.024	1.57	.159	.220	.236	.035	1.48
32	.114	.125	.163	.024	1.43	.162	.229	.285	.042	1.76

[1]See figure 24-46A (bottom) for test setup.
[2]For species mix of flakeboard see footnote[1] of table 24-12.
[3]The 200-pound load was applied through a 1-inch-diameter disk, the 300-pound load through a 2-inch disk.
[4]Based on ovendry weight and equilibrium volume at 50-percent RH.
[5]Relative humidity in the test chamber was changed from 50 to 85 to 50 to 85 percent at regular intervals in 4-, 8-, and 32-day cycles.
[6]Deflection remaining 8 days after load was removed, RH cycle continued; i.e., observation made 40 days after test initiation, at 50 percent RH.
[7]Relative creep = deflection at 32 days/initial deflection under load.
[8]Data based on one specimen; all other values based on two specimens.

24-15 WEATHERING DURABILITY

There is some doubt concerning the suitability of phenolic-bonded flakeboard for long-term exterior applications in which panels are fully exposed to the weather. Efforts to protect structural flakeboard from the effects of weathering might be more promising than attempts to greatly improve its resistance.

Jokerst (1968) found that 8-year exposure of Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) flakeboard (7-3/16- by 13-inch specimens) on an exterior test fence is more severe than six cycles of the ASTM D 1037-72 accelerated aging exposure (American Society for Testing and Materials 1975a). This test requires that the specimens complete six cycles of accelerated aging. Each cycle consists of the following: (1) Immersing specimens in water at 120°F for 1 hour; (2) spraying with steam and water vapor at 200°F for 3 hours; (3) freezing by storing at 10°F for 20 hours; (4) heating at 210°F in dry air for 3 hours; (5) spraying again with steam and water vapor at 200°F for 3 hours; and (6) heating in dry air at 210°F for 18 hours. Execution of the six cycles requires 3 to 4 weeks.

Some of Jokerst's other conclusions were:

- Phenolic-bonded flakeboards far out-performed urea-bonded boards.
- Much of the deterioration of the flakeboards occurred in the first year; deterioration continued at a lesser rate throughout the exposure period.
- The primary causes of deterioration of the flakeboard were springback from compression set, deterioration of the binder, and differential shrinkage of adjacent particles during moisture changes.
- A well-maintained coat of paint on the flakeboards in the test-fence exposure greatly improved durability.

Meierhofer and Sell (1977) found that treating edges and surfaces of particleboard with water repellent and then painting with an alkyd, epoxide, or polyurethane resin effectively improved weathering performance.

There are no data published on the effect of exposure-fence weathering of phenolic-bonded flakeboard made from mixed southern hardwoods. Price[10] is evaluating performance of such flakeboard during 5 years of unprotected exposure in Louisiana (fig. 24-47). This flakeboard was fabricated according to the procedure advocated by Hse et al. (1975), and results should be published by 1985. It is likely that MOE, MOR, and IB of the boards will all be very significantly reduced; because of increase in panel thickness, however, panel stiffness (EI) and capacity to carry loads in bending will be less affected. Figure 24-47 (bottom) gives some idea of panel appearance after 3 years of exposure.

Carrol (1980) noted that in North America flakeboard has a solid history of successful use as sheathing and cladding in general building construction, but there is no general agreement on test procedures appropriate for its accelerated aging or weathering. Readers needing to compare test procedures should find useful overviews by Carrol (1980) and River et al. (1981).

Although not descriptive of panels made from southern hardwoods, readers needing an introduction to the subject of durability will find the following references useful:

Reference	Subject
Hann et al. (1963)	How durable is particleboard?
Gatchell et al. (1966)	Variables affecting properties of particleboard for exterior use.
Heebink (1967)	Degradation of particleboard in exterior use.
Jokerst (1968)	Long-term durability of Douglas-fir flakeboard.
Heebink (1972)	Irreversible dimensional changes in panel materials.
Geimer et al. (1973)	Weathering characteristics of particleboard.
McNatt (1974)	Properties of particleboards at various humidities.
Hall and Haygreen (1975)	Effect of simulated weathering on impact performance of particleboard.
McNatt (1975)	Humidity effects on structural particleboard.
Raymond (1975)	Outdoor weathering of plywood and composites.
Carlson and Haygreen (1976)	Effect of temperature and humidity on toughness of structural particleboard.
Meierhofer and Sell (1977)	Influence of surface treatments on properties of weathered particleboards.
Shen (1977b)	A proposed rapid-acceleration aging test.
Baker and Gillespie (1978)	Accelerated aging of phenolic-bonded flakeboards.
Barnes and Lyon (1978b)	Effect of aging on decking.
Steiner et al. (1978)	Density, thickness expansion, and internal bond strength after accelerated aging.
Hall and Gertjejansen (1979)	Weatherability of Ghanian hardwood flakeboard of ACA-treated flakes.

A North American workshop on exterior durability of structural flakeboard was held in October 1982 in Pensacola, Fla.; the Southern Forest Experiment Station, Forest Service, U.S. Department of Agriculture, Pineville, La., has information on where to obtain the Proceedings from this workshop, which provides state-of-the-art discussions.

24-16 PROPERTIES OF REPRESENTATIVE FLAKEBOARDS

After making the laboratory-scale, mixed-species flakeboard suggested by Hse et al. (1975), with properties as discussed in text related to figure 24-38, the Pineville laboratory of the Southern Forest Experiment Station fabricated three additional series of boards with different mixes of southern woods, and properties as follows (in all cases, flakes were cut on a shaping-lathe—see figure 18-104abcd):

Figure 24-47.—Phenolic-bonded flakeboards of mixed southern woods fabricated according to the procedures of Hse et al. (1975) on a 45° south-facing exposure fence in Pineville, La. (Top) At establishment in March 1977. (Bottom) After 3 years' exposure. (Photos from Price[10].)

Species mix and property	Reference
• Twenty-percent each by weight of hickory, white oak, southern red oak, sweetgum, and southern pine (fabricated in 4- by 8-foot panels)	
MOE and MOR	Table 24-12
IB	Table 24-17
Shear modulus	Table 24-18
Impact properties	Table 24-19
Thickness swell and linear expansion	Table 24-20
Nail withdrawal and lateral resistance	Tables 24-22 and 24-23
Creep	Table 24-25
• Sweetgum (32 percent), hackberry (18 percent), elm (5 percent), southern red oak (14 percent), ash (17 percent), overcup oak (5 percent), and pecan (9 percent)	
MOE, MOR, and IB	Figure 24-33 (see graph lines for 3-inch-long face and core flakes; face flakes 0.015 inch thick and core flakes 0.025 inch thick)
Linear expansion	Table 24-21; figure 24-43
Thickness swell	Table 24-21
• Baldcypress (35. 4 percent), low-density hardwoods (31.4 percent), oak sp. (17.1 percent), other high-density hardwoods (14.7 percent), and minor species (1.4 percent)	
MOE and MOR	Table 24-13
IB	Table 24-13
Linear expansion and thickness swell	Table 24-13

The first of these species mixes, which includes southern pine and four hardwoods, is fairly representative of densities of woods that can be found throughout the entire southern pinery. See table 24-12 for fabrication procedure.

The second mix (seven hardwood species) is representative of bottomlands and pine lands in south central Louisiana. See table 24-21 for fabrication procedure.

The third mix, with baldcypress as its largest component, is appropriate for some areas in North Florida. See table 24-13 for fabrication procedure and the following tabulation for species composition:

Species or species group	Species proportion
	Percent
Baldcypress	35.4
Red oaks (15.4 percent) and white and live oaks (1.7 percent)	17.1
Black tupelo (15.1 percent) and water tupelo (2.3 percent)	17.4
Sweetgum	8.4
Ash. sp.	6.4
Red maple	6.2
Sweetbay	4.8
Elm sp.	1.3
Hickory sp.	.8
Basswood	.4
Magnolia sp.	.4
Cedar	.4
Other minor species	1.0
	100.0

24-17 THICK ROOF DECKING

Hardwood flakeboards for sheathing and decking are usually not thicker than 3/4-inch for use on spans that generally do not exceed 4 feet. It is possible, however, to make thicker structural particleboards of hardwood that can span 5 or 6 feet. Roof decking for commerical and industrial buildings is a major potential market for such thick structural particleboard.

POTENTIAL MARKET

Fergus et al. (1977) studied the market for roof decking applicable to 2,000-sq-ft and larger, non-residential structures that have flat roof systems with a slope of less than 1 inch per foot. They noted that estimates of market size varied from 1/2 billion to over 2 billion square feet annually, and that the largest share of the commercial and industrial market is concentrated in the east north central and northeastern regions of the United States. Other large markets are the Southern States and the West Coast region. Most buildings in the east north central and northeastern regions use ribbed steel decking for roofs. In the Southern States, gypsum and plywood have larger shares of the market, but steel is the major material specified. On the West Coast, plywood is the leading commercial and industrial roof deck material, with reinforced concrete, poured gypsum, and steel decking less frequently used. Fergus et al. (1977) found that most new buildings in the non-residential market are typically one- and two-story, flat-roofed structures with multi-ply, built-up roof coverings. Most of the buildings have concrete floors, steel framing bents on 20-foot centers, decking systems over purlins spaced 5 feet on centers, and metal-clad siding materials. Typically, ribbed metal roof decks are mechanically fastened or spotwelded to metal purlins.

MATERIAL SELECTION

Fergus et al. (1977) concluded that roof deck material should have structural integrity, be light in weight, stable, durable, easily fastened, simple, compatible with other systems, cheap, and resistant to fire, heat flow, sound transmission, and vibration.

The major wood-base roof deck materials that have been used in the commercial and industrial roof deck market include solid and laminated timber decking, tongue-and-groove structural-grade plywood, cementitious composite utilizing wood fibers, and reconstituted wood fiberboards.

Fergus et al. (1977) proposed a study to develop a structural particleboard roof deck material for the commercial-industrial building market.

TARGET SPECIFICATIONS

Based on the Fergus et al. (1977) market analysis, and some preliminary experimentation, Hunt et al. (1978) concluded that a 1-1/8-inch-thick, three-layer particleboard roof deck could be made of red oak sp. that would have density about equal to that of the parent wood, i.e., the compaction ratio could be near unity. To be competitive, they set the following target specifications:

Statistic	Face layers	Core layers
Species	Red oak sp.	Red oak sp.
Thickness, inch	0.1875 (each)	0.75
Density	44 lb/cu ft	40.5 lb/cu ft
Flake type	Disk	Ring
Flake length, inches	3	2
Flake thickness, inch	0.010	0.045
Liquid phenolic resin solids, percent	5	6
Wax content	1	1
Flake arrangement	Aligned	Random
MOE, psi	1,500,000 (parallel), 500,000 (perpendicular)	390,000

Hunt et al. (1978) found that this panel (fig. 24-48) could be cured at 350°F with closed press time of about 10 minutes (fig. 24-49).

Figure 24-48.—Three-layer red oak structural particleboard designed for industrial/commercial roof decking. (Photo from Hunt et al. 1978.)

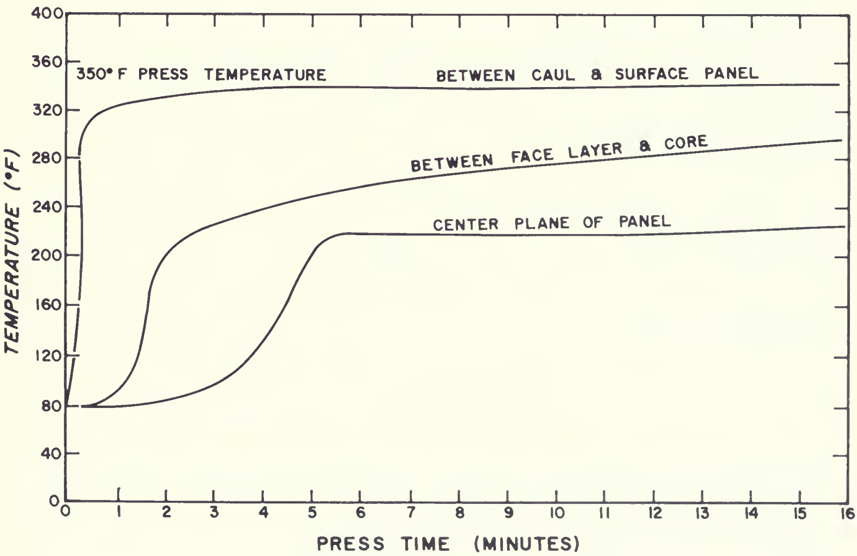

Figure 24-49.—Temperature through panel thickness related to closed press time in 1-1/8-inch-thick red oak sp. structural particleboard with density of 46.2 lb/cu ft based on ovendry weight and volume at 5 percent moisture content. (Drawing after Hunt et al. 1978.)

PROPERTIES ACHIEVABLE IN PRODUCTION

Properties achieved in laboratory boards are discussed in detail by Hunt et al. (1978). Correspondence in 1981 with the team conducting this research indicates that properties shown in table 24-26 are probably achievable in 1-1/8-inch northern red oak roof decking manufactured as previously described.

Additional data on thermal characteristics of thick red oak flakeboard were provided by White and Schaffer (1981).

TABLE 24-26.—*Properties of three-layer particleboard roof deck of red oak sp.*[1]

Statistic	Panel density (based on ovendry weight and volume at 5-percent moisture content), lb/cu ft		
	34.9	37.5	41.9
Panel thickness, inch	1-3/16	1-3/16	1-1/8
Panel MOE, psi			
Parallel to grain of aligned face flakes (D1037)[2]	776,000	768,000	1,064,000
Parallel to grain of aligned face flakes (D198)[3]	1,087,000	1,107,000	1,410,000
Perpendicular to grain of aligned face flakes (D1037)[2]	197,000	247,000	353,000
Panel MOR, psi (D1037)[2]			
Parallel to grain of aligned face flakes	3,410[4]	3,040[4]	6,700
Perpendicular to grain of aligned face flakes	1,140	1,490	2,460
IB, psi	21	23	90
Interlaminar shear strength, psi	72	99	287
Thickness swell, percent			
30 to 90 percent RH	7.1	6.5	5.1
OD-VPS[5]	11.9	15.5	16.8
Linear expansion, parallel[6], percent			
30 to 90 percent RH	.092	.099	.110
OD-VPS[5]	.172	.188	.192
Linear expansion, perpendicular[6], percent			
30 to 90 percent RH	.406	.425	.415
OD-VPS[5]	.701	.835	.885
Thermal resistance, $\frac{h \bullet ft^2 \bullet °F}{Btu}$	1.60		

[1]Data from personal correspondence with M. O. Hunt, Purdue University, March 19, 1981.

[2]American Society for Testing and Materials (1975a).

[3]Two-point bending load applied at third points of 2.5- by 12-foot panels; American Society for Testing and Materials (1975b).

[4]Because almost all of these bending specimens failed in horizontal shear, these MOR values are understated.

[5]Ten cycles, each comprised of placing specimens in an autoclave, covering them with water, subjecting them to a vacuum of 27.5 inches Hg for 30 minutes, followed by a water soak under pressure of 60 psi for 1 to 1-1/4 hours; specimens were then allowed to drain for 30 minutes and then were dried at 180°F for about 30 hours to lower specimen weight to within 5 or 10 percent of original weight.

[6]25-inch gauge length.

ECONOMICS OF MANUFACTURE

On the basis of the market analysis and the test results, Hoover et al. (1979) conducted an economic feasibility study. They concluded that this roof decking, which is capable of spanning 5 or 6 feet, could be competitive with steel roof decking. In 1980, the team presented another economic feasibility study of an operation to manufacture the product; this study is summarized in section 28-29.

24-18 THIN FLAKEBOARDS

With appropriate control of manufacturing procedures, it may be possible to platen-press medium-density thin panels with fiber faces and flake cores to compete with high-density fiberboards used to face doors.

Lyon and Short (1977) found that door skins having cores of 3-inch-long, 0.015-inch-thick sweetgum flakes produced on a shaping lathe, and faces of southern pine disk-refined fibers, have promise. In their study they platen-pressed panels 0.155 inch thick in 2 minutes at 300°F. Content of phenolic-resin solids, applied as a liquid, was 11 percent. Among their conclusions were the following:

- An increase in percentage of flakes in such panels increases MOR, MOE, dimensional stability, and impact strength, but decreases IB strength.
- On laboratory-scale panels, fiber/flake layered panels within the density range of 45 to 60 lb/cu ft have superior MOR and MOE compared to commercial medium-density thin particleboard; IB strength of such layered panels is lower than that for commercial medium-density panels, but is acceptable.
- At 50 lb/cu ft, laboratory-fabricated 50/50 fiber/flake panels are equivalent to commercial high-density boards with respect to MOR and MOE. To achieve equal IB, layered panels of 80/20 fiber/flake furnish are required.
- Laboratory panels made with fiber faces and up to 60 percent flakes in the core have uniform smooth surfaces similar to those of commercial medium-density panels, but are not as uniform or smooth as commercial high-density boards.

Lyon and Short found that these door skins were most stable if made from 100 percent flakes (LE from 50 to 90 percent RH = 0.021 percent); if fabricated with 60/40 fiber/flake layering, LE increased significantly (to 0.058 percent).

Section 28-23 summarizes Briggs' discussion of the economic feasibility of platen pressing oriented flakeboard cores for decorative hardwood plywood. Section 28-24 summarizes Springate and Roubicek's analysis of manufacturing thin fiberboard or particleboard from southern hardwoods to compete with lauan plywood.

24-19 COMPOSITE PANELS WITH VENEER FACES OVER FLAKE CORES

Alignment of face fibers, particles, flakes, or strands can enhance important properties of wood-based panels. Use of veneer as face layers provides a convenient way of obtaining near-perfect fiber alignment.

During the mid-1950's Elmendorf Research, Inc. developed a product, Nu-Ply, which had thin hardwood veneers on a particleboard or fiber core. It was made with green hardwood veneers which were dried, bonded to the core, and the core consolidated, in one hot pressing. The Nu-Ply Corp. in Bimidji, Minn., resulted from this development; applicable patents have since expired.[11]

Potlatch Corporation began research in 1968 on oriented strand board and oriented strand cores for composite softwood panels, and in the fall of 1971 first produced veneer-over-flake-core panels in their pilot plant. Their commercial plant in Lewiston, Idaho, started manufacturing softwood composite panels (PLYSTRAN) in 1976[12]. In the Potlatch process, cores with cross-aligned flakes are pressed separately and combined with veneer faces in a second pressing operation (McKean et al. 1975).

In the South, Biblis and Chiu (1972) described preliminary results with southern pine composite panels, and C.-Y. Hse[13] described composite panels made with faces of southern pine veneer and cores of mixed southern hardwood flakes, fabricated at the Pineville, La. laboratory of the Southern Forest Experiment Station. See also Hse (1976).

In 1973, the American Plywood Association undertook a study of composite panels, financed by the American Plywood Association, the Forest Products Economics and Marketing Research Division of the U.S. Forest Service, and the U.S. Department of Housing and Urban Development (Countryman 1974, 1975a). This study developed performance standards for sheathing and for combination subfloor and underlayment (Countryman 1975b) as described in section 24-2 of this chapter and by the American Plywood Association (1980). Flexural design procedures and performance of softwood composite panels tested by the American Plywood Association are reported by Batey et al. (1975) and Lyons et al. (1975). Buckling performance data are given by O'Halloran (1981).

In 1977 Ellingson Timber Co., Baker, Ore., began pre-production testing of a composite structural panel in which the core mat is formed between face and back veneers in one operation, with cauls on top and bottom. The binder used is isocyanate. Veneer does not require patching as the core furnish squeezes flush with the caul. By 1978 boards made in the demonstration plant were being sold commercially and plans were underway for expanded production. This one-step softwood composite panel, trade-named *ELCOBOARD* has a core of hammer-milled planer shavings (Blackman 1978).

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[11]Personal correspondence with T. W. Vaughan, Elmendorf Research, Inc., August 19, 1980.

[12]Personal correspondence with H. B. McKean, Forest Products Consultant, Lewiston, Idaho, dated August 26, 1980.

[13]Hse, C.-Y. 1972. Hardwood-flake-core-and-pine-veneer-face panel for exterior use. Paper presented at Southeastern Section meeting of Forest Products Research Society, Pensacola, Fla., October.

In late 1979 the Plyboard Corp. in Brownsville, Ore., commenced production of a composite panel trademarked *PLYBOARD*; it is fabricated in a one-step pressing operation in which Douglas-fir veneer is pressed over an electrostatically aligned core derived from Douglas-fir planer shavings and sawdust (Keil 1980).

Economic analyses by Springate (1978), Springate et al. (1978), Koenigshof (1979)—who favors the trade name *COMPLY*—and others, indicated the strong potential for manufacture of southern pine structural composite panels. In 1980 Georgia-Pacific Corp. commenced manufacturing such panels—trade named STABLE-X—at their Dudley, North Carolina plant. As in the Potlatch operation, the Dudley mill used a two-step procedure in which cores with cross-aligned flakes are pressed separately and later combined with face veneers in a second pressing operation.

FURNITURE COMPOSITE PANELS

Only a few studies of structural hardwood composite panels have been published; two relate to furniture panels.

Chow (1970, 1979) found that particleboard stiffness and creep resistance was significantly enhanced by adding hardwood face veneers approximately 1/16-inch thick.

Suchsland (1971) studied linear expansion of three-ply furniture panels comprised of hardwood veneer over a particleboard core. The flat-pressed 3/4-inch-thick particleboard cores he used were practically isotropic in the plane of the board; their low coefficients of hygroscopic expansion effectively restrained across-the-board expansion of thin layers of hardwood veneers. Thin veneer crossbands over these thick flat-pressed particleboard cores had little effect in restraining hygroscopic linear expansion of composite panels with hardwood veneer faces; he concluded that expansion of three-ply panels using flat-pressed particleboard cores can be reduced only by reducing the expansion coefficient of the core.

For 1/2-inch-thick composite sheathing panels comprised of single 1/24- to 1/10-inch-thick southern pine veneers over a core of mixed hardwood veneer flakes randomly placed, however, veneer thickness has a significant effect on across-panel linear expansion. (See following subsection.)

PHENOLIC-BONDED COMPOSITE PANELS WITH SOUTHERN PINE VENEER FACES AND CORES OF SOUTHERN HARDWOOD FLAKES[14]

Hse (1976) fabricated 72 1/2-inch-thick composite panels measuring 19 by 20 inches according to the following experimental design (fig. 24-50):

- Number of face veneers (rotary-peeled southern pine)
  - Single veneer on each face
  - Two veneers, cross-laminated on each face
- Veneer thickness
  - 1/10-inch
  - 1/16-inch
  - 1/24-inch
- Arrangement of hardwood core flakes (50 percent southern red oak, 25 percent hickory, 25 percent sweetgum)
  - Homogeneous, random orientation
  - Homogeneous, oriented in direction perpendicular to the grain of veneer in immediate contact
  - Three-layer, cross oriented
- Replications of panels: 4

Thus the panels were variously constructed with two or four veneers and one core layer (which might be random or oriented), or three oriented core layers (fig. 24-50). Face veneers were rotary-peeled from heated loblolly pine bolts, clear of defects, and dried to an average moisture content of 4 percent. Core flakes, which were also rotary peeled veneer, were 0.015 inch thick, 3 inches long, and 3/8-inch wide; they were dried to the moisture content of 3 percent.

Resin application and panel preparation.—Liquid phenolic resin was sprayed on veneers to achieve 5 lb of resin solids per 1,000 sq ft of single glueline. Core flakes were weighed to yield a core density of about 43.7 lb/cu ft (basis of ovendry weight and volume at 5 percent moisture content) and liquid phenolic resin was spray-applied to achieve resin solids content equal to 3-percent ovendry weight of the flakes. The flakes, after blending, were felted onto a face veneer in a forming box. All cores were prepared as a mixture of 50 percent southern red oak, 25 percent hickory, and 25 percent sweetgum. The core mat with face veneer on both sides was hot pressed at 335°F at sufficient pressure (about 400 psi) to close to stops in approximately 45 seconds. Closed press time was 5 minutes. All boards were then conditioned at 50 percent RH and 80°F, yielding average panel moisture content of about 4.8 percent.

Test procedure.—To evaluate dimensional stability, 3- by 9-inch specimens were given a VPS treatment, i.e., they were soaked in water under vacuum (30 inches of Hg) for 30 minutes and then under 65 psi pressure (at room temperature) for 24 hours. Other specimens of the same size were soaked in boiling water for 5 hours.

Standard mechanical tests were performed and MOR and MOE computed on the assumption that the cross section of the composite panel was homogeneous.

[14]This subsection is condensed from Hse (1976).

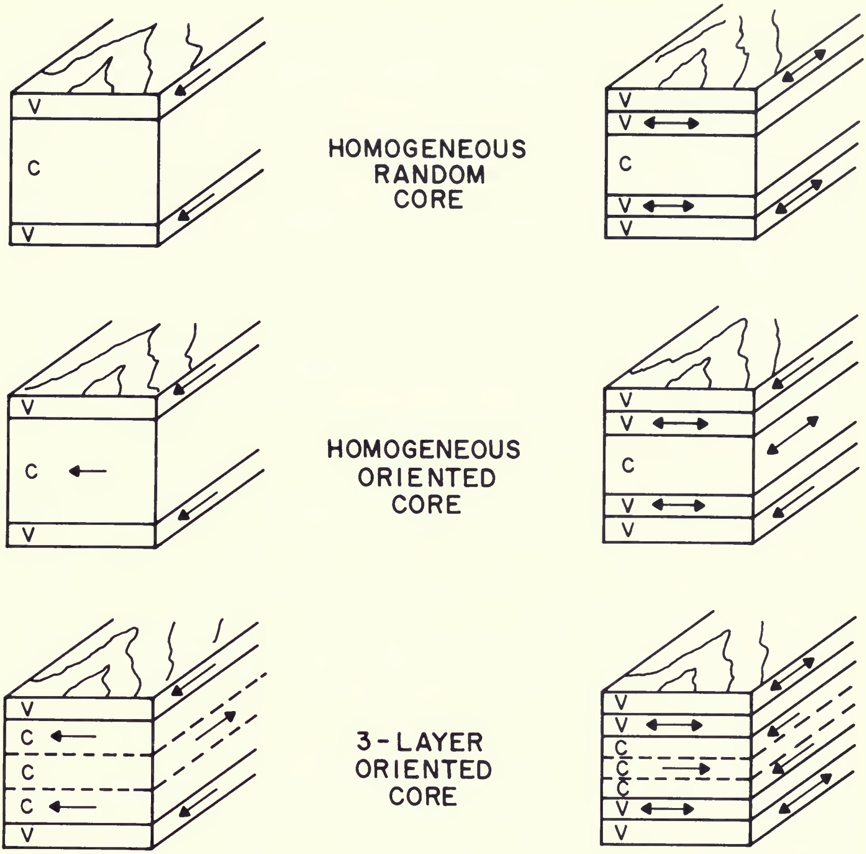

Figure 24-50.—Arrangements of face veneers (V) and core flakes (C). Arrows indicate grain direction in veneer and flake alignment direction in oriented cores. (Left) Single veneer on each face. (Right) Two veneers cross-laminated on each face. (Drawing after Hse 1976.)

Linear expansion.—Ranges of average linear expansion parallel to grain of outermost face veneer were 0.137 to 1.653 percent in the 5-hour boil test and 0.142 to 1.149 percent in VPS. Linear stability differed significantly with flake-core arrangement, as follows (from table 24-27):

Face and core construction	Along-the-grain expansion	
	VPS	5-hour boil
	Percent	
Single veneer		
Random	0.19	0.24
Oriented	1.06	1.44
Three-layer	.48	.76
Two veneers, cross laminated		
Random	.42	.37
Oriented	.26	.32
Three-layer	.57	.64

TABLE 24-27.—*Dimensional stability of phenolic-bonded panels with southern pine veneer faces and cores of southern hardwood veneer flakes, as measured by vacuum-pressure-soak and 5-hour boil tests* (Hse 1976)

Thickness of face veneer (inch) and type of flake core[1]	Vacuum-pressure-soak				5-Hour boil			
	Water adsorption	Thickness swell	Linear[2] expansion		Water adsorption	Thickness swell	Linear[2] expansion	
			Parallel	Perpendicular			Parallel	Perpendicular
	Percent							
ONE FACE VENEER EACH SIDE								
1/10								
Random	105.3	29.7	0.226	1.996	93.7	56.5	0.193	1.619
Oriented	104.9	31.5	.871	.364	94.3	56.1	1.303	.781
Three-layer	104.6	28.6	.317	.563	93.9	56.4	.620	1.116
1/16								
Random	101.2	24.2	.142	.617	95.3	46.5	.191	1.794
Oriented	101.0	27.9	1.148	.177	95.4	47.2	1.653	.386
Three-layer	96.5	22.5	.555	.561	92.5	47.9	.640	1.956
1/24								
Random	100.9	20.0	.212	.481	95.8	40.5	.345	.518
Oriented	97.3	29.9	1.148	.293	94.8	53.9	1.370	.452
Three-layer	98.2	24.6	.540	.673	93.9	53.3	1.013	1.413
TWO-FACE VENEERS CROSS-LAMINATED EACH SIDE								
1/10								
Random	91.4	20.2	.577	.709	83.5	30.1	.543	.567
Oriented	83.5	21.7	.359	.627	73.6	22.8	.652	.696
Three-layer	90.8	20.1	.463	.668	77.6	23.0	.501	.706
1/16								
Random	90.8	23.2	.320	.462	86.2	30.2	.282	.458
Oriented	86.0	25.9	.201	.710	80.2	33.2	.175	1.063
Three-layer	94.0	24.4	.433	.509	78.9	32.3	.624	.505

TABLE 24-27.—*Dimensional stability of phenolic-bonded panels with southern pine veneer faces and cores of southern hardwood veneer flakes, as measured by vacuum-pressure-soak and 5-hour boil tests* (Hse 1976)—Continued

Thickness of face veneer (inch) and type of flake core[1]	Vacuum-pressure-soak				5-Hour boil			
	Water adsorption	Thickness swell	Linear[2] expansion		Water adsorption	Thickness swell	Linear[2] expansion	
			Parallel	Perpendicular			Parallel	Perpendicular
	Percent							
1/24								
Random	94.9	24.1	.369	.254	87.6	32.0	.285	.424
Oriented	91.3	24.9	.211	1.112	83.0	36.9	.137	1.707
Three-layer	98.9	23.9	.800	.542	81.3	34.7	.807	.692

[1]Flakes were of rotary-cut veneer 3 inches long, 0.015 inch thick, and 3/8-inch wide. See figure 24-50 for panel construction. Core flakes were a mixture of species: 50 percent southern red oak, 25 percent hickory; and 25 percent sweetgum.

[2]As evaluated parallel and perpendicular to the grain of outermost face veneers.

With either one-ply or two-ply faces, panels with random cores had most linear stability parallel to the grain of outermost face veneer.

Expansion across the grain was least with one-ply faces if cores were oriented; with two-ply faces, random cores yielded most stability, as follows:

Face and core construction	Across-the-grain expansion	
	VPS	5-hour boil
	Percent	
Single veneer		
Random	1.03	1.31
Oriented	.28	.54
Three-layer	.60	1.50
Two veneers, cross laminated		
Random	.48	.48
Oriented	.82	1.16
Three-layer	.57	.63

Veneer thickness was correlated with linear expansion across the grain of face plys in panels with random cores; thick veneer caused large linear expansion, as follows:

Face construction and veneer thickness	Across-the-grain expansion	
	VPS	5-hour boil
Inch	*Percent*	
Single veneer		
1/10	2.00	1.62
1/16	.62	1.79
1/24	.48	.52
Two veneers, cross laminated		
1/10	.71	.57
1/16	.46	.46
1/24	.25	.42

Thickness swelling.—Average thickness swell ranged from 22 to 57 percent in the 5-hour boil and from 20 to 32 percent in VPS. The 5-hour boil consistently caused more swelling than did VPS test. In both tests face construction and veneer thickness interacted, as follows (data from table 24-26):

Face construction and veneer thickness	Thickness swell	
	VPS	5-hour boil
Inch	*Percent*	
Single veneer		
1/10	30.0	56.4
1/16	24.9	47.2
1/24	24.8	49.2
Two veneers, cross laminated		
1/10	20.7	25.3
1/16	24.5	31.9
1/24	24.3	34.5

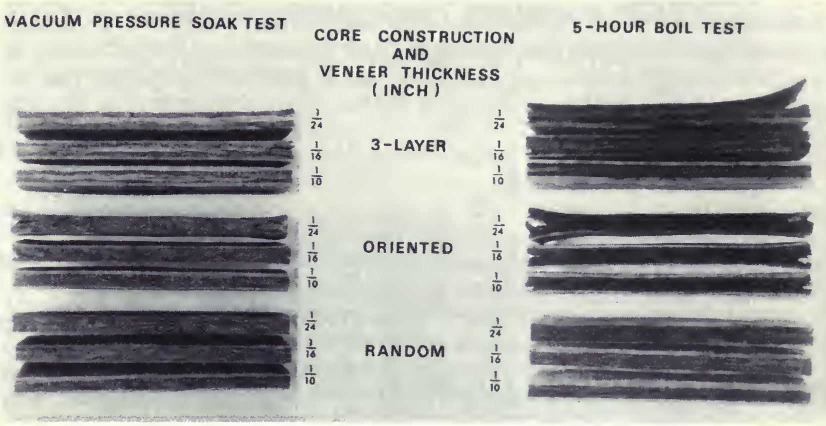

Figure 24-51.—Delamination of composite panels with single veneers on each face after VPS test (left) and 5-hour boil (right). (Photo from Hse 1976.)

In VPS tests, 1/10-inch veneer and two-ply faces resulted in least thickness swelling (20.7 percent); 1/10-inch veneer applied singly to panel faces had most swelling (30.0 percent). With 1/16- and 1/24-inch face veneers, little difference was noted between one- and two-ply construction.

In the 5-hour boil, panels with one-ply faces consistently swelled more than panels with two-ply faces; this was true for all veneer thicknesses. As in the VPS tests, 1/10-inch veneer and two-ply faces resulted in least thickness swelling (25.3 percent); 1/10-inch veneer applied singly to panel faces had most swelling (56.4 percent).

In panels with one-ply faces, random core orientation yielded least thickness swelling. With two-ply faces, swelling did not vary significantly with core construction, as follows:

Face and core construction	Thickness swelling: VPS	Thickness swelling: 5-hour boil
	Percent	*Percent*
Single veneer		
Random	24.6	47.8
Oriented	29.7	52.4
Three-layer	25.3	52.5
Two veneers, cross laminated		
Random	22.5	30.8
Oriented	24.1	30.6
Three-layer	22.8	30.6

Panels with single-ply faces had best integrity if constructed with random cores. After the 5-hour boil test severe delamination was observed in panels with three-layer and oriented cores; delamination was less severe in such panels when subjected to the VPS test (fig. 24-51). The superior stability of random cores is further evident from figure 24-52. Three-layer and oriented cores exhibited delamination and deformation.

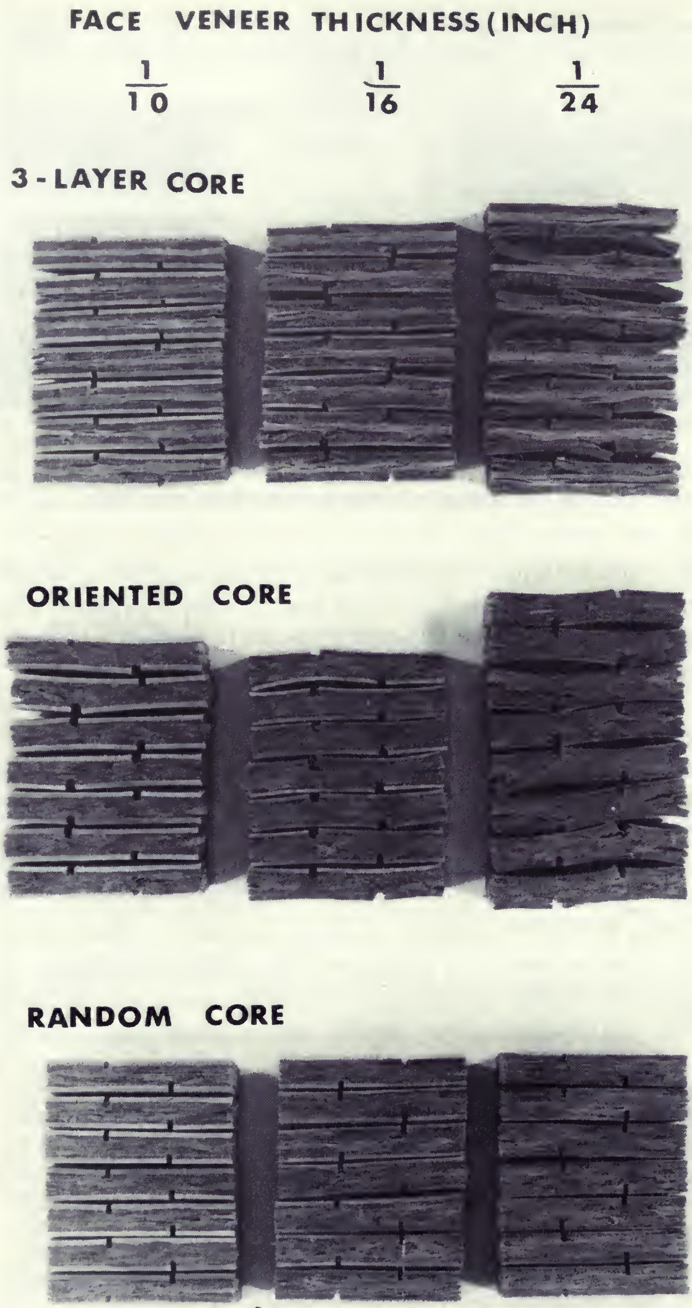

Figure 24-52.—Deformations and delaminations in composite panels with single veneers on each face, after VPS test. Specimens were prepared as if for plywood shear tests. (Photo from Hse 1976.)

Modulus of elasticity.—Average MOE in stress parallel to the grain of face plys was 1,050,000 psi for panels with single 1/24-inch veneers over an oriented core, and ranged to 1,980,000 psi for those with two 1/16-inch veneers cross-laminated on each face over an oriented flake core (table 24-28). MOE varied significantly with thickness of face veneers:

Face construction and veneer thickness	MOE	
	Stressed parallel	Stressed perpendicular
(1)	(2)	(3)
Inch	------psi------	
Single veneer		
1/10	1,844,000	344,000
1/16	1,500,000	650,000
1/24	1,231,000	838,000
Two veneers, cross-laminated		
1/10	1,928,000	—
1/16	1,960,000	—
1/24	1,543,000	—

From column 2 it is seen that, except for panels with 1/10-inch veneer in two-ply construction, MOE parallel to the grain increased with increasing veneer thickness. For one-ply faces, MOE across the grain decreased as veneer thickness increased (col. 3).

Face and core construction interacted to affect MOE as follows:

Face and core construction	MOE	
	Stressed parallel	Stressed perpendicular
	------Psi------	
Single veneer		
Random	1,731,000	314,000
Oriented	1,393,000	735,000
Three-layer	1,462,000	781,000
Two veneers, cross-laminated		
Random	1,737,000	—
Oriented	1,906,000	—
Three-layer	1,788,000	—

When stressed parallel to the grain of outermost veneers, panels with two veneers on each face and with oriented cores had highest MOE (1,906,000 psi); panels with two-ply faces and random or three-layer cores did not differ much in MOE. Panels with single veneers on each face had greatest MOE if fabricated with random cores (1,731,000 psi).

MOE across the grain of panels with single veneers was lowest for random core construction.

TABLE 24-28.—*Modulus of rupture and modulus of elasticity of phenolic-bonded panels with southern pine veneer faces and cores of southern hardwood veneer flakes* (Hse 1976)

Thickness of face veneers (inch) and type of flake core[1]	MOR[2]		MOE[2]	
	Parallel[3]	Perpendicular[4]	Parallel	Perpendicular[4]
	Psi		*Million psi*	
ONE FACE VENEER EACH SIDE				
1/10				
Random	9,814	2,050	1.942	0.209
Oriented	7,125	2,680	1.685	.414
Three-layer	6,588	2,833	1.876	.409
1/16				
Random	10,400	2,453	1.696	.298
Oriented	5,919	6,511	1.445	.791
Three-layer	8,010	6,126	1.359	.862
1/24				
Random	7,245	3,456	1.434	.437
Oriented	4,495	6,640	1.049	1.003
Three-layer	6,902	6,407	1.212	1.073
TWO FACE VENEERS CROSS-LAMINATED EACH SIDE				
1/10				
Random	5,853	—	1.914	—
Oriented	11,359	—	1.952	—
Three-layer	6,017	—	1.920	—
1/16				
Random	11,562	—	1.820	—
Oriented	15,843	—	1.983	—
Three-layer	8,617	—	1.846	—
1/24				
Random	6,753	—	1.344	—
Oriented	12,281	—	1.748	—
Three-layer	6,988	—	1.564	—

[1]Flakes were of rotary-cut veneer 3 inches long, 0.015 inch thick, and 3/8-inch wide. See figure 24-50 for panel construction. Core flakes were a mixture of species: 50 percent southern red oak, 25 percent hickory, and 25 percent sweetgum.

[2]In stress parallel or perpendicular to grain of outermost face veneers.

[3]Of the specimens with 1/10-inch veneers, 86 percent failed in horizontal shear; 27 percent of those with 1/16-inch face veneers failed in horizontal shear. These shear failures precluded accurate determination of true MOR with these veneer thicknesses.

[4]Two-ply panels were not tested perpendicular to the grain of the face plys.

Modulus of rupture.—Average MOR in stress parallel to the grain of face plys was least—4,495 psi—for panels with single 1/24-inch veneers on each face over an oriented core. It was greatest—15,843 psi—for panels with two 1/16-inch veneers cross-laminated on each face over an oriented core.

With values for all core construction pooled, MOR differed significantly with face veneer thickness. As noted in footnote[3] of table 24-27, horizontal shear failures in the specimens with 1/10-inch veneers precluded accurate determination of their MOR, but MOR increased as veneer thickness increased from 1/24- to 1/16-inch. The tabulation of MOE vs. veneer thickness—which could be accurately determined before horizontal shear failures occurred—is probably also a good indicator of variation of MOR (stressed parallel) with veneer thickness.

When stress was perpendicular to the grain of the outermost face veneer, MOR decreased as face veneer thickness increased.

Interactions of core construction with face construction and number of face plys affected MOR, as follows:

Face and core construction	MOR	
	Stressed parallel	Stressed perpendicular
	Psi	
Single veneer		
Random	9,153	2,646
Oriented	5,846	5,277
Three-layer	7,167	5,122
Two veneers, cross-laminated		
Random	8,056	—
Oriented	13,161	—
Three-layer	7,207	—

MOR of panels with two veneers cross-laminated on each face over oriented cores averaged significantly higher than MOR in panels with single face veneers over oriented cores. In panels with random cores, however, MOR was slightly greater for those with single veneers on each face. Little difference was detected between one-ply and two-ply faces when the core was fabricated in three layers.

Of all panels with one-ply veneer overlays, those with random cores yielded highest MOR (i.e., 9,153 psi) when stressed parallel to the grain of the face veneer, but had lowest MOR (2,646 psi) when stressed perpendicular to the grain.

Summary.—Table 24-29 summarizes Hse's (1976) results in terms of the construction giving the best performance in each property tested. Two veneers, cross laminated on each face over a core of oriented flakes, yielded strongest panels. Nevertheless, panels with single-ply faces over random cores appeared more than adequate for most structural applications; MOR was 9,153 psi when averaged over the three veneer thicknesses tested, and MOE was 1,731,000 psi. Economy in use of veneer also favors single-ply faces.

For panels with single-ply faces, a random core is preferable to oriented or three-layer cores in most properties, even though such construction is less stable across the grain direction of the face veneer. Both strength and dimensional stability across the grain can be modified by altering thickness of face veneers; i.e., strength decreased and linear stability increased as veneer thickness decreased. Hse concluded that the 1/16-inch veneer thickness may be a good compromise for commercial applications.

TABLE 24-29.—*Combination of face and core constructions yielding best properties for composite panels with southern pine veneer faces and cores of southern hardwood flakes* (Hse 1976)

Property and measurement direction in relation to grain of outer face ply	Single veneer on each face	Two veneers cross-laminated on each face
MOR (psi)		
With grain	Random (9,153)	Oriented (13,161)
Across grain	Oriented (5,277)	—
MOE (1,000 psi)		
With grain	Random (1,731)	Oriented (1,906)
Across grain	Three-layer (781)	—
Thickness swelling, VPS (percent)	Random (24.6)	Random (22.5)
Linear expansion, VPS (percent)		
With grain	Random (0.19)	Oriented (0.26)
Across grain	Oriented (0.28)	Random (0.48)

Review of available data suggests that long, thin, randomly oriented southern hardwood flakes yield all-flake boards that have linear expansion of less than 0.25 percent when subjected to OD-VPS test (table 24-21) and less than 0.12 percent when subjected to a change from 50 to 90 percent RH (figs. 24-42 and 24-55). Such boards with random flake placement also are strong and stiff at a density of 44 to 46 lb/cu ft (MOR of about 4,700 psi and MOE of about 650,000 psi; see table 24-12).

In view of these more than adequate properties, it seems not necessary to either orient flake layers or to overlay such flakeboard with veneer to alter linear expansion and bending properties. Moreover, if thin flakeboard is faced with thick veneer, linear expansion across the face grain may become excessive. To obtain a smooth paintable surface that will stay smooth with changes in humidity, perhaps very thin veneers or very thin impermeable paintable faces and backs could be applied—rather than thick veneers. These thin faces would not increase linear expansion across the panel, but could retard moisture movement into the panel and preserve smooth surfaces under paint.

Figure 24-53.—Experimental 3/4-inch-thick composite oak panels comprised of rotary-peeled veneer oak faces and backs hot-pressed glued to random flakeboard cores. (Left) White oak panels. (Right) Southern red oak panels. (Photo from Roubicek and Koch 1981.)

ALL-OAK COMPOSITE PANELS 3/4-INCH THICK

To compare properties of all-oak composites to those of solid oak lumber and to 5-ply southern pine plywood—all 3/4-inch thick—Hse and Koch[15] fabricated and tested in flatwise bending 4-inch-wide and 6-inch-wide boards of each material cut to 36-inch lengths, with face grain running parallel to the 36-inch length.

Half the oak composites were made of white oak and half of southern red oak. For each species, 40-inch-square cores with pressed 5.5 minutes at 325°F from 3-inch-long, 0.025-inch thick, shaping-lathe flakes blended with 5.5 percent phenol-formaldehyde resin (solid basis) applied as a liquid spray. Flakes were randomly placed. Density of the cores was 46.5 lb/cu ft at 4- to 5-percent moisture content. The cores were lightly sanded to 0.50-inch or 0.55-inch thickness for overlaying with 1/8- or 1/10-inch veneer, double-spread with 115 pounds of phenol-formaldehyde glue per 1,000 square feet of double glue line, and the log-run veneer faces glued to them to yield six 3/4-inch-thick panels in each of the following four categories (fig. 24-53):

Species	Face veneer thickness
White oak	1/10-inch
Southern red oak	1/8-inch

[15]Hse, C.-Y., and P. Koch. 1981. Strength and stiffness of 3/4-inch-thick white oak and southern red oak composite pallet deckboards made with 1/10- and 1/8-inch-thick veneer over flake cores—compared to 3/4-inch-thick, solid-sawn, log-run deckboards. U.S. Dep. Agric., For. Serv., South. For. Exp. Stn., Alexandria, La., Fin. Rep. FS-SO-3201-8, dated August 26, 1981.

Each panel was ripped parallel to the grain of the face veneers to yield three 4-inch-wide and three 6-inch-wide boards 36 inches long. These 144 composite boards, together with 4- and 6-inch-wide, solid-sawn, log-run southern red oak and white oak boards from small pine-site trees (18 boards of each species and width), and 4- and 6-inch-wide, 5-ply, 3/4-inch-thick southern pine CDX plywood strips ripped from plywood purchased from three Louisiana sources (36 of each width), were equilibrated for 30 days at 72°F and 50 percent RH. At test, the composite boards contained about 6 to 7 percent moisture content, the solid oak about 9 percent, and the southern pine plywood about 7 percent. All boards were broken in flatwise bending with centerpoint loading over a 36-inch span according to ASTM D 805 (American Society for Testing and Materials 1972).

MOE and MOR of the 4-inch-wide boards did not differ substantially from values for 6-inch-wide boards. Solid oak boards had highest MOE and MOR, southern pine 5-ply CDX plywood lowest MOE and MOR, and the composite boards were intermediate (table 24-30). Specific gravity of the solid-sawn oak boards (0.73 based on ovendry weight and volume at test) was greater than that of the composite boards (0.71) because the solid-sawn boards were taken from heart-center cants, which in white oak and southern red oak are typically significantly denser than the outer wood. Oak flakes, veneer, and solid boards were all cut from the same trees, i.e., three 12-inch-diameter, pine-site trees of each species.

TABLE 24-30.—*Modulus of elasticity and modulus of rupture of 3/4-inch-thick oak composite boards with single 1/8- and 1/10-inch veneer faces and backs over random flake cores, compared to solid-sawn oak boards and 5-ply southern pine CDX plywood, all tested in bending parallel to grain of face layers* (Data from Hse and Koch; see text footnote[15])

Species and type of board	MOE[1]	MOR[1]
	Psi	
Southern red oak		
Solid-sawn	2,021,000	17,339
Composite with 1/8-inch faces	1,633,000	11,955
Composite with 1/10-inch faces	1,541,000	10,136
White oak		
Solid-sawn	2,265,000	18,860
Composite with 1/8-inch faces	1,721,000	11,530
Composite with 1/10-inch faces	1,655,000	11,740
Average of both oak species		
Solid-sawn	2,140,000	18,100
Composite with 1/8-inch faces	1,680,000	11,700
Composite with 1/10-inch faces	1,600,000	10,940
Southern pine 5-ply CDX plywood	1,550,000	7,910

[1]Moisture content at test of solid-sawn, composite, and plywood boards averaged 9, 6-1/2, and 7 percent, respectively.

COMPOSITE PANELS AND MOULDINGS WITH VENEER FACES OVER FIBER CORES

Beyond the scope of this chapter, but probably of interest to readers, is Kelly and Pearson's (1977) discussion of properties of panels with southern pine veneer faces over fiberboard cores made from hardwood whole-tree chips.

Also of potential interest is the technology of profile veneer wrapping of medium-density fiberboard cores to fabricate large mouldings such as handrails (Hall 1981).

YIELDS OF HARDWOOD VENEER FOR COMPOSITE PANELS

McAlister (1981) evaluated yields and grades of 0.160-inch-thick, 8-foot-long, rotary-peeled veneer from yellow-poplar, white oak, and sweetgum 12 to 22 inches in dbh from the Georgia Piedmont and the mountains of North Carolina. Also, McAlister and Clark[16] conducted a similar study of black tupelo, sweetgum, and yellow-poplar from the Coastal Plain of South Carolina. Results of these studies are shown in tables 12-5 through 12-10. McAlister (1981) summarized his Piedmont-mountain area study by noting that a typical mix of 100 yellow-poplar, sweetgum, and white oak trees 12 to 20 inches in dbh and containing 3008 cu ft of stemwood to a 4-inch top, yielded about 375 cu ft of dry C-grade and better 1/6-inch veneer; D-grade veneer from these trees totalled another 233 cu ft. A typical mix of 100 trees 12 to 20 inches in diameter of the species studied in the Coastal Plain had stemwood volume to a 4-inch top (dib) of 3,207 cu ft and yielded 618 cu ft of dry C-grade and better veneer, and 259 cu ft of D-grade veneer. Water oak from the Coastal Plain was eliminated from the study because fully half of the stems had severe butt rot extending from the stump upwards 4 to 6 feet. (See table 24-31 for mechanical properties of these veneers.)

24-20 COMPOSITE PANELS WITH FLAKE FACES OVER VENEER CORES

For some panel uses, linear expansion across one or both dimensions of a structural or decorative panel is critical. Elmendorf (1961) suggested a procedure for pressing composite panels with flake faces over a solid lumber or veneer core to exploit the properties of naturally aligned fibers in solid wood.

Suchsland et al. (1979) described a fabrication procedure (fig. 24-54) in which low-grade veneer in single or double plys was used as a core and randomly placed, 3-inch-long, 0.015-inch-thick sweetgum flakes cut on a shaping-lathe were used as faces; in their experiment southern pine veneer 1/10-inch thick was

[16]McAlister, R. H., and A. Clark III. Manuscript in preparation. Veneer yields by grade from three Coastal Plain hardwoods—blackgum, sweetgum, and yellow-poplar. Southeast. For. Exp. Stn., U.S. Dep. Agric., For. Serv., Asheville, N.C.

used for two-ply cores and 1/10- or 1/8-inch-thick veneer for single-ply cores. Panels were pressed to 3/4-inch thickness with density of 0.77 to 0.80 g/cm^3. Measured optically across both panel directions, these veneer-reinforced composites had linear expansion between 47 and 93 percent RH of about 0.06 percent in the direction of veneer alignment—a value close to that of five-ply, 1/2-inch-thick southern pine plywood and slightly less than that for a 3/4-inch-thick, all-random-flake sweetgum panel (fig. 24-55). When disk-refined fibers or planer shavings were fabricated into homogeneous and veneer-reinforced panels, percentage reduction in linear expansion by veneer reinforcement was greater than with flakes.

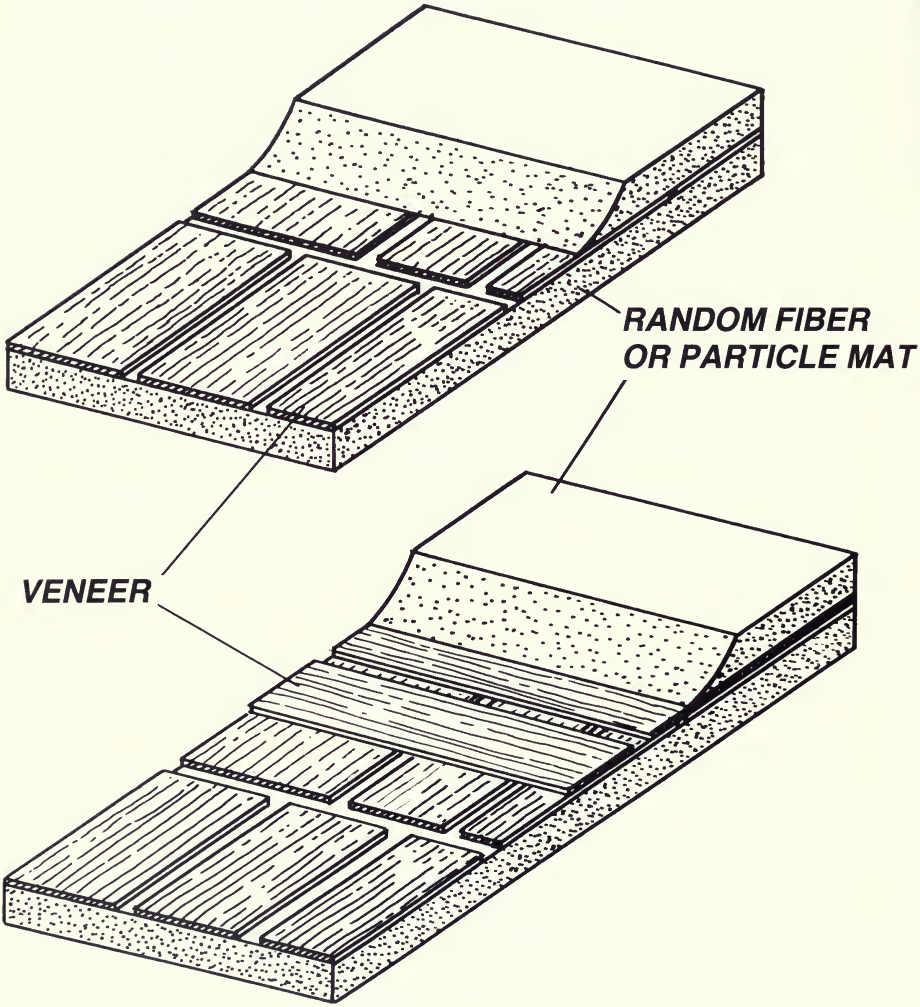

Figure 24-54.—Principle of manufacture of composite panels with single-ply and two-ply veneer reinforcement. (Drawing after Suchsland et al. 1979.)

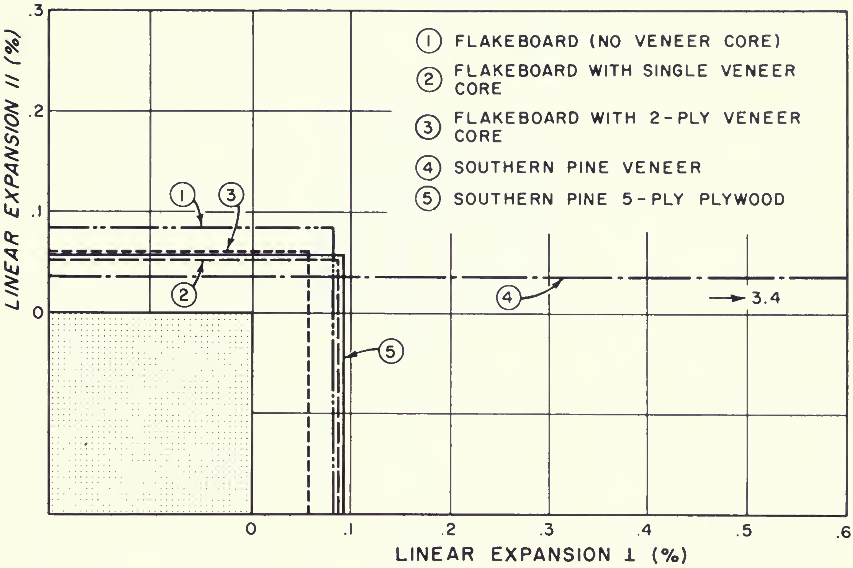

Figure 24-55.—Linear expansion, between 47 and 93 percent RH, of various flakeboard constructions compared with southern pine veneer and southern pine plywood. (Drawing after Suchsland et al. 1979.)

24-21 FABRICATED JOISTS WITH THIN FLAKEBOARD WEBS

Effective use of wood in lightweight I-beam-type composite joists requires uniformly strong, stiff flanges and shear-resistant webs.

Percival et al. (1977) glue-nailed pairs of western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) select structural stress-graded (1,800 f) 2 by 4 flanges to 16-inch-deep structural particleboard webs to fabricate 16.5-foot-long garage headers (fig. 24-56) and compared their performance with a double 2- by 12-inch header of No. 1C Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) lumber, a beam once commonly used for framing a 16-foot garage opening. One-half-inch-thick webs in the composite I-beams were one of three materials: C-C exterior-grade Douglas-fir plywood; phenolic-bonded aspen waferboard; and urea-bonded mixed-hardwood core-board containing flakes smaller than 1/2 -inch long. The plywood-web beam was 71 percent stiffer, the aspen waferboard-web beam 100 percent stiffer, and the mixed-hardwood core-board-web beam 84 percent stiffer than the double 2 by 12 header. The plywood-web beam and the double 2 by 12 header failed at 799 pounds per lineal foot of uniform load, the aspen beam at 1,008, and the mixed-hardwood beam at 1,714 pounds per lineal foot.

From this experiment and others, e.g., Hunt (1975), Johnson et al. (1976), Superfesky and Ramaker (1978), and McNatt (1980), it is evident that composite wood I-beams can serve usefully.

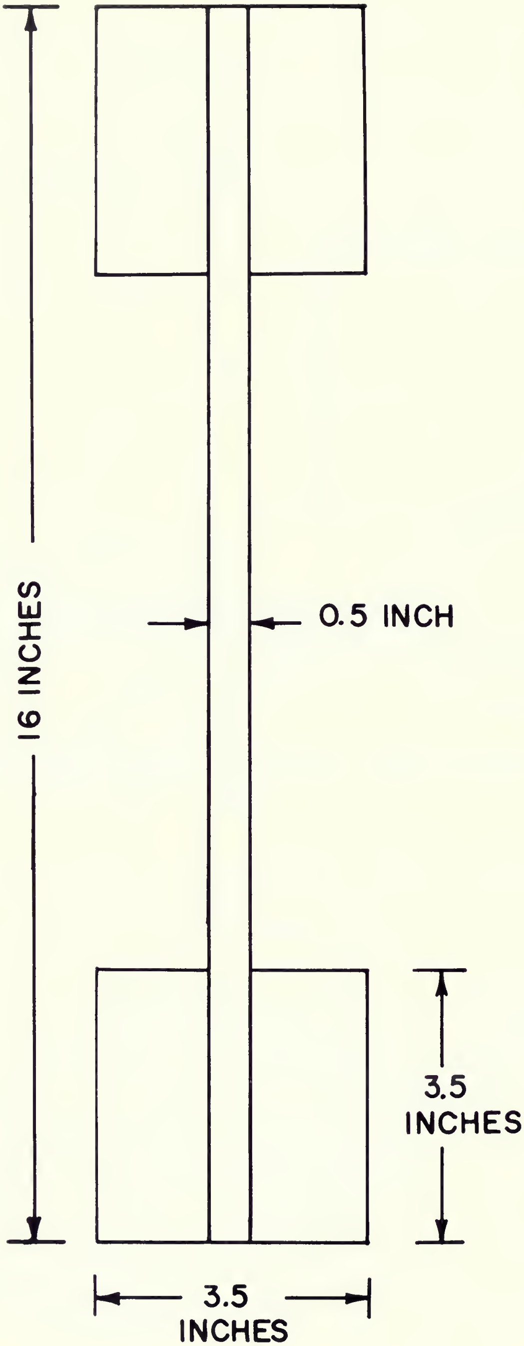

Figure 24-56.—Composite I-beams tested by Percival et al. (1977) Vertical 2 by 4 stiffeners were placed on both sides of the web at 2-foot intervals.

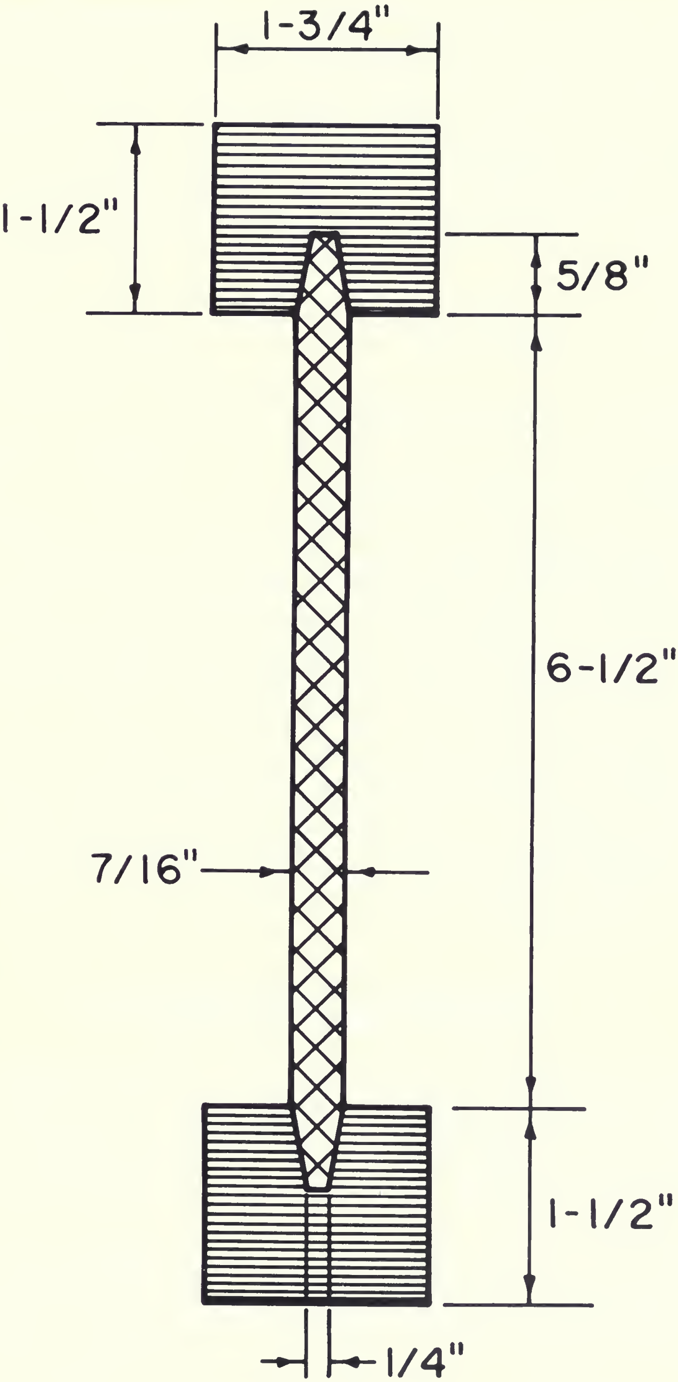

Figure 24-57.—Composite I-beam with parallel-laminated hardwood veneer flanges and flakeboard of mixed hardwood species. (Drawing after Koch 1982.) Webs must be sufficiently thick to resist buckling before flanges fail.

Hunt (1975) showed that waferboards have in-plane shear modulus more than 2.5 times greater than plywood, and Price (1978) found that at 46 lb/cu ft, the plate shear modulus of random-oriented mixed southern hardwood flakeboard was 259,000 psi. (See discussion related to table 24-15). Woodson (1981) showed that 1/8-inch-thick, rotary-peeled hickory veneers—even in short lengths—can be parallel-laminated into very high-strength flange material; bending properties he observed in specimens of such material measuring 2 by 2 inches square and 48 inches long were as follows (at about 11 percent moisture content):

Species and veneer length	MOE	MOR
	Psi	
Hickory veneer 12 inches long; distributed pattern of butt joints	1,759,000	13,230
Hickory veneer 48 inches long; no butt joints	1,882,000	18,735
Southern pine veneer 48 inches long; no butt joints	1,680,000	12,684

These findings indicate that it should be possible to make a high-strength I-beam from hardwood flange veneers and hardwood flakeboard (fig. 24-57); when utilizing such high-strength hardwood flanges in composite joists, webs must be thicker—to preclude buckling failures—than those used with weaker flanges. Woodson (1981) and Koch (1982) have provided economic analyses of such operations. These analyses are summarized in sections 28-21 and 28-31.

R. H. McAlister (table 24-31) evaluated tensile properties of dry rotary-peeled, defect-free veneer of four major southeastern hardwood species. Average modulus of elasticity measured in tension varied from 1,370,000 psi for Piedmont sweetgum to 1,740,000 psi for Piedmont yellow-poplar. Average tensile strength varied from about 3,000 psi for Coastal Plain woods and mountain white oak, to about 7,000 psi for yellow-poplar and white oak from the Georgia Piedmont (table 24-31).

24-22 COMPLY LUMBER

Figure 24-57 depicts a composite I-beam made with high-strength, parallel-laminated hardwood veneer flanges and a thin web of hardwood structural flakeboard. It is possible to use a weaker, but thicker, particleboard web and flanges comprised of as few as two layers of veneer to fabricate composite studs and joists (fig. 24-58).

McAlister (1979) made such studs—trade-named *COM-PLY*—with veneers of yellow-poplar, sweetgum, and white oak. Two 1/6-inch-thick veneers were parallel laminated to each edge of a phenolic-bonded particleboard having average density of 40 lb/cu ft and measuring 1.5 by 2.83 inches; the composite studs therefore measured 1.5 by 3.5 inches in cross section. McAlister found that these studs met performance requirements described by Blomquist et al. (1976) and that they were comparable to similar composite studs made with southern pine veneers and with kiln-dried, stud-grade southern pine lumber.

TABLE 24-31.—*Modulus of elasticity (measured by two methods) and tensile strength of 1.5-inch-wide, defect-free strips of 0.160-inch veneer rotary-peeled from hardwood trees 12 to 20 inches in diameter of four species cut at three locations in the Southeast* (Data from McAlister[1])[2]

Region and species	Modulus of elasticity: Dynamic	Modulus of elasticity: Static tension	Ultimate tensile strength
	----------*Million psi*----------		*Psi*
Georgia Piedmont			
Sweetgum	1.75	1.37	6,032
White oak	2.20	1.67	6,511
Yellow-poplar	2.02	1.74	7,087
North Carolina Mountains			
White oak	2.00	1.51	3,181
Yellow-poplar	2.12	1.73	4,565
South Carolina Coastal Plains			
Black tupelo	1.85	1.48	2,989
Sweetgum	1.91	1.54	2,913
Yellow-poplar	1.88	1.47	3,118

[1]McAlister, R. H. Manuscript in preparation. Modulus of elasticity and tensile strength distribution of veneer of four commercially important southeastern hardwoods. Southeast. For. Exp. Stn., U.S. Dep. Agric., For. Serv., Asheville, N.C.

[2]Each value is an average based on a total of 30 specimens sampled from each of 137 to 277 trees per species. Eight-foot peeler logs from these trees were cut to a minimum top diameter of 8 inches inside bark. Moisture content at test was about 10 percent of ovendry weight.

A similar analysis of composite joists (fig. 24-58 bottom) using oak, yellow-poplar, and sweetgum veneers is available.[17]

Koenigshof's (1981) study of economic feasibility of manufacturing *COM-PLY* studs and joists from southern hardwoods is summarized in section 28-28.

24-23 MOLDED FLAKEBOARD

The molding of flakes is a technology somewhat distinct from that of molding fibres or small cubical particles. Pages 1207 and 1208 of Agriculture Handbook 420 (Koch 1972) describe some parameters affecting molding of fine particles. Section 22-10 of this text describes under paragraph heading *Recycled crossties*, a crosstie molded from particles derived from old crossties. Additional references related to molding particles are Molsemi (1974a), Prusakov et al. (1975), Bazhenov and Samkharadze (1977), Maloney (1977), and Ward (1978). Ruppin (1979) discusses the manufacture of molded articles from waste paper, and Oroszlan (1978) describes a Czechoslovakian three-stage process to mold fiberboard automobile parts.

[17]Koenigshof, G. A. Strength and stiffness of COM-PLY joist. Southeast. For. Exp. Stn., U.S. Dep. Agric., For. Serv., Fin. Rep. FS-SE-3501-26(1), in preparation 1982.

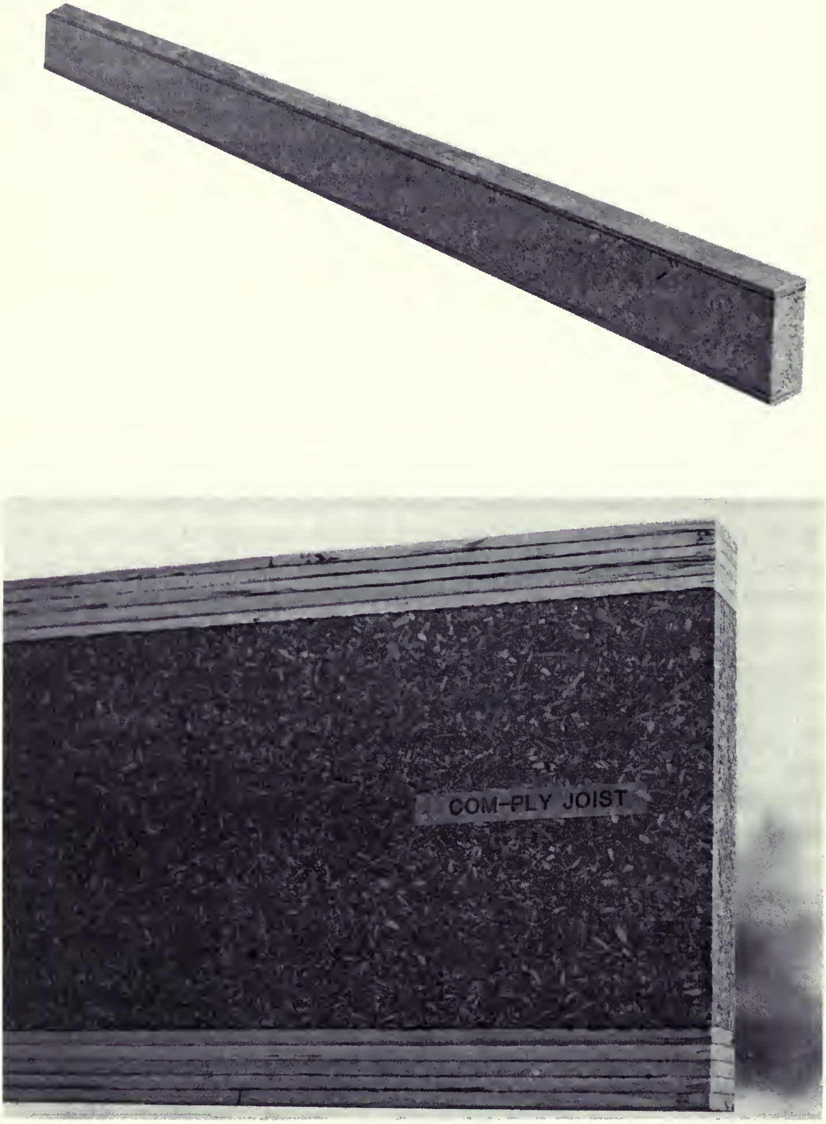

Figure 24-58.—Composite studs (top) and joists (bottom) fabricated from hardwood veneer and particleboard. (Photos from files of R. H. McAlister and G. A. Koenigshof.)

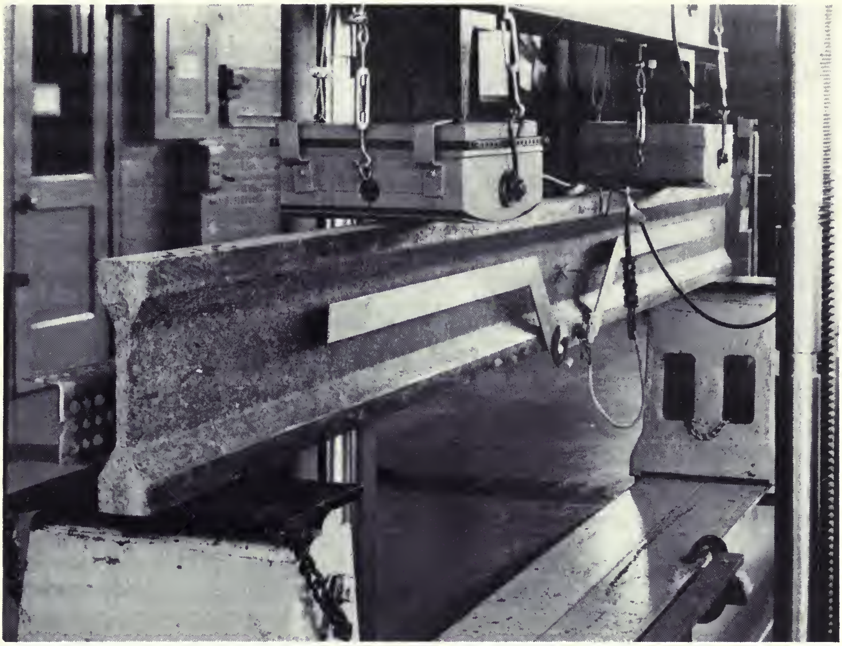

Figure 24-59.—Shaped particle beam under bending load. (Photo from Geimer and Lehmann 1975.)

Elmendorf Research, Inc. (1970ab) developed panel products (*STONE-TEX* and *PLY-TEX*) platen-pressed from shavings in such a manner that surfaces are textured with pronounced elevations and depressions. This molding is accomplished through use of resilient platens and the resulting board is more uniform in density across board width and length than particleboards platen-pressed with rigid cauls.

SHAPED PARTICLE BEAMS

Geimer and Lehmann (1975) evaluated several forming methods in constructing 9.75-inch-deep, 96-inch-long I-beams (fig. 24-59) of wood particles using shaped molds. They found that the forming method holding most promise maintains a level mat during the forming period by utilizing a low-bulk-density fibrous material for the web portion of the beam and aligned flakes with high bulk density for the flange area. Beams having the best bending properties were constructed using aligned 0.020- by 0.5- by 2-inch, disk-cut flakes in the flanges and 0.020- by 2-inch ring flakes randomly dispersed for the web. Such beams had EI of 185,000,000 psi and breaking loads of 10,750 pounds under quarter-span, two-point loading over a 90-inch span. Bending stiffness was comparable to that of a solid lumber beam of equal weight. Bending strength, however, was only half that of a lumber beam.

Geimer and Lehmann concluded that gradually changing from flange to web material through a transition zone should reduce stress concentrations and that horizontal-shear stiffness significantly affects shaped-beam performance.

CORRUGATED-CONTOUR FLAKEBOARD

Price and Kesler (1974) molded long sweetgum veneer flakes 0.015 inch thick and 3/8-inch wide into phenolic-bonded, flat-topped corrugated panels (fig. 24-60). They evaluated flakes of two lengths (2 and 3 inches) and of two types (clipped from veneer sheets and cut on a shaping-lathe headrig). Two-inch-long flakes conformed to molds better than those 3 inches long. Veneer flakes conformed to molds better than shaping-lathe flakes and yielded products with more uniform density and thickness. Flat specimens cut from the corrugated panels (fig. 24-60) had about 40 percent lower MOR and MOE than flat-pressed panels.

MOLDED PALLETS

In Europe, pallets have long been commercially molded from softwood and hardwood sawdust (Anonymous 1976; Suta and Postulka 1978). A plant built in 1979 in Dover, Ohio is using the Werzalit process to fabricate molded urea-bonded pallets (fig. 24-61) from a mixture of hardwood and softwood particles. In this plant, operated by only three people per shift, hot presses are used to

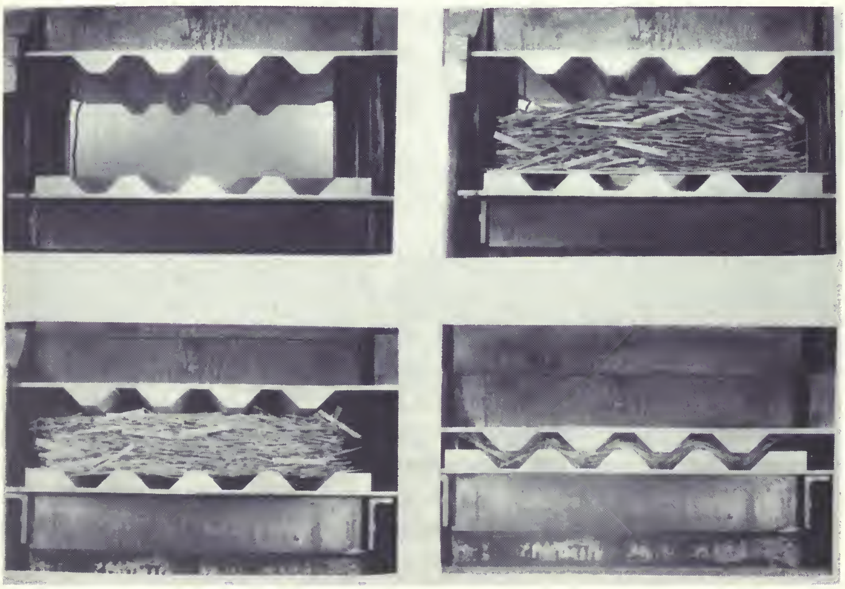

Figure 24-60.—Molded flakeboard fabrication process. (Top left) Mold attached to press. (Top right) Formed mat resting on caul. (Bottom left) Mat resting on mold. (Bottom right) Mold almost to stops. (Photos from Price and Kessler 1974.)

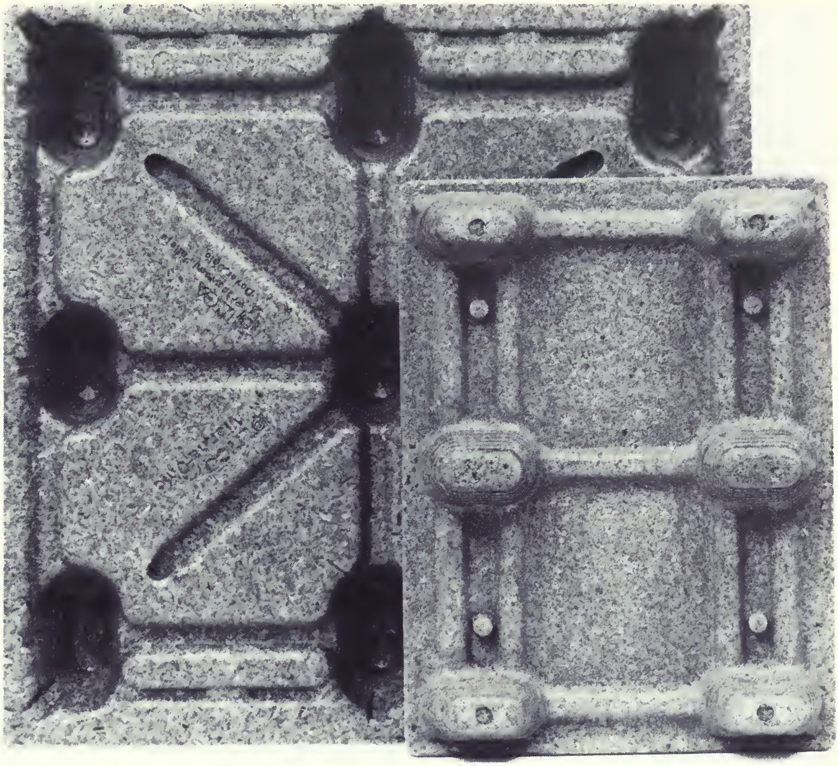

Figure 24-61.—Urea-bonded pallets fabricated from ring-cut particles by the Werzalit process. Large pallet is 42-3/16 by 42-1/16 inches and weighs about 39.5 pounds; small pallet is 31-9/16 by 23-5/8 inches and weighs about 10.4 pounds. Resin-solids content is about 8 percent of ovendry weight of wood. (Photo from Haas 1980.)

make warehouse pallets and smaller pallets for handling case goods in grocery stores; the pallets are molded so they can nest together to save shipping space. For handling bagged material a lip can be moulded around the pallet's top edge to help hold bags in place; molded pallets have low moisture content and do not wet the bags as do solid-wood pallets of green lumber (Wasnak 1980; Maloney 1979).

Molded-flake pallets.—R. A. Caughey of New Hampshire Flakeboard, Inc., Antrim, N.H., and researchers at Michigan Technological University, Houghton, Mich., have performed much development work on pallets molded from hardwood flakes (fig. 24-62). These pallets are pressed with dimpled decks (visualize a muffin tin with nine recesses) to form integral feet in such a configuration that the pallets nest for shipping. Haataja (1981) reported that Industrial Packaging Corporation, Detroit, Mich., was constructing a plant to produce about 800,000 expendable and returnable pallets per year, and other material-handling products. Service performance data on these products are not published. Haataja's (1981) study of the economic feasibility of producing molded-flake pallets is summarized in section 28-19. Koch and Caughey (1978)

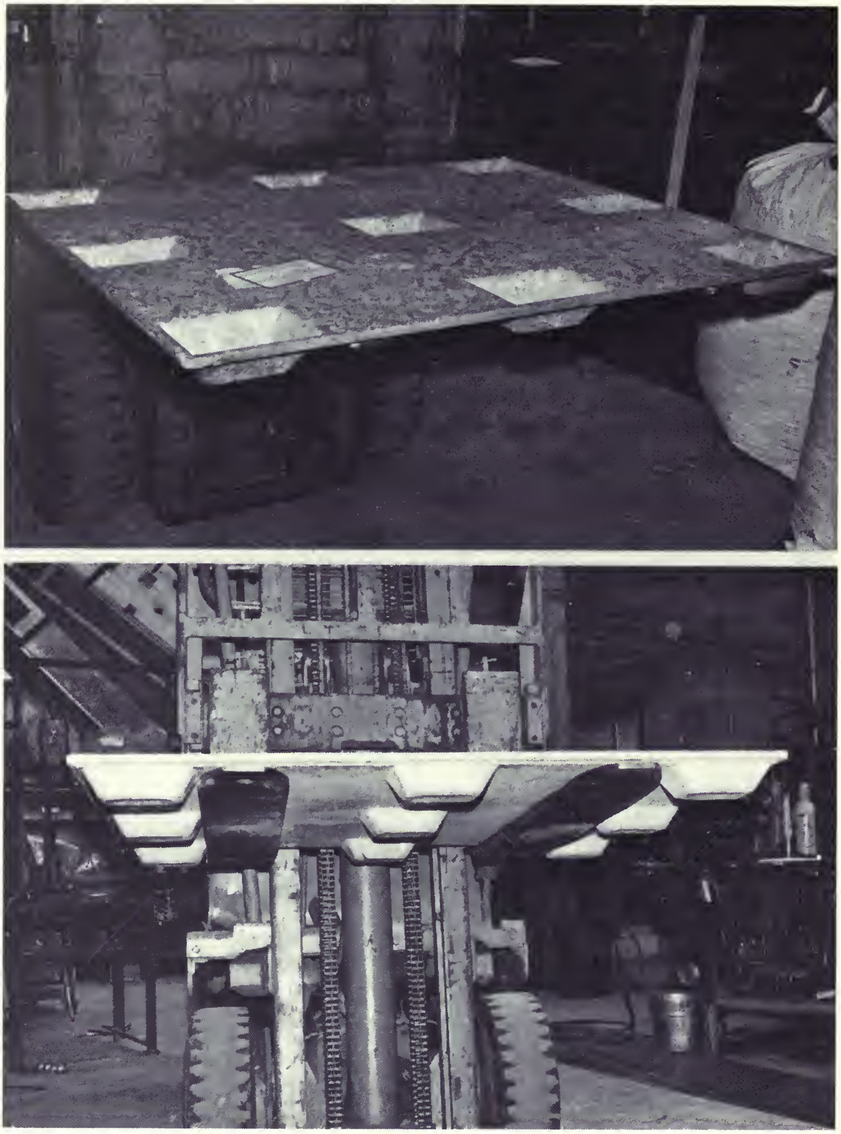

Figure 24-62.—Urea-formaldehyde bonded pallet molded from aspen flakes nominally measuring 2 inches long, and 0.020 inch thick. The pallet, which measures 40 by 48 inches, weighs 25 pounds and will nest for shipping. The pallet deck is 5/8-inch thick and feet are 1-3/4 inches high. Pallet feet with heights of 3-1/2 inches have been successfully produced in the laboratory. (Photo from Haataja 1981.)

described an operation utilizing a shaping-lathe headrig (fig. 18-104abcd) to yield solid and molded-flake hardwood products, and concluded that it should be economically feasible if molded pallets can be proven serviceable.

24-24 MOLDED PRODUCTS BONDED WITH FOAMED URETHANE

Deppe (1969) noted that particleboard made with a foamed-plastic binder can be lightweight with low hygroscopicity, and yet have high strength and excellent insulating properties. The high cost of plastic foams, such as urethane, has prohibited their use in the manufacture of flat panels, however.

Marra et al. (1975) studied the technical and economic potential of using high-density southern hardwoods comminuted into particles having a three dimensional branched shape (fig. 18-285), bonded with foamed resin to form low-density molded, as well as flat, products (fig. 24-63). By this procedure, particles are charged to a mold, binder is meter-mixed and added, and the mold is closed and compacted if necessary. The finished part is extracted 10 to 30 minutes later; no heat is required to cure the resin. Pressures of 3 to 5 psi are normally generated by expanding foam on the surfaces of the mold—greater if a large excess of resin is introduced. For most wood-foam products below 24 lb/cu ft density, a counter pressure of 10 to 20 psi is needed to obtain the necessary compaction. Higher densities require proportionately higher compaction pressure.

Figure 24-63.—Guitar case molded from hardwood particles bonded with foamed urethane. (Photo from Marra et al. 1975.)

Marra et al. found that when blended in a ratio of 50 percent southern red oak, 25 percent sweetgum, and 25 percent hickory, mats of particles were somewhat more difficult to diffuse with foaming resin than mats produced from northern red oak. Limbwood produced more particles of desired shape than stemwood. Panels made with the southern woods and urethane resin in a ratio of 2:1 had strength properties proportional to density over a range from 10 to 42 lb/cu ft; modulus of rupture was about 500 psi at a panel density of 10 lb/cu ft, and about 3,800 psi at 42 lb/cu ft.

Marra et al. found that wood particles of low moisture content yielded products of higher strength and greater stability than moist wood, as follows (wood at 70°F):

Property	Wood moisture content	
	10 percent	60 percent
Mechanical		
Modulus of elasticity, psi	175,000	100,000
Modulus of rupture, psi	1,800	800
Internal bond strength, psi	200	70
Stability during 24-hour water soak		
Thickness swell, percent	2	7
Linear expansion, percent	3	5
Weight increase, percent	17	62

Because of the high proportion of resin needed to insure formability, material costs are closely tied to the cost of resin. At costs prevailing in 1975, a board foot of panel at a density of 24 lb/cu ft required materials (wood and resin) costing about $0.23. For this reason, Marra et al. (1975) concluded that only molded products such as speaker cabinets or possibly caskets could absorb process costs. A further economic analysis of the potential was provided by Marra (1981); his conclusions are summarized in sect. 28-14.

24-25 CEMENT-BONDED BOARDS

Dinwoodie (1978) reviewed the numerous attempts to produce a particleboard bonded with portland cement. The German firm Bison-Werke Bahre & Greten GmbH. in partnership with the Swiss Durisol AG, began large-scale industrial *DURIPANEL* production in 1974 at Dietkon, Switzerland. This cement particleboard has superior dimensional stability, stiffness, fire resistance, durability, insect and fungus resistance, and resistance to freezing/thawing. Its density is about twice that of more conventional particleboard and its cost is between that of particleboard and asbestos-cement board.

In 1976 Fulgurit-Vertriebsgesellschaft mbH began large-scale production of an air classified, fine-surfaced, wood-cement particleboard in Wunstorf, Federal Republic of Germany. The wood used is all spruce (*Picea* sp.) pulpwood debarked in the forest, chipped and ring flaked, but not dried (Fraser 1977). Water, cement, and other chemicals are added and blended in a horizontal drum with agitators. Air classifying heads form a graduated mat with a superfine surface. Mats 1,300 mm wide and 3,250 mm long are placed on steel cauls and stacked in clamp-cradles closed under pressure. The clamp-cradle is then removed from the press and transported to a slightly heated curing chamber where it remains for 10 hours. The press is then employed a second time to permit removal of locking pins from the clamp-cradle. The partially cured boards are removed, trimmed to size, and further cured for 14 days at ambient temperature. Finally they are conditioned to 12 percent moisture content (Fraser 1977).

THE CEMENT-WOOD BOND[18]

Softwoods have been favored for cement-particleboards because some hardwoods inhibit bonding. Ahn and Moslemi (1980) discussed some of the bonding mechanisms involved. They observed that in a wood-portland cement-water system, various sugars such as mannose, galactose, fructose, glucose, xylose, and arabinose are present and that as wood particles dry these sugars migrate to particle surfaces where some of them inhibit cement hydration and interfere with formation of cement crystals.

Type I portland cement contains oxides of silicon, aluminum, iron, and calcium, as follows:

Compound	Proportion
	Percent
Tricalcium silicate ($3\ CaO \bullet SiO_2$)	48
Dicalcium silicate ($2\ CaO \bullet SiO_2$)	27
Tricalcium aluminate ($3\ CaO \bullet Al_2O_3$)	12
Tetracalcium aluminoferrite ($4\ CaO \bullet Al_2O_3 \bullet Fe_2O_3$)	8

Other elements comprise the balance of cement but are not essential to bond formation.

All four major components hydrate on contact with water, but at different rates. Hardened cement develops a crystalline structure that intergrows and interlocks; at contact points crystals bond to each other. Calcium chloride promotes crystal formation and bonding, while sugars adversely affect it. Some softwoods such as western hemlock (*Tsuga heterophylla* (Raf.) Sarg.) and grand fir (*Abies grandis* (Dougl. ex D. Don) Lindl.) form strong bonds when mixed with cement, while many hardwoods produce weak bonds.

To study the cement-wood bond, Ahn and Moslemi (1980) utilized grand fir and Type 1 portland cement with calcium chloride dihydrate as an accelerator and anhydrous D-glucose and sucrose as inhibitors. Modulus of rupture of cured specimens nearly quadrupled with addition of 3 percent calcium chloride, but addition of glucose or sucrose greatly reduced modulus of rupture. Trends were similar in modulus of elasticity.

[18]Text under this heading is condensed from Ahn and Moslemi (1980).

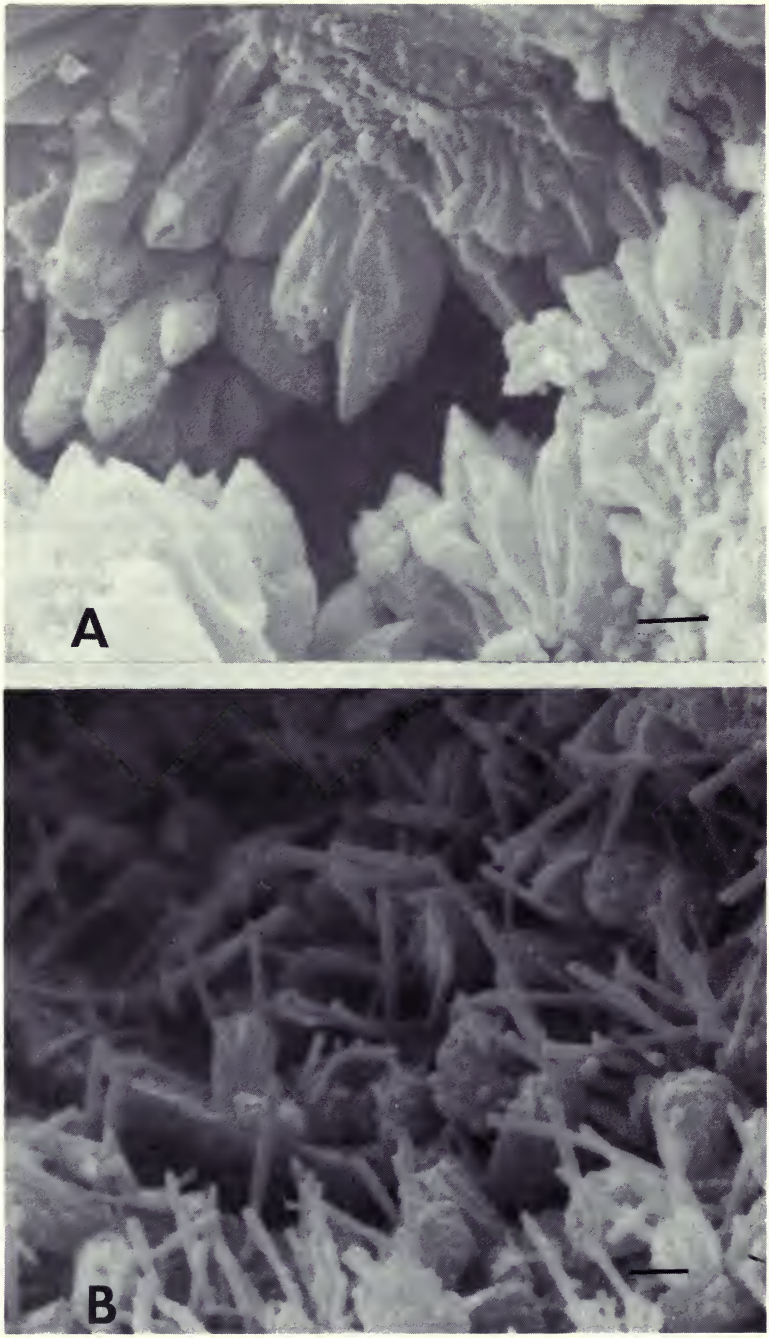

Figure 24-64.—Scanning electron micrograph of hydrated cement in cell lumens. (Top) With 3-percent calcium chloride added. (Bottom) With no additives. Scale mark shows 1 micrometer. (Photos from Ahn and Moslemi 1980.)

Crystals formed in cement with no additives were needle-like and crisscrossed (fig. 24-64 bottom). Addition of calcium chloride caused crystals to be better defined and more conical in shape (fig. 24-64 top).

Ahn and Moslemi (1980) concluded that the crystals interlock with wood surfaces within cell lumens and elsewhere, and that when crystals butt against wood they tend to grow into whatever cavities are present; if they abutt a flat location they form flat ends (fig. 24-65).

They found that addition of 0.5 percent sucrose interfered with hydration and virtually prevented crystal formation (fig. 24-66 top). Addition of glucose caused formation of a cloth-like mass of thin long fibers that contribute little to strength development (fig. 24-66 bottom).

DATA SPECIFIC TO SOUTHERN HARDWOODS

Moslemi et al.[19] used a wood-to-cement ratio of 15:200 (by weight) to screen trees of the following southern species harvested from among southern pines: sweetgum, white oak, hickory sp., southern red oak, post oak, yellow-poplar, black tupelo, water oak, chestnut oak, black oak, scarlet oak, and red maple.

Cement (200 g) and 20-40 mesh wood (15 g ovendry weight) were dry-mixed in a polystyrene cup. To this dry mix, 91 ml of distilled water was added and kneaded for 5 minutes. The wood-cement mixture was placed into a 1-pt Dewar flask, iron-constantan thermocouple wires were inserted through a cork into the mixture, the flask sealed, and hydration temperature measured. The time to obtain maximum temperature of hydration was considered as the required setting time of the mixture. Four replications for each species of wood-cement mixture were made, each representing a blend of breast-height samples from four trees (6 inches dbh) of each species. Hydration temperature (TE), time to reach maximum temperature rise (T_2), and slope of the time-temperature curve were considered indicators of inhibitory characteristics of each species. To reduce inhibition to set, matched specimens were boiled (treated) in distilled water for 6 hours; at 2, 3, 4, and twice at 6 hours, these wood particles were washed with boiling distilled water, and then collected and dried for evaluation as described above.

[19]Moslemi, A., Y. Lim, and A. D. Hofstrand. 1982. Propensity of wood and bark from twelve southern hardwoods to inhibit setting of wood, portland-cement, and water systems. South. For. Exp. Stn., U.S. Dep. Agric., For. Serv., Fin. Rep. FS-SO-3201-26, dated February 26, 1982. (Also, manuscript in preparation.)

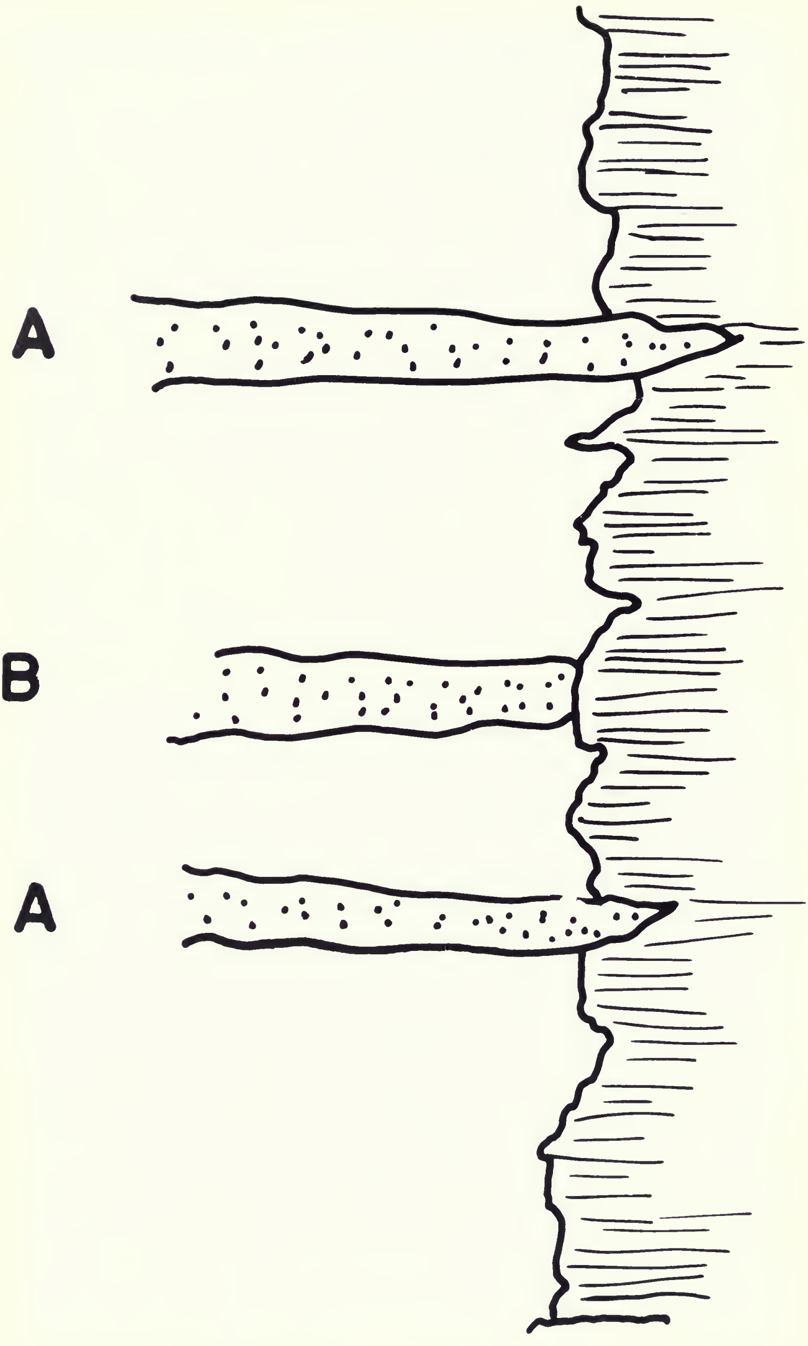

Figure 24-65.—Schematic drawing illustrating mechanical interlocking of wood and cement crystals at locations (A); at location (B) crystals form flat ends where no cavity is present. (Drawing after Ahn and Moslemi 1980.)

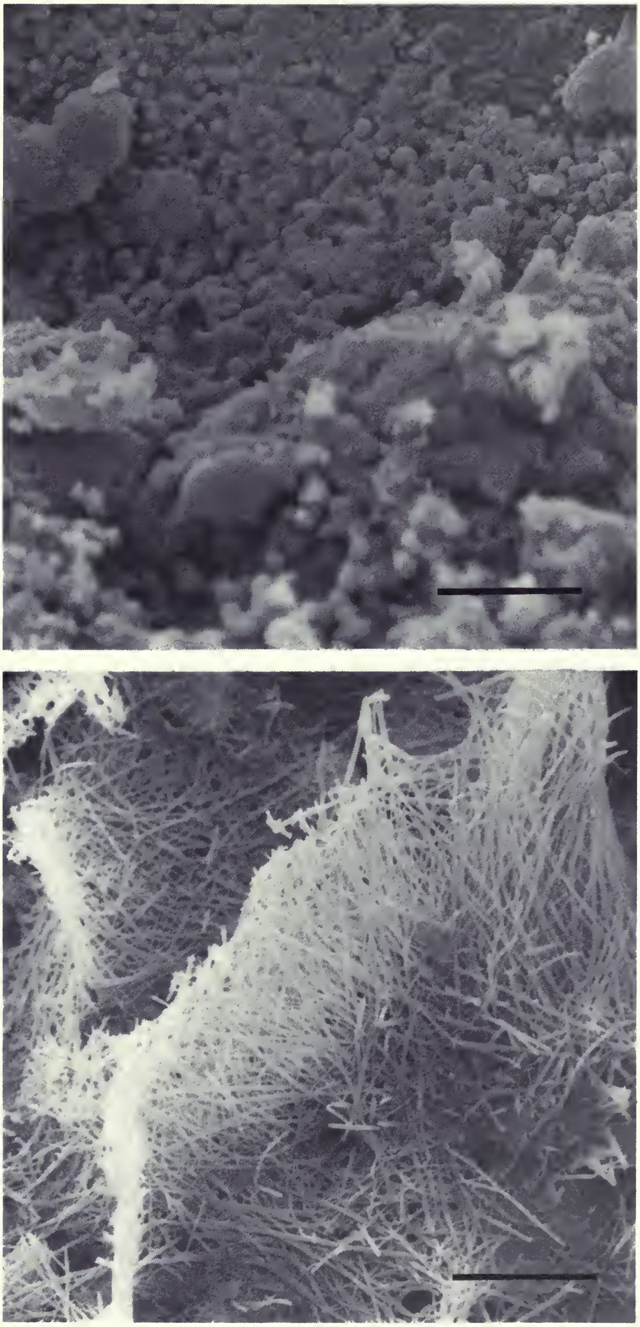

Figure 24-66.—Scanning electron micrographs of hydrated portland cement in a cell lumen with inhibitor added. (Top) With 0.5 percent sucrose added. (Bottom) With 0.5 percent D-glucose added. Scale mark shows 10 micrometers. (Photo from Ahn and Moslemi 1980.)

Neat cement (no wood) and water has TE of about 65° and T_2 of about 7 minutes. Without treatment, only chestnut oak seemed suitable for wood-cement board; with treatment an additional eight species might be used (black, southern red, scarlet, post, water, and white oaks plus red maple and black tupelo. Results are summarized as follows (fig. 24-67):

Treatment and species	T_2	TE
	Hours	*°C*
Untreated		
Chestnut oak	11.25	59.8
Yellow-poplar	12.00	36.1
Sweetgum	21.75	33.3
Water oak	22.00	51.8
Black tupelo	22.75	47.4
White oak	23.25	53.4
Hickory	24.25	25.8
Post oak	26.00	51.8
Black oak	27.75	51.3
Scarlet oak	30.75	47.6
Southern red oak	31.75	47.4
Red maple	44.25	48.4
Treated		
Hickory	8.00	49.7
Sweetgum	8.00	43.7
Yellow-poplar	8.66	43.0
Black tupelo	9.00	53.0
Scarlet oak	9.00	51.3
Southern red oak	9.00	54.7
Red maple	9.33	52.4
Water oak	10.00	54.7
Chestnut oak	10.00	60.8
Post oak	10.00	57.7
Black oak	10.33	56.0
White oak	10.33	57.2

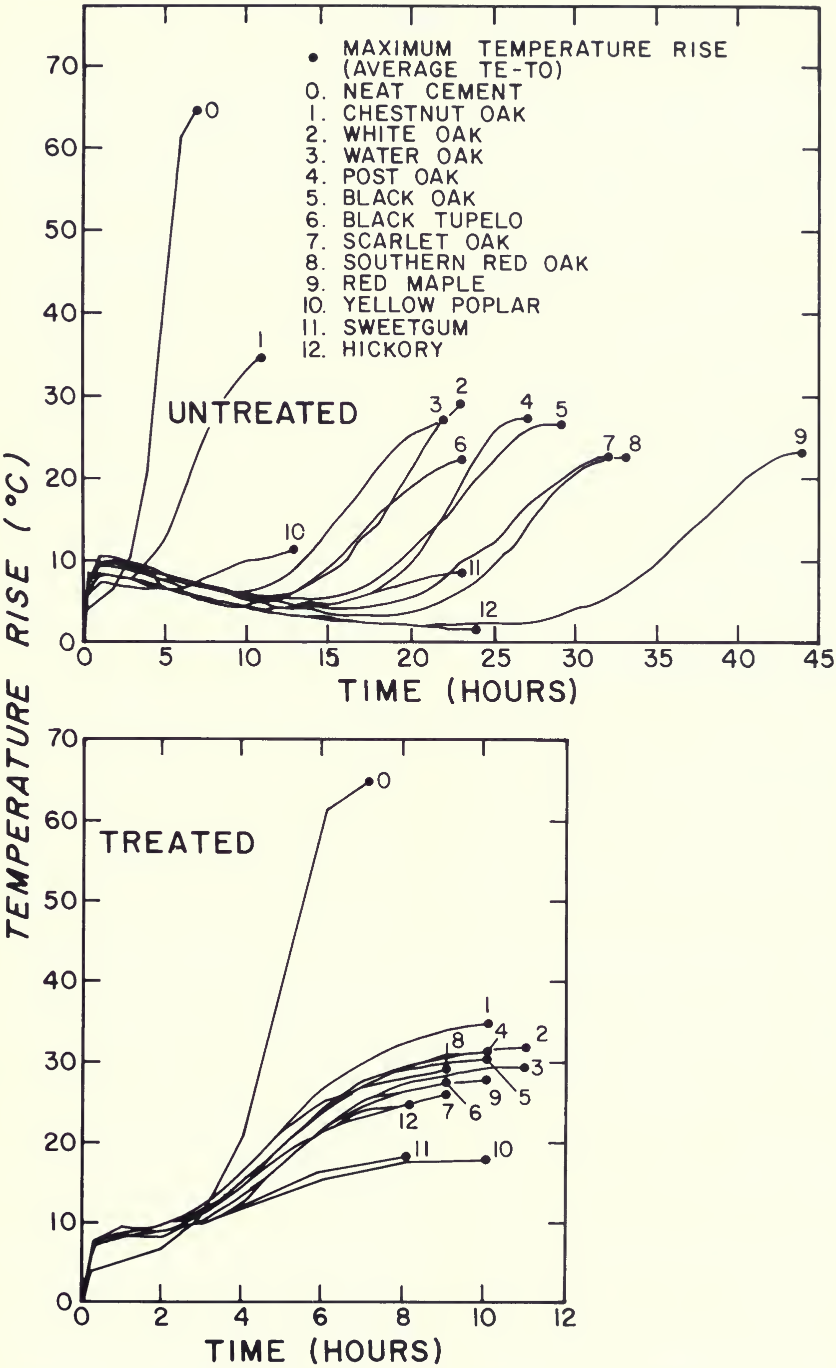

Figure 24-67.—Effect of species on the hydration of portland-cement, wood, water mixtures. Maximum temperature rise = hydration temperature (TE) minus initial temperature (TO). (Top) Untreated wood. (Bottom) Wood boiled and washed 6 hours in distilled water. (Drawings after Moslemi et al., text footnote[19].)

24-26 ECONOMIC FEASIBILITY STUDIES

Rapidly changing costs make economic analyses of only short-term value, but the economic feasibility studies listed below will give interested readers an introduction to the many investment opportunities in manufacture of structural flakeboards and composites from southern hardwoods; those with asterisk are summarized in chapter 28:

Products and references	See section
Flakeboard sheathing	
Koch (1978ab*cd; 1982)	28-27, 28-31
Harpole (1978; 1979)	
Vajda (1978b)	
Springate and Roubicek (1981b)*	28-25
Anderson (1981)*	28-32
Thick roof decking	
Hoover et al. (1979)	
Hoover et al. (1981)*	28-29
Thin flakeboards	
Briggs (1981)*	28-23
Springate and Roubicek (1981a)*	28-24
Composite panels with veneer faces over flake cores	
Roubicek and Koch (1981)*	28-26
Fabricated joists with thin flakeboard webs	
Woodson (1981)*	28-21
Koch (1982)*	28-31
COM-PLY lumber	
Koenigshof (1981)*	28-28
Molded-flake pallets	
Koch and Caughey (1978)	
Haataja (1981)*	28-19
Molded products bonded with foamed urethane	
Marra (1981)*	28-19

The demand for structural flakeboards and composites has been studied extensively. Figure 24-1 and table 24-1 describe plant locations and capacities. Figure 29-14 graphs growth of the softwood plywood industry, with which structural hardwood flakeboard will compete. Readers needing further information on the subject should find the following references useful:

Reference	Subject
Guss (1975)	Determinants of particleboard demand.
Wilson (1975)	Outlook for particleboard to 1980.
Dickerhoof (1976)	Production, markets, and raw material in the United States.
Dickerhoof and Marcin (1978)	Factors affecting market potential for structural flakeboard.
Daar (1978)	Export market for lumber and panel products from the South.
Dickerhoof and McKeever (1979)	Board plants in the United States—capacity, production, and raw material trends, 1956-1976.
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25

Pulp and Paper

Information on demand and trends contained in section 25-1 is principally from U.S. Department of Agriculture, Forest Service (1980), papers by R. H. Reeves, and graphs from R. P. Whitney and the American Paper Institute. In section 25-2, definitions of paper types are from the American Paper Institute. Subsections on trends in mechanical and semichemical pulp production, neutral sulfite semichemical pulping, and green liquor semichemical pulping (in sec. 25-6) are condensed from a review by J. W. McGovern and R. J. Auchter. Section 25-7 on chemical pulping is from a review by H. A. Schroeder; B. K. Mayer provided the description of a kraft chemical recovery furnace.

Other major portions of data were drawn from research and reviews by:

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CHAPTER 25

Pulp and Paper

CONTENTS

CHAPTER 25

Pulp and Paper

Pulp, i.e., fibers separated by mechanical or chemical methods from vegetable material (usually wood) can be formed, usually with the aid of water, into cohesive sheets of **paper.**

The technology of pulp and paper manufacture is complex, the products diverse, and the literature describing processes and products very extensive. This chapter involves only a brief overview, emphasizing products from hardwoods. Readers needing more information are directed to the following references.

Reference	Title
Casey (1980)	Pulp and paper chemistry and chemical technology
Clark (1978)	Pulp technology and treatment for paper
Weiner and Pollock (1972)	Constitution and pulping of hardwoods (a bibliography)
Britt (1970)	Handbook of pulp and paper technology
Rydholm (1970)	Continuous pulping processes
Macdonald and Franklin (1969)	Pulp and paper manufacture (three volumes)
Weiner and Roth (1967)	Constitution and pulping of hardwoods (a bibliography)
Wenzl (1967)	Kraft pulping theory and practice
Gavelin (1966)	Science and technology of mechanical pulp manufacture
Rydholm (1965)	Pulping processes
Wenzl (1965)	Sulphite pulping technology
Forman and Niemeyer (1946)	Kraft pulping of southern hardwoods

Aspects of pulp and paper manufacture are discussed elsewhere in this text, as follows:

Subject	Reference
Storage of roundwood and chips	Sect. 11-6
Storing of paper	Sect. 16-20
Debarking pulpwood	Chapter 17
Chipping	Sect. 18-24
Mechanical defibration	Sect. 18-27 and 23-6

25-1 SIZE AND SCOPE OF THE INDUSTRY

Most of the pine-site hardwood used as industrial raw material during the 21st Century will likely be fabricated into solid wood products such as pallets, crossties, and furniture; panel products such as structural flakeboard and fiberboard; energy related products such as solid, liquid, or gaseous fuels; and into pulp and paper. Use for pulp and paper will probably dominate (fig. 2-2).

The pulp and paper industry originated with simple manual equipment designed to form single paper sheets; such small-scale operations are still producing specialty papers (Brandis 1978; Paper 1978). In some countries, such as India, small paper mills producing less than 30 tons per day are commercially viable (Western 1979). In the southern United States, however, both pulp mills and paper mills are very large; these pulp mills have average output of more than 800 tons per day and paper mills average perhaps 600 tons per day, airdry basis.

The size and scope of the southern pulp and paper industry, and prospects for its use of hardwood pulpwood, can be assessed by studying national demand for pulp and paper.

NATIONAL DEMAND[1]

Pulpwood consumption in domestic mills has increased thirteenfold since 1920, rising from 6.1 million cords to 78.6 million cords in 1978. As a result of such growth, about half of the cubic volume of timber harvested from domestic forests is used for pulpwood. Annual consumption of paper and paperboard (not including insulating board and fiberboard which are discussed in chapter 23) increased from about 8 million tons in 1920 to about 67 million tons in 1978. Per capita annual consumption of paper and paperboard rose about 420 percent between 1920 and 1978, increasing from 145 pounds to about 611 pounds in 1978. (For trend charts of the industry see figs. 29-5ABC and 29-10AB, as well as figs. 25-1 through 25-8.)

Since 1920, average consumption of pulpwood to produce a ton of pulp has not changed greatly, averaging about 1.6 cords/ton of ovendry pulp; values of 1.5 and 1.4 are projected for the year 2000 and 2030, respectively. These reduced wood requirements per ton of pulp are expected because of technological advances in high-yield pulping and because of increased use of hardwoods, which are denser than the softwoods traditionally used.

[1]Condensed from U.S. Department of Agriculture, Forest Service (1980).

There were 331 pulp mills in the United States in 1972; this included 60 mills that produced market pulp and 271 mills integrated with paper and paperboard mills. Employment was 161 thousand people, or 25 percent of total employment in the primary wood processing industry.

PULP AND PAPER INDUSTRY IN THE SOUTHERN UNITED STATES[2]

The South's share of national pulp production increased from about 17 percent in 1930 to about 65 percent in 1978. A similar growth appeared in paper manufacture, where the southern industry's share rose from 8 percent in 1930 to over 50 percent in 1978. Pulp mills in the southern pine region have, since the late 1930's, dominated kraft pulp production and in recent years have accounted for more than 80 percent of the kraft pulp in the United States (roughly 45 percent of world production). The major growth in the South during these years was in unbleached pulp used for papers and paperboard.

In 1933 there was no white paper made in the South, although Dr. C. H. Herty had demonstrated that southern pine was suitable for making quality newsprint. After development of chlorine dioxide multi-stage bleaching of southern pine in the 1940's, and in response to demand for white papers throughout the country, production of bleached pulps rose dramatically in the south. By 1978, the southern mills were producing about 70 percent of the bleached hardwood and softwood kraft pulps produced in the United States.

By 1978 there were 122 pulp mills in the 12 Southern States producing, in aggregate, approximately 100,000 tons/day. (See fig. 25-1 for locations and capacities of major mills.) Most of this production was for use in the 185 paper and paperboard mills in the region at that time. About 90 percent of total southern pulp production is used in integrated (captive) operations, with the remainder for sale on the open market. In 1978, the South provided about 60 percent of the pulp consumed by the domestic market (mostly bleached kraft) and nearly 80 percent of U.S. export pulp tonnage.

The paper and paperboard mills of the South comprise only 28 percent of the number of mills, but account for more than half the Nation's total production. The average annual production of a southern mill was 192,000 tons in 1978—compared to a nation-wide average of 106,000 tons.

Similarly, southern pulp mills comprised 44 percent of the total number of mills in the United States in 1978, but produced more than 65 percent of the pulp. Average annual pulp production per southern mill was 295,000 tons, compared to a national average of 200,000 tons.

In 1978 the South produced about 52 percent of the newsprint, 20 percent of the tissue, 30 percent of the printing and writing papers, 90 percent of the bleached foodboard, and most of the bleached bag and wrapping papers made in the United States. Moreover, most of the pulp exported from the United States consists of bleached kraft hardwood and softwood pulp from the South.

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[2]Text under this heading is condensed from Reeves (1979a).

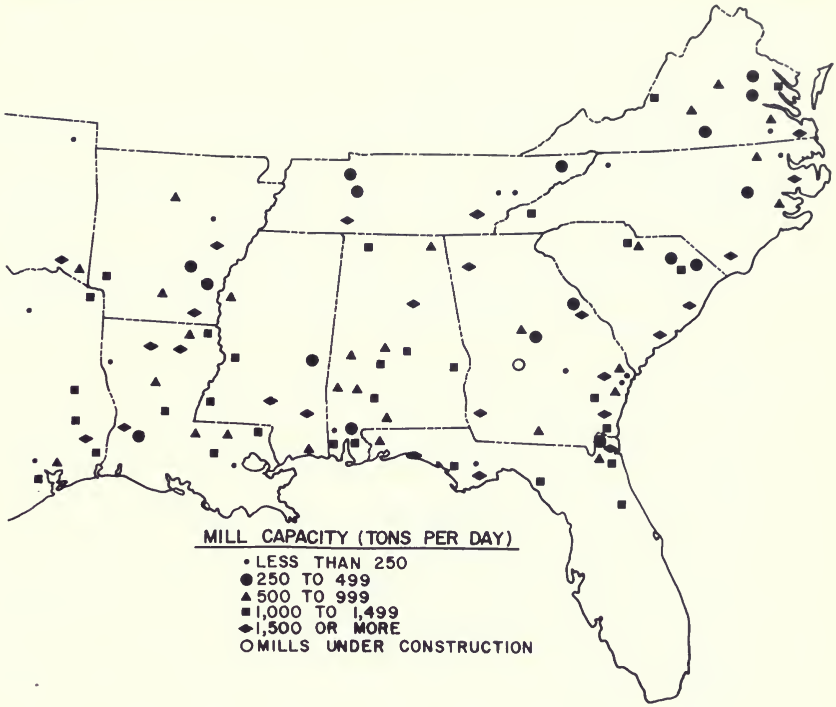

Figure 25-1.—Locations and capacities of 116 southern pulp mills. (Drawing after Bellamy and Hutchins 1981).

Reeves (1979a) concluded his discussion of the dominance of southern mills by observing that "all types of printing and writing grades of paper are now made in southern, as well as northern mills. In every case, where volume is large for a particular grade of paper, it is certain that a mill in the South manufactures it, or soon will. This has been a general trend for the past 30 years and is likely to continue, as the South has the available wood supply, the fiber and processing technology, and the modern high-speed machines to make virtually any qualities of paper."

THE PROSPECT FOR HARDWOOD PULPS[3]

Hardwood pulps are most frequently used in white papers, that is, in printing paper, writing paper, and in tissues. Reeves (1979b) noted that for these products, use of hardwood pulps is virtually essential to provide the properties needed at an acceptable cost. Use of hardwood pulps is increasing faster than that of softwod or non-wood fibers, because of the great demand for white papers occasioned by increased populations and increased information exchange.

[3]Text under this heading is condensed from Reeves (1979b).

Reeves (1979b) enumerated several reasons for using hardwood pulps in papermaking:

- The hardwood is readily available.
- Use of hardwoods will improve resource utilization and facilitate good silvicultural practices.
- Hardwoods are generally denser than softwoods, so more weight of hardwood than softwood can be charged in digesters.
- Lignin in hardwoods is easier to digest than softwood lignin and hardwoods generally give higher pulp yields than softwoods; this permits more throughput with improved yield and less expenditure of energy and chemicals.
- Hardwood pulpwood costs less than softwood pulpwood.
- Many paper properties are improved by the addition of substantial amounts of short, fine hardwood fibers. Hardwood fibers generally contribute to improved formation, opacity, and surface properties of a sheet. Since the fibers do not require extensive refining to obtain uniform dispersions, the hardwood pulps have a beneficial effect on papers (e.g., tissue products) requiring bulk, softness, and absorbancy. Papers containing appreciable amounts of hardwood pulps also are more stable and curl less with moisture changes. Although hardwood fibers are not as strong as softwood fibers, these positive contributions of hardwood pulps to paper properties have made them essential to many grades of paper.

Reeves (1979b) noted that offsetting these advantages are some disadvantages. Hardwoods are more difficult to debark (see chapter 17), and the amount of bark available for fuel is thereby reduced. This disadvantage is negated to some degree because barks of many southern hardwoods have a significant fiber content (table 13-48). Hardwoods, being denser than softwoods, require more power to chip. Southern pine has a significant content of resin, which yields turpentine and rosin. Hardwoods, however, contain fatty resins in lesser amounts than the resin in pine, and these fatty resins do not yield turpentine and rosin; byproducts from hardwood kraft pulping are therefore less valuable than those from southern pine.

Hardwoods, but not softwoods, contain a substantial proportion of vessel elements (table 5-3). These short, wide, and thin-walled elements (figs. 5-52 bottom and 5-99 with related discussion) bond less well than fibers in the paper sheet and have a tendency to be picked off the surface as viscous, tacky printing inks split between the paper and applicator surfaces. This tendency varies with species; white oak vessels are particularly subject to picking. Use of starch or other adhesives applied at a size press can completely control picking, and any procedure which improves internal bonding in a sheet tends to improve picking resistance (Reeves 1979b). Thus gyratory refining of oak pulps reduces their picking tendency (Byrd and Fahey 1969). Most manufacturers of fine paper, especially papers for offset printing, use a variety of hardwood pulps with no apparent difficulty.

Some properties of typical pulps made from southern hardwoods are given in table 25-1. The lower strength of hardwood pulps has traditionally limited their use in papers where high strength is the primary requirement. For the majority of white papers, however, hardwood pulps offer special properties—particularly when they are optimally blended with softwood fibers and non-fibrous additives during papermaking. Recent developments in press drying hardwood pulps (Setterholm 1979) will likely increase the use of hardwood kraft pulps for linerboard (see section 25-4).

Table 25-2 lists some paper grades and the percentages of hardwood pulps used in them, as produced in southern paper mills.

TABLE 25-1.—*Some properties of hardwood pulps at three freeness values*[1] (Reeves 1979b)

Property	Freeness, °SR[2]		
	15[3]	25	40
Tear factor	—	100	91
Burst factor	—	32	46
Breaking length	—	5,400	7,200
Fold	—	80	250
Bulk	2.14	1.68	1.55
Opacity	78.5	74.7	70.1

[1]Data based on 51 samples of pulps from 17 southern mills in the United States.
[2]Schopper-Riegler (°SR).
[3]Unbeaten.

TABLE 25-2.—*Percentages of hardwoods typically used by southern paper mills in 17 grades of white papers* (Reeves 1979b)

Paper grade	Hardwood content
	Percent
Bond	40-95
Continuous stationery	40-75
Ledger	60-85
Tissue, facial	35-60
Tissue, sanitary	25-70
Light weight coated	20-50
Offset, uncoated	50-70
Offset, coated	40-70
Litho, coated one site	40-70
Litho, cast coated	25-50
Publication, mechanical	50-65
Envelope	50-75
Tablet	40-70
Milk container	25-40
Tag	30-55
Glassine	10-40
Cover, coated	50-80

In recent years, use of hardwood for pulp and paper increased 2.5 times as fast as that of softwood. In 1978 about 25 percent of the pulpwood used by southern pulpmills was hardwood; this hardwood pulpwood yielded more than 25 percent of pulp production because hardwood yields more pulp than softwood in full chemical processes and also hardwoods are more used than softwoods in high-yield pulping processes.

TRENDS

Consumption of hardwood pulpwood.—Hart (1980), discussing the potential for expanded use of hardwoods for pulp and paper, noted that usage of hardwood pulpwood in eastern mills of the United States increased 6-fold (6.6 percent annual rate) between 1950 and 1978, compared to a less than three-fold increase (4.2 percent annual rate) for softwood (table 25-3). Since 1970, the increase in hardwood usage has slowed, however.

Major users of hardwood pulpwood in the United States are mills making bleached and unbleached sulfate pulp, and semichemical pulp (table 25-4). Only mills producing groundwood pulps used less hardwood in 1977 than in 1963. Application of press drying (Setterholm 1979) could significantly accelerate usage of hardwood pulps made by the kraft process for use in linerboards; the press drying process significantly increases strength and stiffness of hardwood pulps (see section 25-4).

TABLE 25-3.—*Hardwood and softwood annual pulpwood consumption for the eastern United States, 1950-1978* (Hart 1980)[1]

Year	Total	Hardwoods		Softwoods	
	......*Million cords*......		*Percent*	*Million cords*	*Percent*
1950	19.8	3.2	16	16.6	84
1955	26.9	5.5	20	21.4	80
1960	32.5	8.0	25	24.5	75
1965	40.4	11.8	29	28.6	71
1970	52.7	15.6	30	37.1	70
1975	53.3	15.6	29	37.7	71
1978	62.8	19.4	31	43.4	69

[1]Based on data from the American Paper Institute.

TABLE 25-4.—*Hardwood pulpwood usage in 1963 and 1977 in the entire United States according to pulping process* (Hart 1980)[1]

Pulping process	1963		1977	
	Million cords	*Percent*	*Million cords*	*Percent*
Bleached sulfate	3.3	31	8.3	45
Unbleached sulfate	1.3	12	2.7	15
Bleached sulfite	1.2	11	1.6	9
Semichemical	2.4	21	3.4	17
Groundwood	.6	6	.5	3
Other[2]	2.0	19	2.0	11
Total	10.8	100	18.5	100

[1]Data based on U.S. Department of Commerce, Current Industrial Reports.
[2]Includes dissolving and special alpha pulps, unbleached sulfite pulps, and defibrated or exploded pulps.

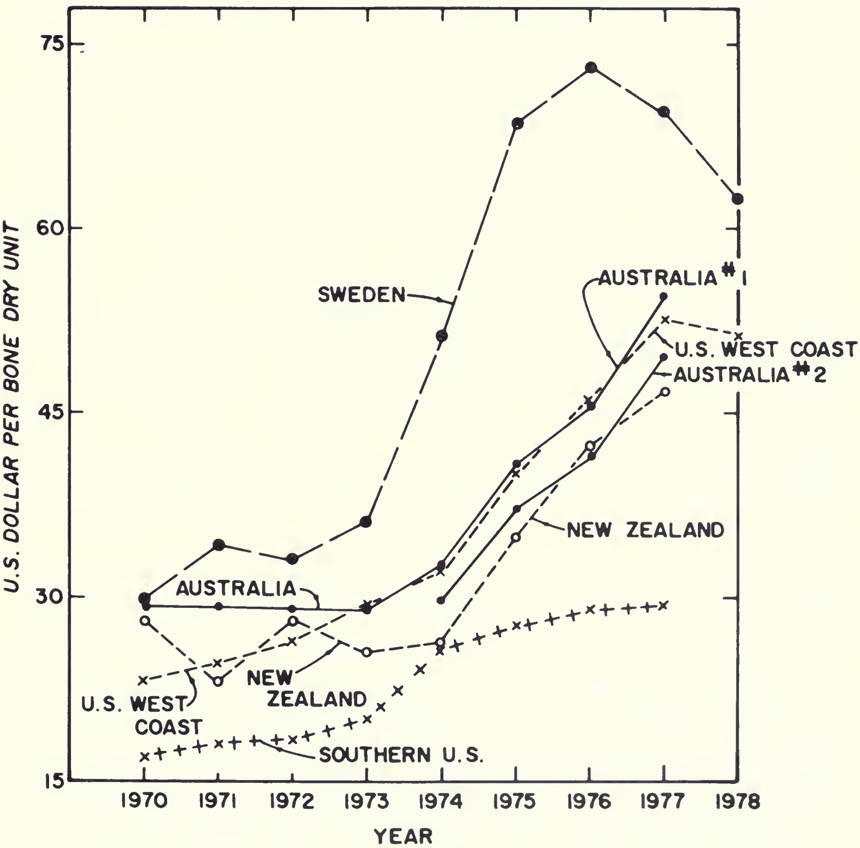

Figure 25-2.—Trends of wood chip prices for the export markets of Australia, New Zealand, and the United States West Coast; and the domestic markets of Sweden and the southern United States. A "bone dry unit" of chips contains 2,400 pounds of moisture-free fiber. Data for the southern United States is for softwood chips FOB railcar at sawmill. The export chips from the U.S. West Coast contain both softwoods and hardwoods, those from Australia are *Eucalyptus* sp., those from New Zealand are mostly softwood, with perhaps 10 percent native hardwoods, and those from Sweden are softwood and hardwood. (Drawing after Overgaard 1978.)

Pulp chip prices.—On the world market, prices of pulp chips for export increased significantly during the 1970's (fig. 25-2). Overgaard (1978) found that with the Japanese pulp and paper industry as the buyer, the value of exported chips from Australia, New Zealand, and the U.S. West Coast were similar. Price trends for the domestic markets of Sweden and the southern part of the U.S. differed markedly. Swedish prices in 1977 were more than double those of the southern United States, and have more than doubled every 3 years. During this same period pulp chip prices in the southern United States increased only 45 percent (fig. 25-2).

In the southern United States, prices for pulp chips and pulpwood have increased slowly but steadily in response to inflation (fig. 25-2); hardwood, however, has consistently cost less than southern pine.

Data from V. A. Rudis of the southern Forest Experiment Station and C. C. Hutchins, Jr. of the Southeastern Forest Experiment Station, U.S. Department of Agriculture, Forest Service, indicate that prices for cordwood and residue chips delivered to southern pulp mills (or fob rail siding) rose sharply in 1979 and continued to rise in 1980, as follows:

Year	Roundwood		Chipped residues	
	Hardwood	Softwood	Hardwood	Softwood
	---Dollars/standard cord ---		*------Dollars/green ton-------*	
MID-SOUTH STATES				
1970	16.94	18.81	6.69	7.13
1971	17.34	19.12	6.70	7.63
1972	18.56	20.80	7.18	7.79
1973	21.32	23.84	8.44	8.50
1974	25.32	28.24	9.73	11.12
1975	25.71	28.71	10.04	11.76
1976	26.50	29.76	10.21	12.39
1977	28.10	31.42	10.93	13.46
1978	30.35	33.15	12.28	14.66
1979	33.92	40.09	15.02	18.37
1980	36.69	43.31	15.69	21.08
SOUTHEASTERN STATES				
1977	26.55	34.65	11.55	15.25
1978	28.15	36.25	12.00	15.90
1979	30.40	40.65	13.05	17.15
1980	32.90	43.90	15.00	19.80

Hart (1980) noted that historically hardwood and softwood prices differ widely, for both standing timber and wood delivered to the mill; this difference, and the typical higher yield of pulp from hardwoods make wood costs per ton of pulpwood significantly less for hardwood than for softwood (table 25-5). Softwood delivered costs of $38 per cord and hardwood delivered costs of $30 per cord, are equivalent to wood costs of $68.40 and $42.00 per bone-dry ton of pulp, respectively—a $26.40 per ton advantage for hardwood. If the softwood price goes to $44 per cord, a typical situation in many parts of the South in 1980, the cost advantage is $37.20 per ton of pulp—a major incentive for hardwood utilization (Hart 1980).

Pulping processes.—In the United States, the number of mills producing sulfate (kraft), semichemical, and defibrated/exploded pulps have increased significantly, while the number producing sulfite, groundwood, and soda pulps have decreased (fig. 25-3).

Total U.S. annual capacity for pulp production increased in all categories, except sulfite pulp, between 1960 and 1974; the major increase was in capacity to manufacture sulfate (kraft) pulps (figs. 25-4 and 25-5).

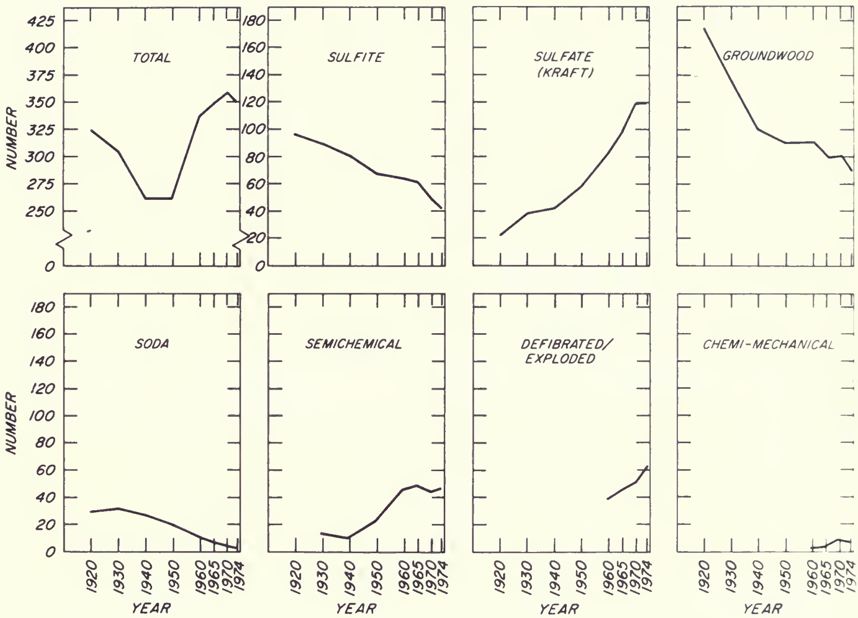

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Figure 25-3.—Number of woodpulp mills in the United States, by type, 1920-1974. (Drawing after McKeever 1977.)

Demand for paper and paperboard.—Whitney (1980) provided (fig. 25-6) a breakdown of paper production into its three principal categories of construction paper and board (i.e., roofing felts and insulation boards), paper, and paper board; see section 25-2 for the components of the latter two categories.

Paper production is comprised principally of tissue, packaging, and industrial papers, and printing and writing papers (fig. 25-7). The latter is the fastest growing segment, making up about two-thirds of paper production. The dashed line at the top of figure 25-7 shows paper consumption, which runs about 7 million tons higher than production. Most of this difference represents imports from Canada, which supplies about two-thirds of United States newsprint requirements (Whitney 1980).

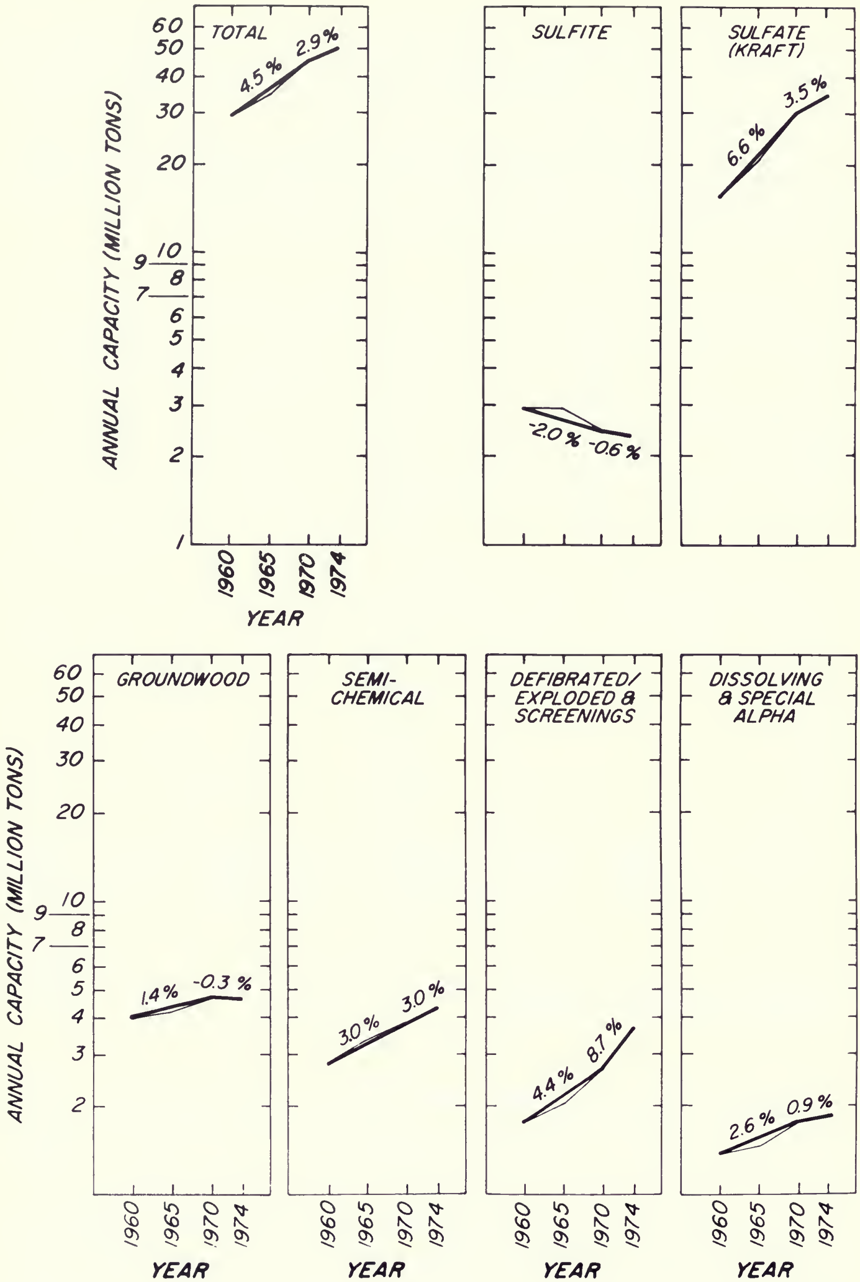

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Figure 25-4.—Growth trends (heavy lines) in annual capacity of woodpulp mills in the United States, by type, 1960-1970 and 1970-1974. The light lines indicate actual data points. (Drawing after McKeever 1977.)

TABLE 25-5.—*Stumpage costs and FOB mill costs for hardwood and softwood pulpwood related to wood cost per bone-dry ton of pulp* (Hart 1980)[1]

Species and statistic	Pulpwood stumpage	Pulpwood FOB mill
	...........*Dollars*..........	
Hardwood		
$/cord	3.00	30.00
$/bone-dry ton of pulp........................	4.20	42.00
Softwood in lower-cost area		
$/cord	12.00	38.00
$/bone-dry ton of pulp........................	21.60	68.40
Softwood in higher-cost area		
$/cord	18.00	44.00
$/bone-dry ton of pulp........................	32.40	79.20

[1]Assumed wood usage per bone-dry ton of pulp: hardwood 1.4 cords; softwood 1.8 cords.

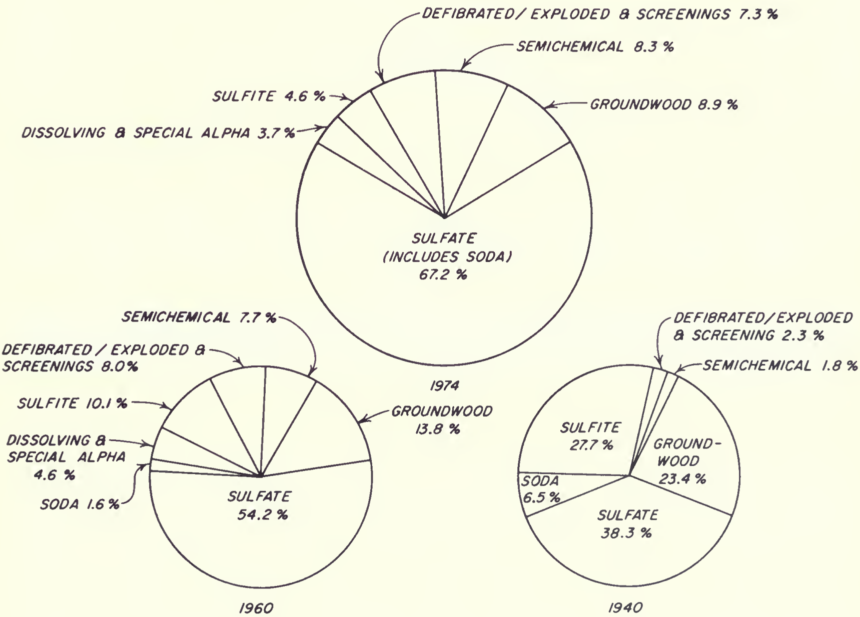

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Figure 25-5.—Percentage of annual capacity of woodpulp mills in the United States, by type, 1974, 1960, 1940. (Drawing after McKeever 1977.)

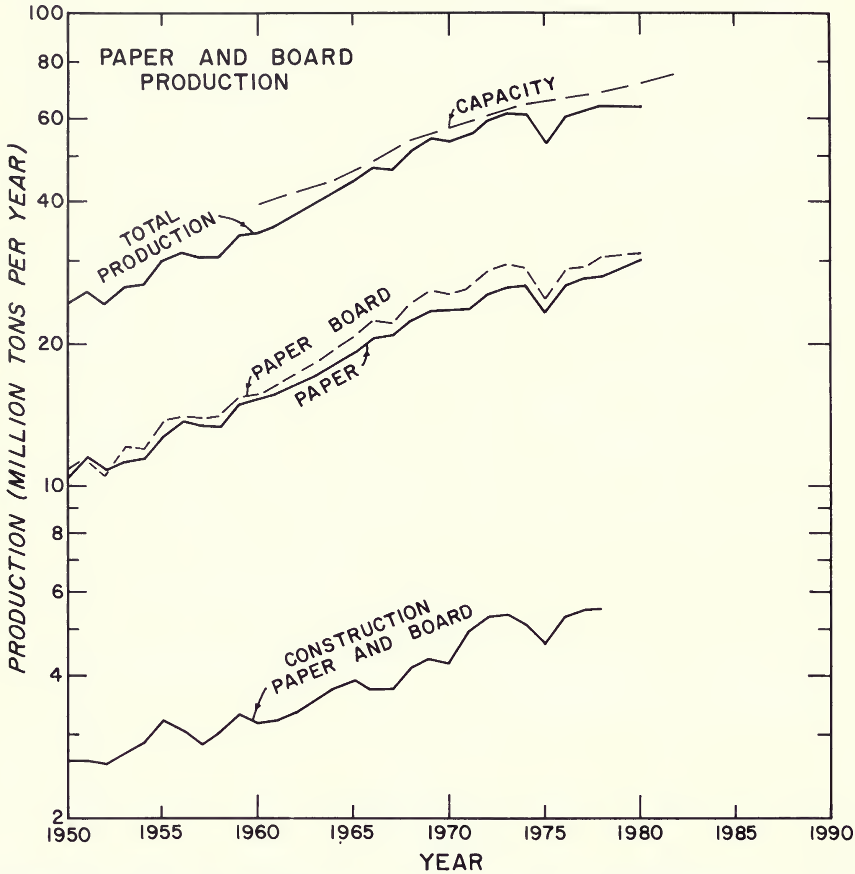

Figure 25-6.—Production of paper, paperboard, and construction paper and board in the United States, 1950-1978. (Drawing after Whitney 1980; data from the American Paper Institute.)

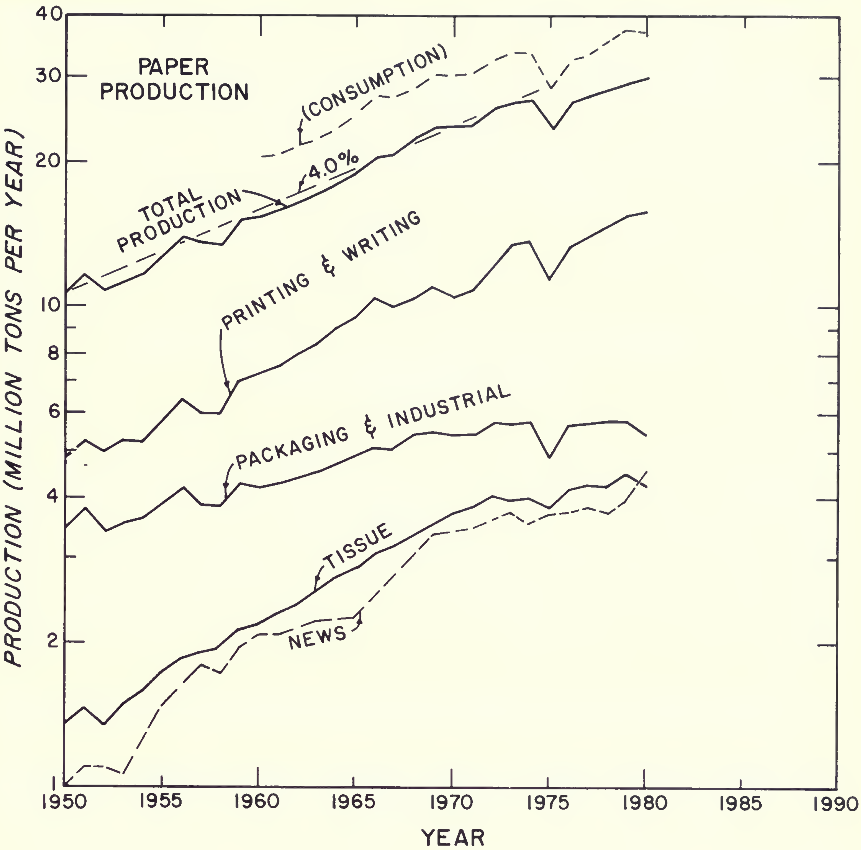

Figure 25-7.—Paper production in the United States, 1950-1980, by category, and total consumption 1960-1980. (Drawing after Whitney 1980; data from the American Paper Institute.)

Paperboard production (fig. 25-8) is dominated by unbleached kraft board, which mostly goes into the linerboard of corrugated boxes. Production of **combination** furnish (now called recycled board), a paperboard made largely from recycled fiber, remained more or less stable in the 1960's and 1970's. Semichemical board goes principally into corrugating medium, and bleached grades are used mostly in food packaging. The dashed line at the top of figure 25-8 indicates that the United States is a net exporter of paperboard, the principal grade being linerboard. Whitney (1980) concluded that the corrugated container is the principal product of the paperboard industry.

Hagemeyer (1980), in assessing world markets for paper, concluded that the growth rate for total consumption of paper is moderating and that the annual compound growth during the 1980's may be about 3.6 percent for paper and 4.5

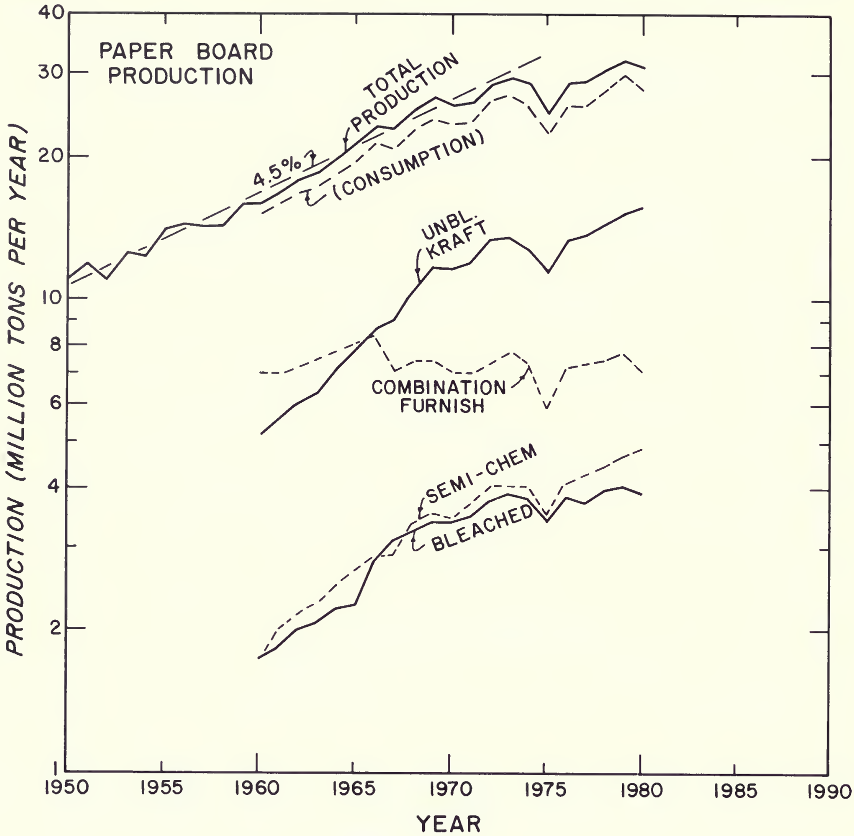

Figure 25-8.—Paperboard production in the United States, 1950-1980, by category. Combination furnish is sometimes termed "recycled". (Drawing after Whitney 1980; data from the American Paper Institute.)

percent for paperboard. He suggested that world consumption of printing and writing paper, which includes coated papers, will grow at a faster rate than that for total paper and paperboard consumption.

The future of printed magazines in a world that increasingly uses radio, television, and computers for information transfer, has been questioned by some. Gardner (1980), however, concluded that the future for magazines is promising; magazine readership has grown steadily as competitive information technologies have matured.

Energy consumption.—The southern pulp industry is increasing its self-sufficiency in energy. In 1977 about 40 percent of total energy used by southern pulp mills came from spent pulping liquors burned in recovery furnaces, and about 10 percent from bark and other mill residues. The remaining 50 percent was mostly derived from purchased fossil fuels (Whitney 1980). In spite of industry efforts to reduce use of fossil fuel, however, the cost of such fuel increased from 7.0 percent in 1972 to 11.2 percent in 1979 of the value of shipments from pulp mills in the United States (Slinn[4]).

If bark from pulpwood is dry and it is burned efficiently, and energy conservation is practiced, it is estimated that kraft pulp mills can be about 68 percent self sufficient in energy without resorting to additional residues available from forest operations (Personal correspondence with H. A. Schroeder, December 1981).

25-2 TYPES OF WOOD PULP, PAPER, AND PAPERBOARD[5]

There are dozens of pulping procedures and perhaps thousands of different kinds of construction paper and boards, paper, and paperboards; a summary of definitions provided by the American Paper Institute (1978) is helpful in classifying the most important of these pulps, papers, and boards. The few major procedures for pulping southern hardwoods are further described in sections 25-3 and 25-5 through 25-8.

WOOD PULP, MECHANICAL FOR PAPER AND PAPERBOARD

Mechanical pulps are produced by stone grinding or disk defibration. For use in paper and paperboard pulps are fine-textured and usually bright.

Stone groundwood pulp is produced by grinding wood logs or bolts (usually 4 feet in length) into relatively short fibers. In general, this process is not practical for pine-site hardwoods.

Refiner pulp is produced by subjecting wood chips and/or residues to atmospheric or open-discharge refining (sections 18-27 and 23-6).

Thermomechanical pulp is a high-yield pulp produced from wood chips and/or residues softened by preheating before defibrating in pressurized (or non-pressurized) refiners (sections 18-27 and 23-6, and fig. 25-21). It is used to replace or reduce the chemical pulp component in newsprint or groundwood papers.

[4]Slinn, R. J. 1980. Energy in the pulp and paper industry. Paper presented to the 1980 Ann. Meet., Amer. Pulpw. Assoc., Atlanta, Ga., March 18. 6 p.

[5]Definitions in this section are from American Paper Institute (1978).

WOOD PULP, MECHANICAL FOR "OTHER" PAPER AND BOARD

These coarse, often brown, pulps are used in the manufacture of insulating board, construction paper, and wet-machine board.

Stone groundwood and refiner pulps are produced by stone groundwood or refiner processes.

Defibrated/exploded pulps are produced by explosion process (see sections 18-27 and 23-6), and by pressurized refining to yield an economical, coarse brown pulp suitable only for "other" paper and board

Screenings are rejects and off-quality screenings from all grades of wood pulp, except dissolving pulp.

WOOD PULP, CHEMICAL

Semichemical pulps are high-yield pulps produced with some chemical agent such as neutral sulfite, or alkaline liquor followed by mechanical refining.

Sulfate and soda paper grades of pulp are produced by the sulfate (kraft) or soda process. Bleached pulp must achieve a G.E. Brightness of more than 75. Semi-bleached pulp must achieve a brightness of not less than 45 or more than 75.

Sulfite paper grades of pulp are produced by the sulfite process. Bleached pulp must achieve a G.E. Brightness of more than 75.

Dissolving and special alpha pulps are highly refined bleached white and sulfite or sulfate pulps with a high content of alpha (pure cellulose) fiber.

CONSTRUCTION PAPER AND BOARD AND "OTHER"

Construction paper includes sheathing paper, felts (for roofing, floor covering, automotive use, sound deadening, pipe covering, and use in refrigerators), asbestos paper and asbestos-filled paper, and flexible wood fiber insulation.

Insulating board is a fibrous-felted homogeneous panel made by inter-felting of fibers, e.g., interior building board, wallboard, sound-deadening board, acoustical tile, exterior sheathing board, roof insulation board, and trailer board.

Wet machine board includes binder's board, shoe board (e.g., counter board, heel board, and innersole), automotive board, chair seat backing, coaster board, luggage board, panel board, table-top board, mill board, and others of similar type.

PAPER

Newsprint is paper made largely from groundwood pulp, used chiefly in the printing of newspapers. Most newsprint is made with **basis weight** from 30 to 35 pounds; i.e., 500 sheets measuring 24 x 36 inches weigh 30 to 35 pounds.

Uncoated groundwood includes uncoated papers containing more than 25 percent groundwood, excluding newsprint.

Machine and offset coated paper is bleached paper with a coating weight of at least 2.5 pounds (per 500 sheets of 25- x 38-inch paper) on either side, and at least 50 percent of the coating consisting of pigment.

Coated groundwood is coated paper containing more than 25 percent mechanical pulp.

Coated free sheet is coated paper containing 25 percent or less mechanical pulp.

Uncoated free sheet (book paper, uncoated and chemical writing) includes bleached uncoated printing and writing papers containing no more than 25 percent groundwood pulp, e.g., offset, tablet, envelope, form bond, cover, and text papers, and business papers (bond, ledger, mimeo, and duplicator papers).

Bleached bristols include coated bristols for tabulating indexes, tags, file folders, and covers; and uncoated bristols for indexes, printing and postcards. Bristols are stiff, with smooth surfaces, and have a minimum thickness of 0.006 inch.

Cotton fiber papers contain 25 percent or more cotton, cotton rags, cotton waste, linters, linter pulp, flax, or similar fibers.

Thin papers include carbonizing, condenser, cigarette, and similar thin specialty papers.

Packaging and industrial converting paper includes wrapping paper, shipping sack, bag and sack paper other than shipping sack, and other converting papers having a basis weight of 18 pounds or more.

Unbleached kraft papers contain more than 50 percent unbleached sulfate wood pulp.

Bleached packaging and industrial converting paper contains more than 50 percent bleached wood pulp. This class includes glassine, greaseproof, vegetable parchments, and some unbleached sulfite papers.

Special industrial paper and board includes paper and board of all weights, calipers, and furnishes, designed for specialized end uses such as abrasive paper, cable paper, electrical insulation, vulcanized fiber, resin-impregnating stock, and similar grades. It does not include wet machine board.

Tissue includes sanitary grades of paper, i.e., toilet, facial, napkin, toweling, sanitary napkin, wiper, and special sanitary papers. It also includes wax paper, wrapping paper, and wadding.

PAPERBOARD

Unbleached kraft paperboard is made from a furnish containing not less than 80 percent wood pulp produced by the kraft sulfate process.

Unbleached linerboard is kraft paperboard used as facing material in corrugated or solid fiber boxes. It includes solid unbleached kraft linerboard made on fourdrinier or cylinder paper machines, mottled white linerboard, and clay-coated unbleached kraft linerboard.

Bleached linerboard is solid bleached paperboard made on fourdrinier or cylinder paper machines, manufactured for use as facing material when combining paperboard for conversion into corrugated or solid fiber boxes.

Recycled linerboard is paperboard containing less than 80 percent virgin kraft wood pulp and used as facing material when combining paperboard for conversion into corrugated or solid fiber boxes.

Corrugating medium is principally hardwood semichemical pulp used as fluting material for combination with paperboard to make corrugated boxes.

Corrugating medium (recycled) is paperboard containing less than 75 percent virgin woodpulp and used as fluting material.

Container chip and filler board is recycled paperboard manufactured as a filler for solid fiberboard for conversion into solid fiber boxes, or for container chipboard. All chipboard weighing less than 26 pounds per thousand square feet is manufactured for use in facing corrugated, solid-fiber, or single-faced products used for interior packing, e.g., pads, partitions, dividers, layers, and cushioning.

Unbleached folding paperboard is manufactured for conversion into folding cartons and beverage carriers; it may be clay-coated unbleached kraft, or unbleached kraft backed with bleached kraft lining. It may also contain pulp other than kraft.

Recycled folding paperboard is manufactured with bending quality for conversion into folding cartons, including those of unlined chipboard, and those kraft lined, or white lined and clay coated.

Recycled set-up paperboard has non-bending specifications for conversions into rigid or set-up boxes, including those of plain chipboard, or those newslined or white vat lined.

Other paperboard (unbleached) includes all unbleached kraft paperboard whose end use is not otherwise classified, e.g., paperboard for a filler in solid fiberboard to be fabricated into a shipping container, table, drum, can, file-folder tab, or automotive panel.

Solid bleached packaging paperboard is made for use in packaging from a furnish containing not less than 80 percent virgin bleached chemical wood pulp. (Bleached bristol boards not manufactured for packaging are described under PAPER).

Milk carton and food service paperboard (bleached) includes solid bleached paperboard for conversion into milk cartons, heavyweight cups, and round nested food containers, plates, dishes, and trays; also used for packaging moist, liquid, or oily foods.

Other paperboard (bleached) is solid paperboard for conversion into packaging of blister packs, tubes, and other products not classified above. Also used for industrial products not classified under bleached bristols.

Semichemical paperboard contains not less than 75 percent virgin wood pulp, the predominant portion of which is produced by a semichemical process.

Recycled paperboard is manufactured from a predominance of recycled fibers from various grades of paper stock, and sometimes including a very minor portion of virgin fibers.

Gypsum wallboard facing is recycled paperboard manufactured for use as liner or facing on gypsum board and plasterboard; the paperboard may be white, cream, gray, blue, or other color.

Other paperboard (recycled) is recycled paperboard with the same characteristics as paperboard for bending or non-bending packaging but for non-packaging uses; also includes recycled paperboard for end uses not otherwise classified, such as tags, file folders, tubes, cans, drums, match stems, tablet backs, and toys.

These brief definitions are presented as useful in visualizing the scope of the industry and in interpreting industry statistics; they do not fully describe the products. Readers interested in more complete descriptions are referred to The Dictionary of Paper published by the American Paper Institute (1980), and to the 38th Annual Paper Yearbook, 1980, published by Harcourt and Brace, New York.

25-3 OVERVIEW OF HARDWOOD PULPING AND SHEET FORMING AND DRYING

Conversion of hardwoods into paper or paperboard involves freeing individual fibers by pulping and bleaching processes that remove much of the binding materials present in solid wood, beating these fibers to promote flexibility and bonding, and formation and drying of prepared fibers into sheets.

MORPHOLOGY

The anatomy of the hardwoods that are the subject of this text can be quickly grasped from scanning electron micrographs of small wood cubes (fig. 5-21 through 5-45). Morphology of individual hardwood fibers is illustrated in figures 5-53AB. Average stemwood fiber length is 1.27 mm, much shorter than that of the southern pines which average about 4 mm in the four major species. There are significant differences among the pine-site hardwood species, e.g., black tupelo fibers are about 1.76 mm long, while those of red maple are only 0.83 mm long (table 5-4). Transverse dimensions of fibers in solid wood (table 5-7) are primary indicators of wood specific gravity, but also give some indication of probable properties of sheets formed of pulped fibers. Fibers comprise about 44.4 percent of the stemwood volume of small pine-site hardwoods (41.3 percent in the 11 oaks and 47.4 percent in the non-oaks (table 5-3). Vessel elements, comprising about 20.5 percent of stemwood of small pine-site hardwoods, are much larger in diameter than fibers, have thinner walls, are shorter, and are more or less open-ended (figs. 5-52 bottom and 5-99 with related discussion).

Parenchyma cells (figs. 5-22 and 5-51), including ray parenchyma (figs. 5-56 through 5-61), comprise on average about 35.1 percent of stemwood of small pine-site hardwoods (table 5-3); when these hardwoods are pulped, the parenchyma cells become fines, i.e., particles so small they are detrimental to sheet bursting and tensile strength.

Readers needing fiber and vessel micrographs of species additional to those illustrated in chapter 5, will find useful Côté's (1980) atlas of papermaking fibers; the atlas illustrates 24 softwoods, 40 hardwoods, and 10 miscellaneous plants.

The morphology of pulped hardwood cells is related to properties of sheets made from them. Figure 25-9 illustrates the anatomy of a diffuse-porous hardwood after removal of most lignin, but before cell separation. When pulped fibers, vessel elements, and parenchyma cells are separated, dispersed in water, and then formed on a screen to yield a paper sheet, they form a random network (fig. 25-10). Mechanical properties of the sheet vary with the morphology of the pulped cells comprising the network, and with other factors including cell hemicellulose and lignin content, beating procedures after pulping, additives to the pulp, forming technique, and sheet drying procedures. Vessel elements bond poorly in these fiber networks and may be picked from paper surfaces by ink application rolls; Byrd et al. (1967) found that gyratory refining of hardwoods pulps at high consistency disintegrated vessel elements, improving internal bond and pick resistance in offset press papers.

Amidon (1981) reviewed the effects of wood properties of hardwoods on kraft paper properties. He noted that **fiber flexibility** (sometimes expressed as lumen diameter/exterior fiber diameter) is a key to chemical pulp quality because flexible fibers have more interfiber bonds than stiff fibers. Long fibers yield papers with greater tear strength than short fibers, until strength of bonds exceeds strength of fibers. Increases in specific gravity generally increase tear

Figure 25-9.—Scanning electron micrograph of sweetgum after removal of most of the lignin by a pulping reagent, but before disturbing the matrix of different cell types. Individual fibers (f), vessel elements (ve), and ray parenchyma cells (rp) are distinguishable. (Photo from Côté 1980.)

strength, lower tensile and burst strength, decrease apparent density and folding endurance, and increase resistance to beating, with decreased printability.

Horn (1978) also investigated the influence on paper strength of morphology of hardwood fibers pulped by the kraft process (a very alkaline system using sodium hydroxide plus sodium sulfide). He observed unbeaten, unbleached pulp fibers of five southern hardwoods and five other North American hardwoods (table 25-6). He found a range in pulp-fiber length from 0.85 mm in sugar maple

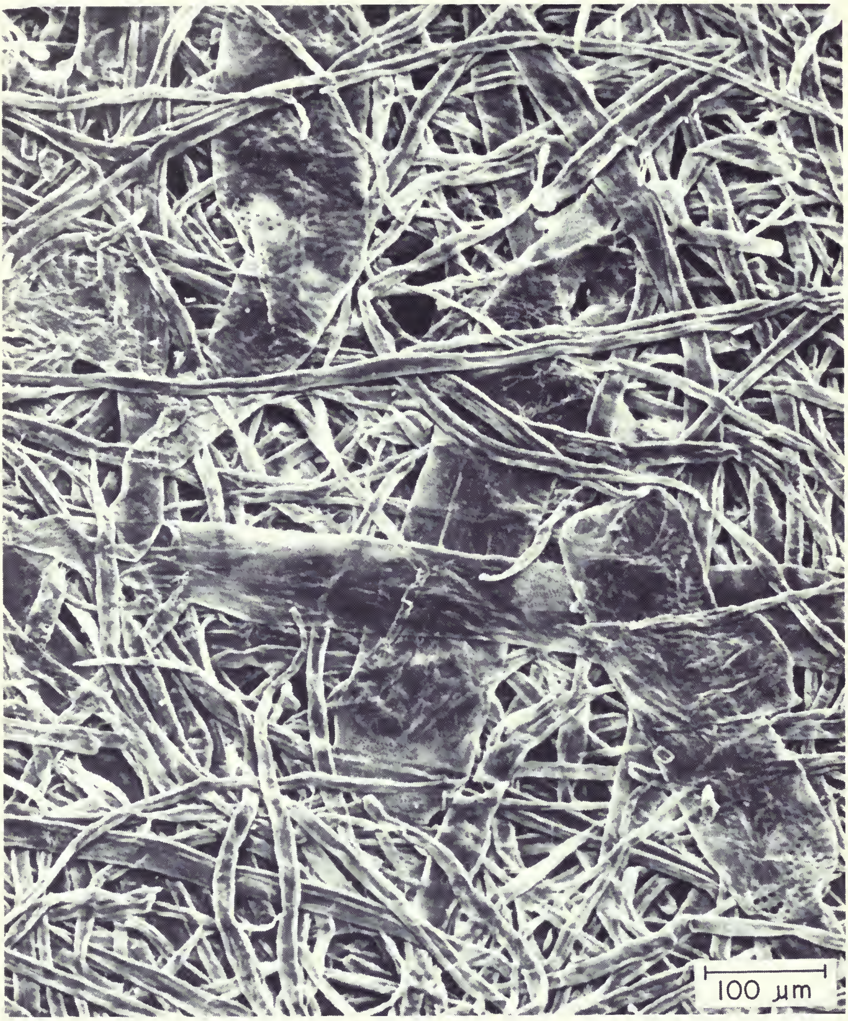

Figure 25-10.—Scanning electron micrograph of a paper sheet formed from hardwood cells; wide, short vessel elements are evident among the long narrow fibers. (Photo from Côté 1980.)

to 1.85 in black tupelo. Length-to-thickness ratio varied from 207 in American beech to 403 in paper birch, and fibril angle from 6.3° in sugar maple to 19.4° in shagbark hickory. In addition to the five hardwoods commonly found in the South (American elm, sweetgum, black tupelo, shagbark hickory, and white oak), the study included paper birch (*Betula papyrifera* Marsh.), sugar maple (*Acer saccharum* Marsh.), quaking aspen (*Poplus tremuloides* Michx.), American beech (*Fagus grandifolia* Ehrh.), and red alder (*Alnus rubra* Bong.).

TABLE 25-6.—*Morphological properties of unbeaten unbleached kraft pulp fibers of 10 hardwood species* (Horn 1978)

Species	Specific gravity[1]	Fiber length[2]	Fibril angle[3]	Cell wall thickness[4]	Cross sectional area[5]	Length/thickness ratio (L/T)	Pulp fiber coarseness[6]	Fibers/gram[7]	Fibers/cubic centimeter
		mm	*deg*	μ	μ^2		mg/100 m	10^5	10^6
Alder, red	0.380	1.25	7.8	3.54	183	353	12.38	81.60	5.47
Aspen	.391	1.05	9.4	3.20	149	328	8.59	118.90	8.09
Beech, American	.579	1.16	9.9	5.60	181	207	13.10	75.96	4.33
Birch, paper	.531	1.51	14.7	3.75	180	403	13.08	76.12	5.10
Elm, American	.500	1.35	15.5	4.20	156	322	9.53	108.30	6.39
Hickory, shagbark	.582	1.29	19.4	4.10	141	315	10.59	97.50	5.36
Maple, sugar	.588	.85	6.3	4.05	140	210	7.86	127.90	7.29
Oak, white	.627	1.25	13.7	5.80	130	216	14.08	68.91	3.79
Sweetgum	.454	1.65	14.3	6.40	353	258	24.60	24.20	1.40
Tupelo, black	.507	1.85	15.8	6.32	350	293	25.40	22.35	1.34

[1]Ovendry weight and green volume, unextracted.
[2]Based on measurement of 50 whole, unbeaten fibers.
[3]Method from Page (1969).
[4]Average of four measurements per fiber of 35 fibers.
[5]By planimetry measurements on same fibers as footnote 4.
[6]Weight of fiber substance per unit length of fiber. Method from Britt (1966).
[7]Method from Horn and Coens (1970).

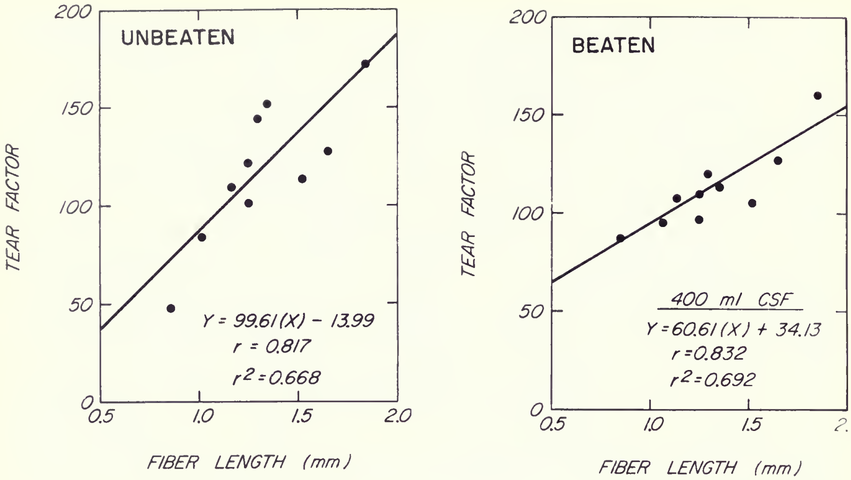

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Figure 25-11.—Influence of hardwood kraft pulp fiber length on the tearing resistance of pulp sheets made from the unbleached fibers. (Left) Unbeaten. (Right) Beaten to 40 ml Canadian Standard Freeness. (Drawings after Horn 1978.)

Horn (1978) cooked all the pulps to a comparable lignin content, i.e., to a Kappa number from 18 to 22, and made the morphological measurements (table 25-6) before beating the fibers. Mechanical properties of the pulps were determined before and after beating to a Canadian Standard Freeness (CSF) of 400 ml, and all pulp handsheets were prepared according to TAPPI Standard Procedures (T205-m60). Relationships observed are summarized in table 25-7.

Tear strength.—Horn (1978) found that tearing strength of sheets made from either unbeaten or beaten hardwood fibers is principally dependent on fiber length (fig. 25-11)—longest pulp fibers yielded greatest tearing strength, which contrasts with paper made from softwood pulps in which cross-sectional area and cell-wall thickness are the dominant variables affecting tearing strength (Horn 1974). Fibril angle also showed a significant correlation in unbeaten pulps with tearing strength (fibers with largest fibril angles had greatest tearing strength). Multiple regression analysis showed that the interaction of fiber length and fibril angle could account for 78 percent of the variation in tearing strength of unbeaten pulps—indicating that tearing strength is influenced more by fiber extensibility than fiber strength. In hand sheets made of unbeaten pulp, fiber length was the dominant factor related to tearing strength.

TABLE 25-7.—*Regression models relating morphological properties of unbeaten and beaten, unbleached kraft-pulp hardwood fibers to five sheet properties* (Horn 1978)

Sheet property and degree of beating	Equation[1,2]	r^2
Tear factor		
Unbeaten	−13.99 + 99.61 (fiber length)	0.668
	34.18 + 6.60 (fibril angle)	.571
	−16.67 + 68.81 (fiber length)	
	+ 3.43 (fibril angle)	.758
400[3]	34.13 + 60.61 (fiber length)	.692
	45.87 + 3.29 (fibril angle)	
	+ 0.14 (cross-sectional area)	.860
Stretch		
Unbeaten	0.16 + 1.42 (fiber length)	.776
	0.87 + 0.09 (fibril angle)	.704
	0.44 + 2.47 (fiber length)	
	− 0.06 (fiber coarseness)	.923
400	2.97 + 0.08 (fibril angle)	.447
	2.09 + 3.03 (fiber length)	
	− 0.15 (fiber coarseness)	.745
Burst factor		
Unbeaten	−18.94 + 37.50 (fiber length)	.694
	7.56 + 0.15 (L/T)	
	− 0.25 (fibers/gram)	.973
400	25.29 + 0.17 (L/T)	.642
	17.31 + 81.84 (fiber length)	
	− 3.62 (fiber coarseness)	.736
Tensile strength		
Unbeaten	1465 + 19.10 (L/T)	.634
	4686 + 22.31 (L/T)	
	− 28.35 (fibers/gram)	
	− 148.94 (fibril angle)	.979
400	5400 + 23.68 (L/T)	.694
	4862 + 16809 (fiber length)	
	− 503 (fibril angle)	
	− 605 (fiber coarseness)	.899
Modulus of elasticity		
Unbeaten	1594 (10^3) − 1560 (specific gravity)	.533
	269 (10^3) + 1.80 (L/T)	.439
	526 (10^3) + 2.26 (L/T)	
	− 30.84 (fibril angle)	.889
	668 (10^3) − 2.39 (L/T)	
	− 36.10 (fibril angle)	
	− 1.39 (fibers/gram)	.952
400	421 (10^3) + 2.34 (L/T)	.596
	1936 (10^3) − 1620 (specific gravity)	.462
	678 (10^3) + 2.80 (L/T)	
	− 30.65 (fibril angle)	.954

[1]Units as follows: fiber length, mm; fibril angle, degrees, fiber coarseness, weight of fiber substance per unit length of fiber expressed as mg/100 m; cross sectional area μm^2; L/T ratio, ratio of fiber length to cell wall thickness measured in pulped fiber; specific gravity, ovendry weight unextracted and green volume.

[2]Significant to the 0.01 probability level.

[3]Canadian Standard Freeness, ml.

From extensive studies relating hardwood (mostly tropical) fiber morphology and strength to paper sheet properties, Wangaard and Williams (1970) concluded that tear strength tends to increase with increasing fiber length in the lower range of sheet densities, culminates at a level of sheet density which increases with increasing fiber strength and, at a specified level of fiber strength, at high sheet tear strength declines with increasing fiber length. They found that kraft pulps made from hardwood fibers 1 mm long attained maximum tear strength at sheet densities of 0.62 to 0.85 g/cm^3. At the very lowest levels of sheet density there was essentially no effect of fiber length on tearing strength. At some sheet density beyond a critical level of bonding, long fibers had an adverse effect on tear resistance. Readers wanting to further study relationships between hardwood fiber morphology and pulp sheet mechanical properties should read Tamolang and Wangaard (1961), Wangaard (1962), and Kellogg and Wangaard (1964).

Stretch.—Horn (1978) found that fibril angle and fiber length were individually correlated with stretch properties of paper made from hardwood pulps; those made with long fibers or those having a large fibril angle stretched most.

In unbeaten pulps, fiber length accounted for 78 percent of the variation in stretch. After beating, the effect of fiber length was negligible and fibril angle was the dominant single variable, accounting for 45 percent of the variation in stretch.

By multiple regression analyses, fiber coarseness was related to stretch, i.e., paper with the longest fibers of least coarseness stretched most. For unbeaten pulps these two factors accounted for 92 percent of the variation; for beaten pulps they accounted for 75 percent of the variation in stretch.

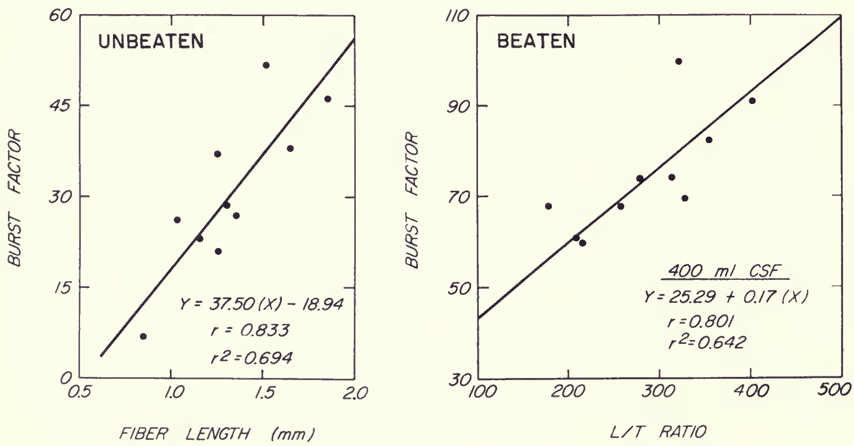

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Figure 25-12.—Burst strength of sheets made from unbleached hardwood kraft pulps. (Left) Unbeaten, related to pulp fiber length. (Right) Beaten to 400 ml Canadian Standard Freeness, related to L/T ratio, i.e., the ratio of fiber length to cell wall thickness of the pulp fiber. (Drawings after Horn 1978.)

Bursting and tensile strengths.—Horn (1978) found that, as in softwood pulps, bursting and tensile strengths of hardwood pulps are highly dependent on fiber-to-fiber bond strengths. In unbeaten pulps, bursting strength was most highly correlated with fiber length (fig. 25-12 left), with L/T ratio (ratio of fiber length to cell wall thickness) a secondary influence (r = 0.709); tensile strength of unbeaten pulps was mostly closely correlated with L/T ratios (r = 0.796).

Horn (1978) found that after beating, L/T ratio was the dominant factor for both bursting strength (fig. 25-12 right) and tensile strength (fig. 25-13). Bursting and tensile strengths of handsheets made of white oak kraft pulp fibers were increased by removal of fine material, chiefly parenchyma cells (table 25-8). The presence or absence of vessel elements from handsheets had little influence on the tensile strength of handsheets made from either unbeaten or beaten white oak kraft pulp fibers; the white oak pulp contained 1.9 percent vessel elements by weight (Horn 1978).

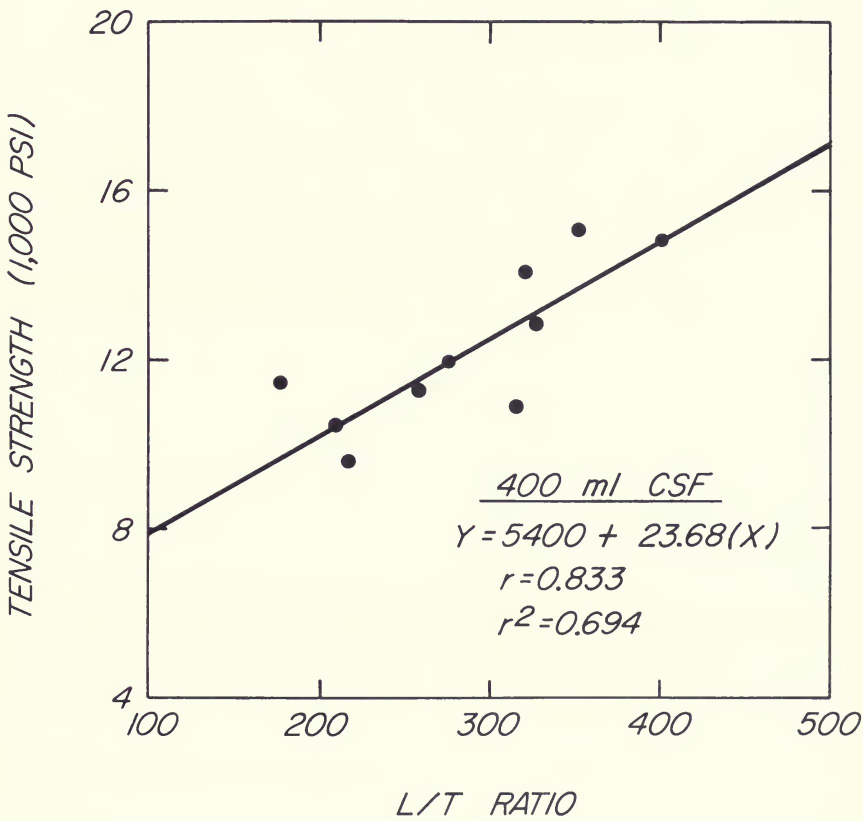

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Figure 25-13.—Relationship of tensile strength to L/T ratio (fiber length to cell wall thickness) for pulp sheets made from unbleached hardwood kraft fiber beaten to Canadian Standard Freeness of 400 ml. (Drawing after Horn 1978.)

TABLE 25-8.—*Variation in bursting and tensile strengths, due to fines content, of handsheets made from beaten white oak kraft pulp* (Horn 1978)

Proportion of fines[1] (percent)	Burst factor	Tensile strength
		Psi
0[2]	65	9,500
18.8[3]	56	8,950

[1]Fines defined as that fraction of furnish passing 200-mesh screen; this fraction was comprised primarily of parenchyma cells plus a small amount of short fiber segments and vessel element fragments.
[2]Fines removed and fiber fraction beaten to 400 ml Canadian Standard Freeness.
[3]Fractionated fiber furnish beaten to 400 ml Canadian Standard Freeness, and fines added.

Modulus of elasticity.—Horn (1978) found that the best single factor for predicting modulus of elasticity of unbeaten pulps was unextracted specific gravity of wood ($r = -0.730$). The second-best was L/T ($r = 0.663$). Multiple regression analysis suggested that, of the fiber parameters, fibril angle and L/T could account for 89 percent of the variation in modulus of elasticity of unbeaten pulps. Thus, for unbeaten pulps, stiffness was promoted by use of low-density woods having long slender fibers with small fibril angles.

For beaten pulps, the best indicator was L/T ratio ($r = 0.772$), and the second best was unextracted specific gravity ($r = -0.680$). Multiple regression analyses indicated that 95 percent of the variation in modulus of elasticity could be accounted for by fibril angle and L/T ratio.

Horn (1978) concluded that attainment of good stiffness properties in paper made from hardwoods is greatly dependent upon fiber characteristics that promote fiber bonding, i.e., flexibility, collapsibility, and conformability. Also, Horn found that sheet density accounted for 92 percent of the variation in modulus of elasticity when using unbeaten pulps and 82 percent when using beaten hardwood kraft pulps from this study.

Press drying of hardwood paper and paperboard (see section 25-4) may significantly alter relationships observed in handsheets formed by the traditional standard methods.

PULPING

There are three principal methods for producing pulp fibers from wood:

- by application of mechanical force
- by reacting wood with chemicals at elevated temperatures
- by combination of the two foregoing methods

Selection of pulping process depends on wood species, product requirements, and a host of economic and environmental factors. Primarily, however, process selection is influenced by the completeness with which lignin must be removed from the pulped fibers, or conversely, the purity of the resulting cellulose pulp. Chemical constitution, as well as fiber morphology, of the wood to be pulped is therefore of great importance when considering pulping alternatives.

H. A. Schroeder (personal correspondence, December 1981) approximated this chemical constitution in hardwoods and softwoods as follows:

Constituent	Typical hardwood	Typical softwood
	...Percent of ovendry extractive-free weight...	
Cellulose	45	42
Hemicelluloses	31	29
Lignin	22	28
Pectin, ash, etc	2	1
	100	100

Summative chemical analyses of stemwood of 18 of the principal pine-site hardwoods are given in table 6-1. Percentages of the components range as follows:

Component	Percent[6]
Cellulose	33.8 - 48.7
Hemicellulose	23.2 - 37.7
Lignin	19.1 - 30.3
Extractives	1.1 - 9.6
Ash	.1 - 1.3
	100

The distribution, as well as the summative analysis, of cellulose, hemicellulose, and lignin is of interest to the pulp maker. As noted in section 6-2, mature cell walls of hardwood fibers are complex layered structures (figs. 5-73 and 5-74). The true middle lamella, completely enclosing individual cells and cementing them together, is a continuous lignin-rich matrix. The thin outer primary cell wall—difficult to distinguish from the middle lamella—is also highly lignified, but contains hemicellulose, cellulose, pectin, and protein. Together these layers are known as the compound middle lamella. The major portion of the cell wall, the secondary wall, is primarily cellulose and hemicellulose, but contains some lignin.

No data are available on lignin distribution across fiber walls of southern hardwoods, but Fergus and Goring (1970ab) found that about 80 percent of the lignin in fibers of *Betula papyrifera* Marsh. is in the secondary wall layers; the rest is in the very thin middle lamella regions where it is a principal constituent. They found that the secondary wall is 16-19 percent lignin, the middle lamella 30-40 percent, and the cell corner regions 72-85 percent.

[6]Hergert, H. H., T. H. Sloan, J. P. Gray, and K. R. Sandberg. The chemical composition of southeast hardwoods. Unpublished data privately communicated to the author December 12, 1977. (See section 6-1.)

Timell (1967) found cellulose distribution in fibers of *Betula verrucosa*, as follows:

Cell layer	Cellulose portion of total polysaccharides in layer
	Percent
Middle lamella-primary wall	41
Secondary wall	48-60

Cellulose concentration was highest and hemicelluloses lowest, in wall regions nearest fiber lumens.

Wood rays of hardwoods, e.g., white oak, have appreciably greater lignin content and lower cellulose content than total stemwood (Harlow and Wise 1928). Timell (1969) reported that tension wood (figs. 5-71 and 5-72), on a gross weight basis, has less lignin and hemicellulose and more cellulose than normal wood; per fiber, however, there is as much lignin in tension wood as in normal wood.

Distribution of chemical constituents across annual growth increments of scarlet oak is shown in figure 6-1.

Historically, the first approach to pulping was mechanical. Softwoods, but not hardwoods, can be successfully ground—usually in 4- or 5-foot-long lengths—against a revolving cylindrical stone. (See page 2238, and Koch 1972, p. 1423-1426 for descriptions of the process). Short-fibered southern hardwoods yield principally unusable fines when prepared by this method. In another mechanical process, hardwood chips can be reduced to refiner groundwood fiber by passing the chips through at least two stages of single- or double-disk refiners. This process is described in sections 18-27, 23-6, and 25-5. Mechanical pulps have essentially the same composition as the wood from which they were made, except for loss of a small percentage of water-soluble material. These mechanical pulps, retaining all lignin, produce poorly bonded paper with low strength and short life, but good printability (Whitney 1980). Mechanical pulps from hardwoods are usually combined with other types of fiber in papermaking.

Freeing cellulose fibers and leaving them intact requires a chemical treatment to remove non-cellulosic wood components. In practice neither objective is completely realized, but several processes reach satisfactory compromises at pulp yields of 45-55 percent of wood weight (Whitney 1980). For some specialized pulps, higher-yield semichemical pulping processes, retaining some hemicelluloses and lignin, may yield 60 to 90 percent. They usually require some mechanical attrition to disintegrate the wood chips after chemical treatment. Whitney (1980) concluded that all commercial chemical and semichemical pulping processes remove more carbohydrate material than lignin from wood, but that this may not be true in the future.

The chemical reagents commonly used for pulping can be arranged according to pH and grouped according to pulping process (fig. 25-14). Development of these processes, as described by Whitney (1980), has occurred over the past 150 years.

Alkalies have been used for centuries to separate cellulose fibers from the other components of nonwoody plants but their successful use for the pulping of wood dates from the mid-1800's. In 1854 Watt and Burgess used a sodium hydroxide solution under pressure to produce wood pulp from aspen, initiating chemical pulping and the **soda process** in this country. Partial recovery of the soda (sodium carbonate) used as makeup chemical was practiced within a few years. Use of the soda process has declined, but less drastic alkali cooking is again of some interest.

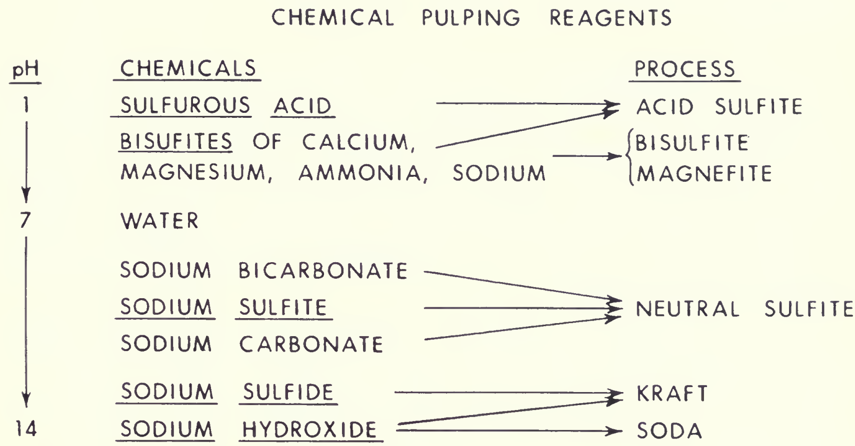

Figure 25-14.—Chemical reagents commonly used for pulping, arranged by pH, and grouped according to pulping process. (Drawing after Whitney 1980.)

In the **acid sulfite process,** wood is digested in a solution of sulfurous acid containing alkali or alkaline earth bisulfites. Long the source of fine bleached pulps for stationery and high-grade printing papers, and still viable in certain situations, sulfite pulp production in this country is decreasing rapidly.

During the 1880's, the German chemist Dahl developed a cooking liquor containing sodium hydroxide and sodium sulfide. This **sulfate,** or **kraft** process was cheaper than soda pulping, yielded stronger pulp, and proved capable of pulping most wood species. Production of kraft pulp has grown for a century and now dominates the pulping scene. One important reason for its dominance is its excellent system for chemical recovery.

Of the semichemical processes, probably **neutral sulfite** comes closest to being standard. The principal reagent is sodium sulfite, and the pH is kept around 8 or 9 with carbonate and bicarbonate. Neutral sulfite pulping is particularly well suited to hardwoods; its product is a preferred grade for corrugating medium. Several variants of the process are now being practiced.

In days of scarce and costly energy and rigid environmental control, no pulping process can remain viable without an effective system to recover and reuse the pulping chemicals and to generate energy from those organic residues not otherwise used more profitably.

Trends shown in figure 25-4 continued during the latter half of the 1970's, i.e., production of kraft, semichemical, and mechanical pulp increased, while that of sulfite pulp declined. Waste paper consumption, for recycling, increased from about 8 million tons in 1950 to nearly 15 million tons in 1978. By 1981 about 20 percent of the paper and paperboard consumed in the United States was from recycled paper.

BEATING

Paper has strength because wet cellulose surfaces bond to each other when brought together and dried—chiefly by forming hydrogen bonds. The strength of these bonds is enhanced if fibers are collapsed to flexible ribbon-like form (rather than tubular), and if fibers are **fibrillated** (i.e., fibrils partly loosened) on ends and surfaces. For adequate sheet strength, most stock is prepared in **beaters** or **refiners** which mechanically alter fiber form to yield strong bonds. Most strength properties of paper, particularly tension and bursting strength, are enhanced by beating (fig. 25-15).

The two major effects of beating are cutting and fibrillation. While **cutting** shortens average fiber length, and impairs strength if carried to extreme, it forestalls undesirable floculation of clumps of long flexible fibers which otherwise appear as dense mottled areas in paper sheets.

Fibrillation in beaters or refiners alters fiber surfaces by macerating, fraying, brooming, and generally loosening the fibrillar structure of the cell wall—making more surface on each fiber available for bonding. Beaten fibers (fig. 25-16 bottom) are less well defined than unbeaten ones (fig. 25-16 top), but they bond together to produce stronger, smoother, denser (more compact), and generally better paper.

Differences in beatability between hardwoods and softwoods are attributable primarily to their differing fiber morphology. Most investigators have found that hardwood pulps are beaten faster and with less energy than softwood pulp. Pulps with a small hardwood component may be beaten as a mixture, but if the hardwood component is near 50 percent or greater, better paper properties may be obtained by beating the hardwood separately from the softwood pulp. There is a very large literature on the subject of beating hardwoods. Following are a few references on the subject: Ai et al. (1978); Bobrov and Ershov (1978); Gorbacheva and Ivanov (1968); Hamada and Matsumoto (1977); Higgins et al. (1973); Hunt and Hatton (1976); Kibblewhite and Brookes (1977); Kijima and Yamakawa (1978ab); Levlin (1976, 1980); Lonnberg (1976); and Marton (1976).

SHEET FORMATION

Prepared fibers are continuously formed into paper sheets by suspending the pulped fibers in a water slurry and causing the slurry to flow from a headbox onto

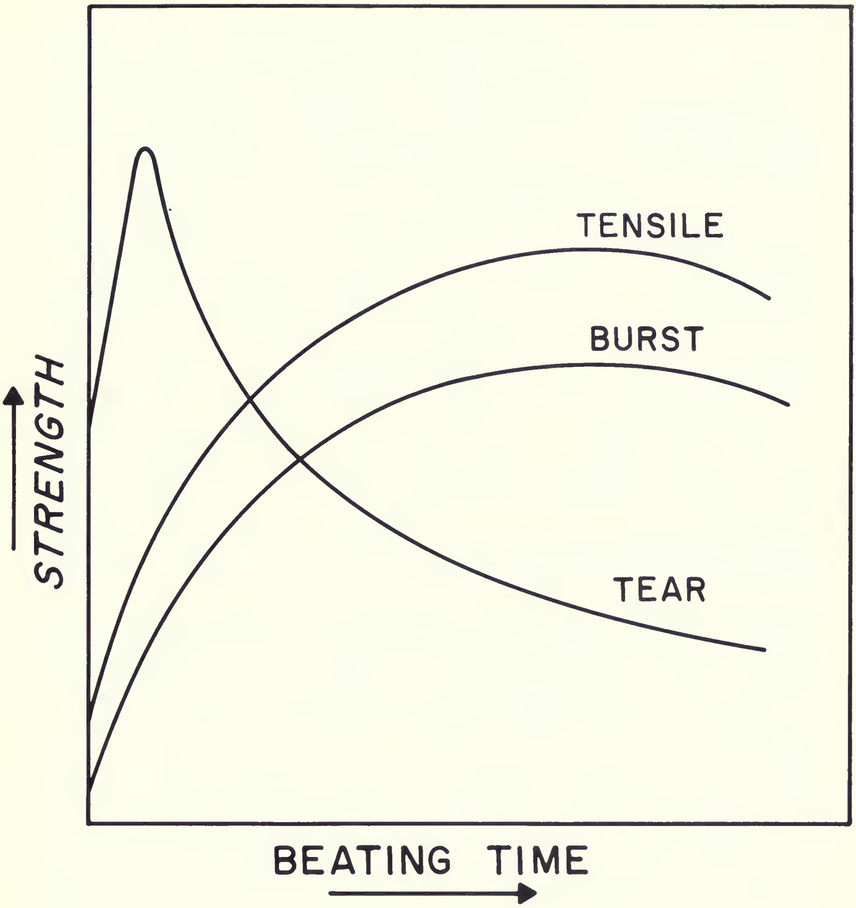

Figure 25-15.—Typical relationships between pulp beating time and three strength properties of paper. (Drawing after Whitney 1980.)

an endless, moving, horizontal wire screen. After drainage on the moving screen the partially dewatered sheet is passed through continuous drying processes. This **Fourdrinier** machine has not changed in principle since its invention in 1799, but evolutionary developments have been significant. Machine widths have been increased from about 3 feet to about 30 feet, and speeds from a few feet per minute to 3,000 feet per minute. Most paper machines have a single wire screen, but some have two screens so that the sheet being formed is always contained between the moving wires and never encounters an air-slurry interface (Whitney 1980).

Readers interested in further study of the technology of forming paper sheets from hardwood pulps should find the following references useful:

Reference	Subject
Britt (1978)	Effect of turbulence before and after chemical addition on drainage and polymeric retention during sheet forming of a 1:1 blend of bleached and jointly beaten hardwood and softwood kraft pulps.
Ershov (1978)	Sheet formation of blends comprised of 40- and 60- percent hardwood kraft pulp with sulfite pulp.
Higgins (1969)	Advantages and disadvantages, with respect to sheet formation, drainage, and sheet properties of hardwood and softwood pulps.
Nakata et al. (1978)	High-consistency refining of mixed hardwood and softwood unbleached kraft pulps related to sheet formation and properties.
Przybysz and Czechowski (1977)	Strength of consolidating web during sheet formation of hardwood and softwood kraft pulps.

SHEET DRYING (CONVENTIONAL)

As paper is formed on a moving wire screen by deposition of pulp fibers suspended in water, most of the water drains through the screen—often aided by suction boxes. The density of the fiber mat deposited on the screen varies locally to some degree, but excessive variation causes uneven drying and a poor quality sheet. The mat is further dewatered to near the fiber saturation point by its passage between pairs of nip rolls that mechanically press or wring out most of the free water.

The sheet is then further dried by heat conduction as it passes over a series of large (e.g., 6 feet in diameter) drying rolls. Target final moisture content may be from 2 to 9 percent depending on product. The drying rolls or cylinders may have surface temperatures as low as 190°F or as high as 290°F; they are often in the range of 260 to 280°F (Gardner 1967). The paper probably does not attain intimate contact with the dryer rolls; except where thick spots in the mat touch the rolls, a very small airgap generally separates the paper from the roll.

Dryer rolls are mounted in multiples, the paper threading through them; felts or synthetic screens are commonly used to back up the paper sheet for closer contact between the paper and the hot surface of the roll (fig. 25-17 top).

The extreme width of modern paper machines (up to 30 feet) aggravates uneven drying across the width of the sheet (fig. 25-17) resulting from moist dead air in pockets between rolls. Metcalfe (1968) described remedies applicable only to paperboard, whereby dry air at jet velocities from 3,000 to 10,000 feet per minute blows either vertically against the full width of the moving sheet, or parallel to the roll axis. Also effective, and applicable also to thin papers, is pocket ventilation with dry air blown through the more or less permeable backup felts; moist air is exhausted laterally out the front and back sides of the machine (fig. 27-17 top, inset).

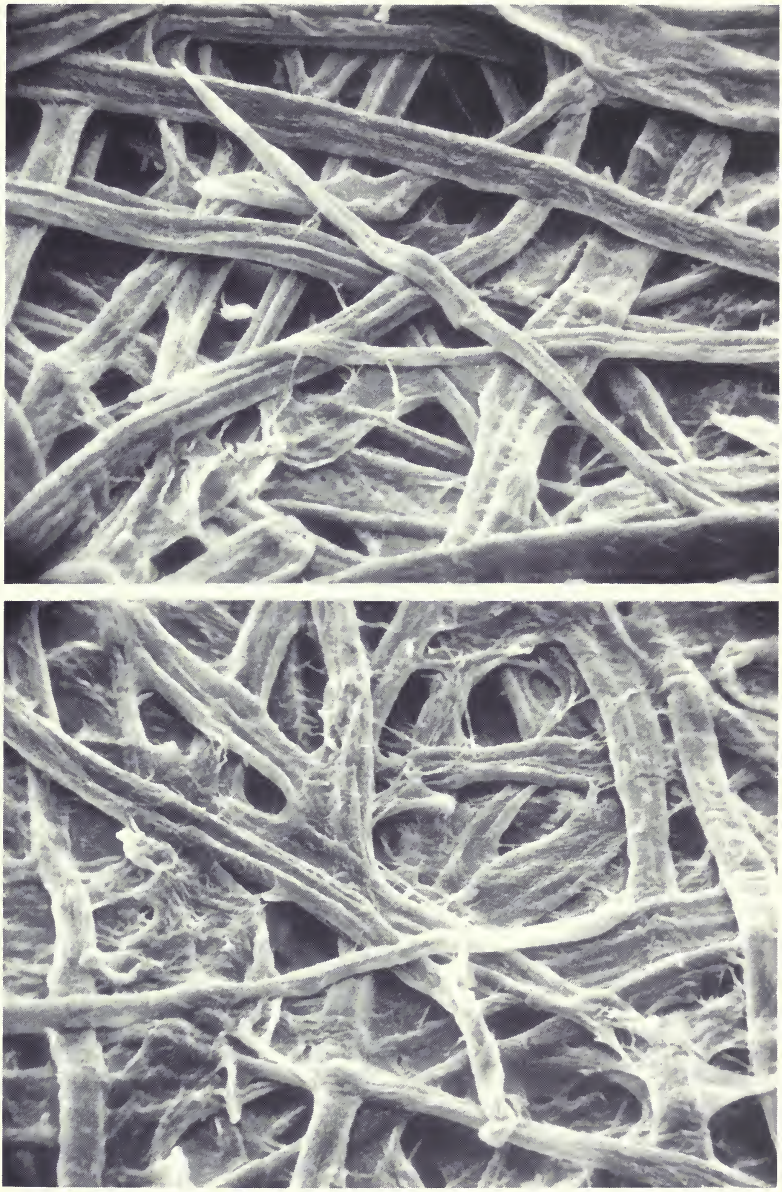

Figure 25-16.—Handsheets of southern red oak fibers pulped by the kraft process. (Top) Unbeaten fibers. (Bottom) Beaten fibers. 500X. (Photos from U.S. Forest Products Laboratory.)

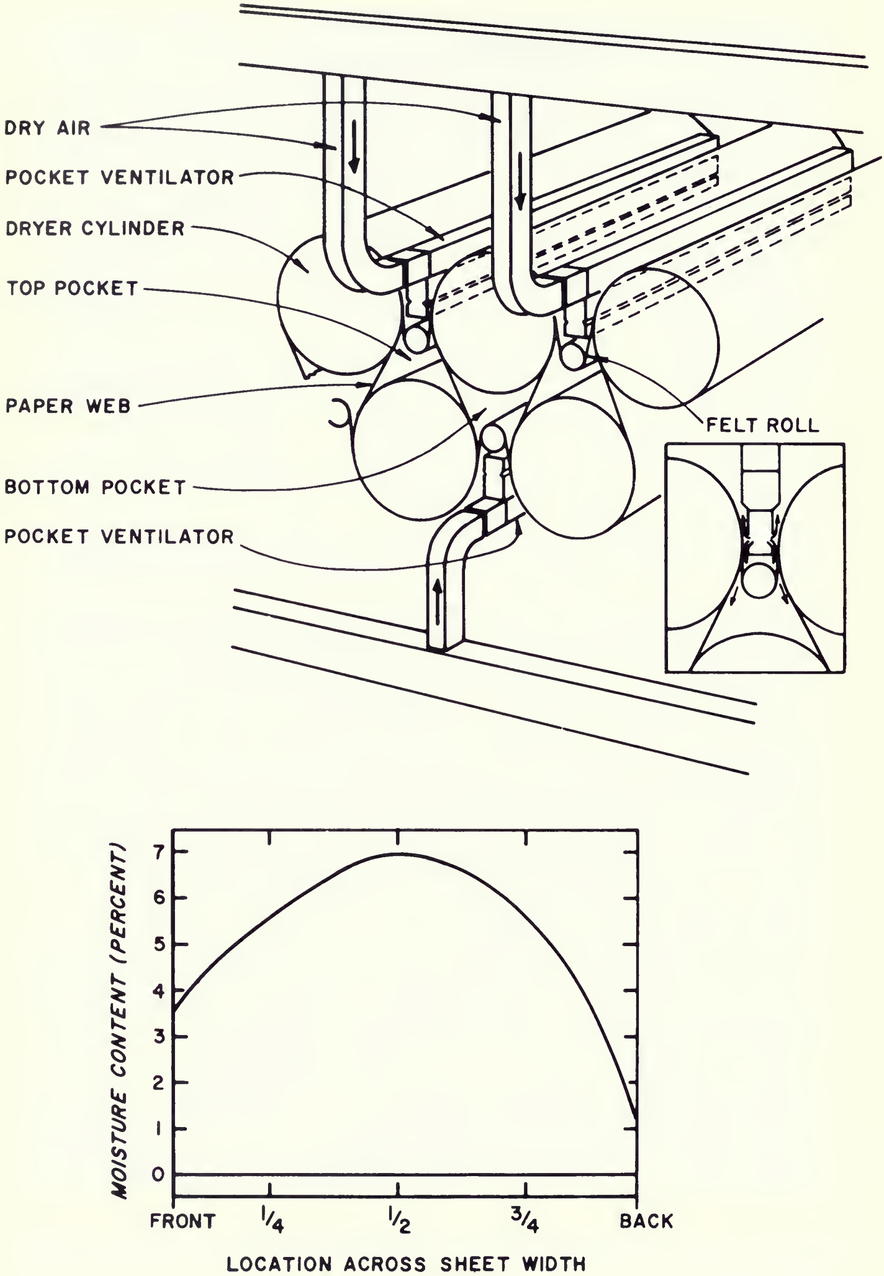

Figure 25-17.—Paper drying. (Top) Paper passes over heated drying rolls; backup felts on top and bottom hold paper in contact with rolls. Pocket ventilators even out variation in moisture content. (Bottom) Example of variation of moisture content across width of paper sheet emerging from dryer. (Top drawing after Gardner 1966; bottom drawing after Metcalfe 1968.)

While variations as prominent as those shown in figure 25-17 (bottom) are not uncommon, current practice when drying newsprint to 8-percent moisture content might give moisture differences across the sheet of ± ¾-percent. Metcalfe (1968) states that with proper attention to drying conditions, moisture differences across the sheet can be reduced to 0.3 percent.

Dryers on modern paper machines are fast, large, and expensive. Newsprint running at 2,500 lineal fpm might pass over 50 rolls each 5 feet in diameter and 25 feet long. Temperature of the first rolls is usually about 180°F, and of the main group of rolls about 240°F. Passage through such a dryer would reduce the moisture content of newsprint from about 62 percent to about 9 percent.

The reader desiring a more fundamental discussion of fiber and mat drying phenomena is referred to Wrist (1966) and Han and Matters (1966). Other papers, that should be helpful to readers desiring additional information include: Coulson (1981); Gardner (1970); Han (1970); Hankin et al. (1970); Herdman (1970); Iannazzi and Strauss (1970); Janett (1970); Kennedy (1970); Khandelwal (1970); Lee and Hinds (1981); Race (1970); Rantala (1970); Sledge and Knox (1981); Wieselman (1970); Rhorer (1971); and Wahlstrom (1970, 1981).

25-4 PRESS DRYING

The shortness and thick walls of hardwood fibers limit their use in paperboards and papers requiring high strength. Extensive beating of such fibers to improve their bonding capability develops excessive fines that cause drainage problems or low wet-web strengths that prevent their use on fast paper machines (Klungness and Sanyer 1981).

As Whitney (1980) has noted, the corrugated container is the principal product of the paperboard industry. Unbleached kraft board, which mostly goes into the linerboard of corrugated boxes, dominates paperboard production (fig. 25-8). Thus, if use of hardwood pulps is to be greatly expanded in southern mills, their utility in corrugated containers must be enhanced by new technology.

V. C. Setterholm and his associates at the U.S. Forest Products Laboratory in Madison, Wisconsin have made significant progress in developing such technology (Setterholm et al. 1975; Setterholm and Benson 1977; Byrd 1979ab; Setterholm 1979; Horn 1979; Setterholm and Ince 1980). They found that **press drying** of hardwood paper, particularly heavier weights such as linerboard and corrugating medium for containers (fig. 25-18), offers outstanding potential. In press drying (fig. 25-19) stiff pulp fibers are dried under a compressive force that induces greater conformability and interfiber bonding, as well as more restraint during drying, than attained by conventional methods for drying paper. The result is paper having the highest specific strength and stiffness available for any given pulp furnish. These improvements over conventionally dried paper increase with increased fiber stiffness; press drying improves paper from high-yield pulp fibers more than that from low-yield well-beaten fibers. Setterholm (1979) found that high-yield hardwood pulp fibers could be press dried to make linerboard (fig. 25-18 top) having higher compression strength and stability than

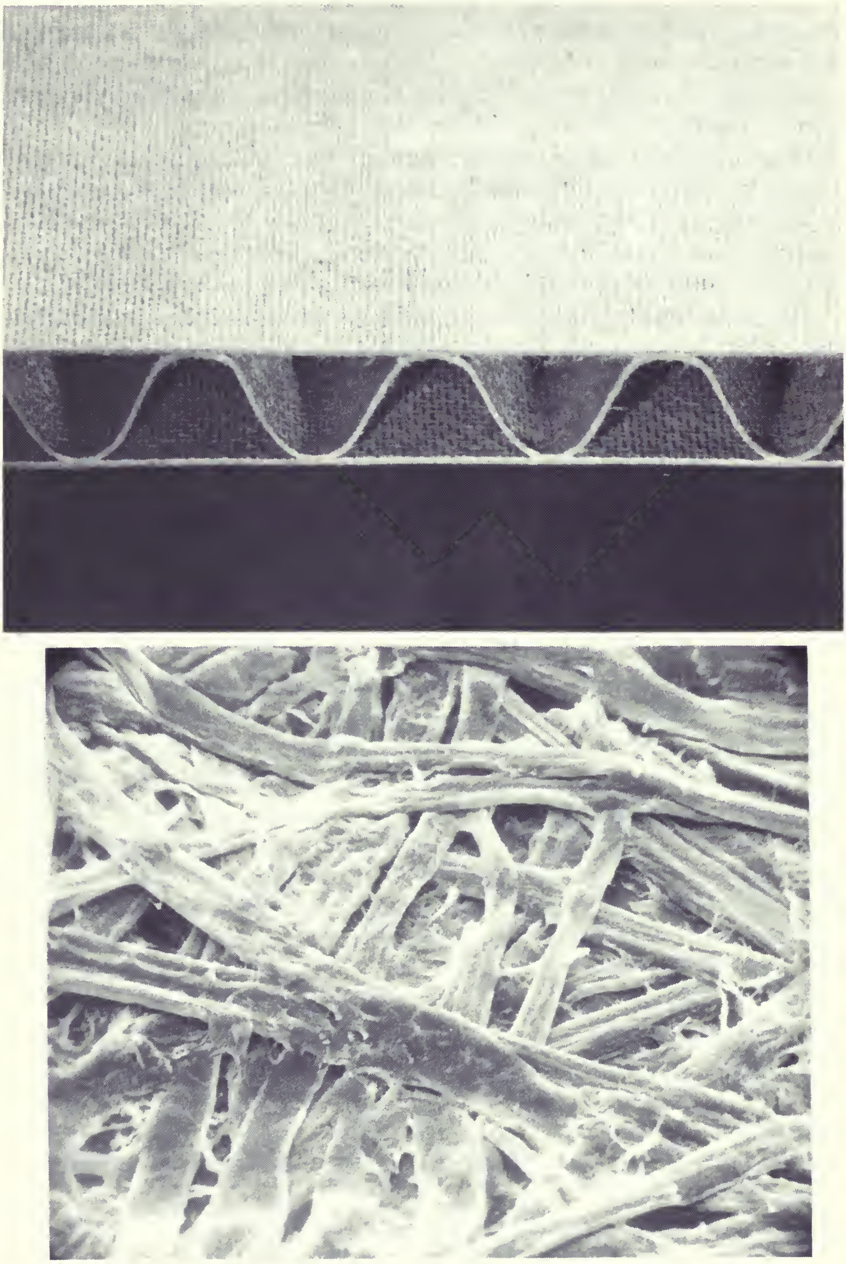

Figure 25-18.—(Top) Linerboard combined with corrugating medium for use in corrugated boxes. (Bottom) Scanning electron micrograph (500X) of press-dried high-yield southern red oak linerboard showing compact consolidation of the pulp fibers. A screened texture on both sides of the sheet is typical of linerboard made by the press drying process. (Photos from U. S. Forest Products Laboratory).

available by conventional technology. Some representative properties of laboratory-produced paper are summarized in table 25-9.

Byrd (1979b) and Horn (1979) found that hemicellulose is primarily responsible for the high levels of bond adhesion and strength developed by press drying. They found that lignin retards the initiation of flow and contributes little to bond adhesion and strength, but does enhance wet-strength development in press-dried high-yield pulps by flowing and protecting the hemicellulose bonds.

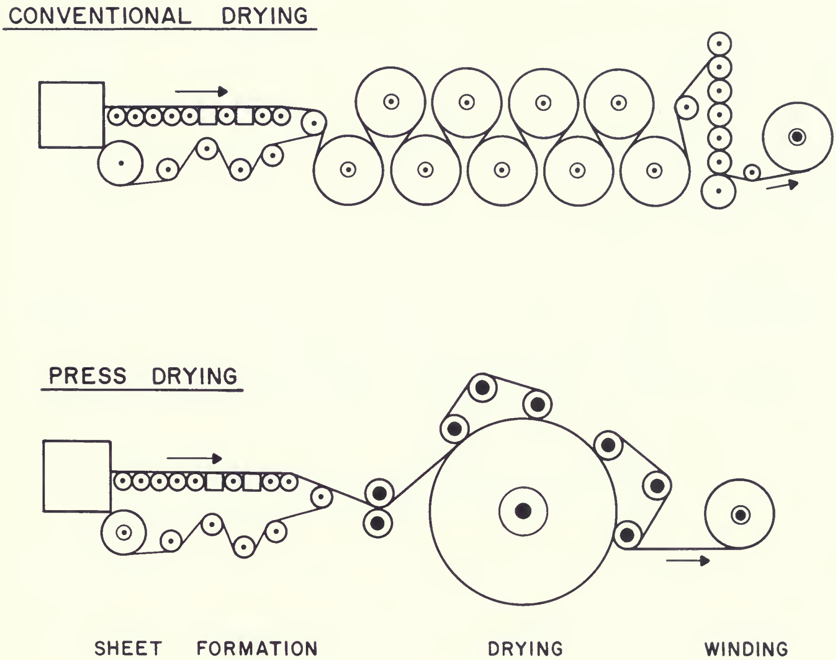

Figure 25-19.—Paper drying systems. (Top) Conventional. (Bottom) Press drying. (Drawing after Setterholm and Ince 1980.)

TABLE 25-9.—*Properties of handsheets of beaten, unbleached, low-yield Douglas-fir kraft pulp dried conventionally compared with those of unbeaten, unbleached, high-yield sweetgum and northern red oak kraft pulps press dried* (Data from Setterholm[1])[2]

Handsheet property	Douglas-fir low-yield kraft beaten pulp conventionally dried[3]	Sweetgum high-yield kraft unbeaten pulp press dried[4]	Northern red oak high-yield kraft unbeaten pulp press dried[5]
Basis weight, g/m^2	205	205	205
Specific gravity	.85	.91	.92
Burst, points	156	125	191
Ring crush, pounds	120	194	205
Folds, number	1,500	180	462
Tear, g	375	176	160
Tensile strength, psi	7,920	8,150	11,110
Modulus of elasticity, thousand psi	774	940	1,170
Strain to failure, %	3.30	2.35	3.32
Edgewise compressive strength, psi	2,700	4,800	5,090

[1]Personal correspondence with V. C. Setterholm December 1981. All paper tested at 7.5 percent moisture content.
[2]Temperatures and pressures used in press drying the hardwood pulps are in the range probably achievable in industrial practice.
[3]53 percent yield, beaten to 550 ml Canadian Standard Freeness.
[4]72 percent yield, pressed at 400 psi and 400°F, to 0 percent moisture content.
[5]60 percent yield, pressed at 800 psi and 400°F, to 0 percent moisture content.

25-5 MECHANICAL PULPING

Methods for making mechanical fiber for hardboard, medium-density fiberboard, and insulation board are described in section 23-6; southern hardwoods are much used in these products.

For paper and paperboard, however, mechanical pulping of southern hardwoods is limited by the low strength of these pulps and by their high power requirements. Accounts of efforts to make paper and paperboard from dense hardwood mechanical pulps follow.

GROUNDWOOD

Stone grinding, in which a bolt of freshly cut wood is pressed against a revolving grindstone, was the first mechanical defibration process developed. It is still widely used to produce mechanical pulp from softwoods to be mixed with chemical pulp for newsprint. Stone groundwood, mostly softwood, is also used for wallpaper, in some toilet tissue, toweling and wrapping paper, and in paperboard for boxboard furnish, bottlecap stock, and matchstick stock. Also, stone groundwood is an important ingredient of groundwood printing papers. For a description of the stone grinding process, and sectional views of a stone grinder and the pulp stone it carries, see Agriculture Handbook 420 (Koch 1972, p. 1421-1425). See also references cited on page 2238 of this text.

The short, thick-walled fibers (tables 5-4 and 5-7), large proportions of vessels and parenchyma (table 5-3), high-density (table 7-7) and excessive color (figs. 5-16 and 5-4 through 5-15) of most pine-site hardwoods reduce their suitability for the groundwood process, and they are little used for paper-grade mechanical pulp.

Schafer and Pew (1942, 1943) found that green ash and hackberry, both light in color, have some potential for the groundwood component of newsprint. American elm yielded a groundwood pulp that is both short fibered and dark colored, which would appear to limit its application to filler stock for dark colored boards and papers.

McGovern and Auchter (1976) tabulated data (table 25-10) on experimental groundwoods produced in 1947 from sweetgum, black tupelo, and yellow-poplar—all medium- and low-density hardwoods comprising about one-third of the volume of hardwoods on southern pine sites; these groundwood pulps were relatively low in strength and required much power to grind. Yellow-poplar approached southern pine in freeness, burst, and tensile strength; tear strength of yellow-poplar pulp, however, was only about one-tenth that of the pine pulp.

Schafer and Hyttinen (1949) stone-ground yellow birch, red maple, American beech, and white oak on a 3-pocket grinder equipped with a 53-inch diameter aluminum oxide pulpstone. They found that red maple produced the strongest pulps and beech the weakest. They concluded that the best use of these hardwood pulps would be as filler pulps in the softer bulkier grades of paper, and that with the possible exception of white ash, the hardwood pulps would need to be bleached before they could be used in appreciable quantities in white papers. Groundwood pulps containing up to 35 percent of these hardwoods, with stone-ground eastern white pine (*Pinus strobus* L.) had strength and brightness suitable for newsprint.

TABLE 25-10.—*Specific energy requirements and properties of experimental pulps obtained by stone grinding southern woods* (McGovern and Auchter 1976)[1]

Species	Wood density (oven-dry basis)	Specific grinding energy[2]	Freeness[3]	Fiber length index[4]	Burst	Tear	Tensile strength
		Hp days/ton	*ml*		*Points/lb*	*g/lb*	*m*
Sweetgum........	0.51	69	50	0.072	0.13	0.37	632
Tupelo, black.....	.51	75	95	.075	.08	.30	210
Yellow-poplar	.40	83	120	.089	.15	.45	870
Southern pine.....	.45	60	115	.090	.17	4.90	850

[1]Based on data from U.S. Forest Products Laboratory files, 1947.
[2]Per ovendry ton of wood
[3]Canadian Standard
[4]Proportional to fiber length

CHEMIGROUNDWOOD

Libby and O'Neil (1950) reviewed potential pretreatments of hardwoods prior to grinding and described their development of a chemigroundwood process by which 2- to 4-foot lengths of hardwood were pretreated in a digester. Optimum strengths and brightness with *Poplus* sp., *Betula* sp., and *Fagus* sp. were obtained with neutral sulfite liquors of sodium sulfite (Na_2SO_3) and sodium bicarbonate ($NaHCO_3$) in water. The sodium bicarbonate partially neutralized organic acids formed during the cook and prevented wood darkening. Liquors containing 1 to 1-½ pounds chemical per gallon and having a chemical ratio of 6:1 (sodium sulfite:sodium bicarbonate) were optimum for pulp strength. About 10 percent of the chemical was consumed during digestion. Wood was subjected to a vacuum for 30 minutes before the liquor was admitted and cooking continued at a temperature of 150°C and a pressure of 200 psi for 6 hours. In their experiment they used a stone peripheral speed of 3,300 fpm, grinding pressure of 40 psi, and grinder pit consistency of 5 percent with temperature of 130°F. Strength values of pulp from beech and birch were further improved about 20 percent and power consumption was lowered 5 hp days/ton if the pretreated wood was stored for 16 hours before grinding. Pulp yields were 85 to 90 percent of the weight of the original wood. The slightly dark pulps could be successfully bleached with sodium peroxide or hydrogen peroxide. The pretreatment increased burst strength of birch groundwood pulp about 10-fold; effect of the pretreatment on tear strength of birch and beech was not reported, but on aspen the improvement was significant.

Hyttinen and Schafer (1955) treated 2- and 4-foot lengths of sweetgum, black tupelo, red oak sp., and other hardwoods with neutral sulfite solutions for 1 to 5.5 hours at temperatures from 125° to 155°C, pressures from 100 to 150 psi, and with liquor concentrations of 0.5 to 1.5 pounds of chemical per gallon. The ratio of sodium sulfite to sodium bicarbonate was 6:1 (4:1 in one test), and the ratio of liquor to wood was about 2.5:1. Mild treatments before grinding increased freeness and the long-fiber fraction of the pulps; strength, brightness, and density were only slightly affected. Increasing the severity of the pretreatment increased the strength and density of the pulps and decreased the brightness and opacity of the papers in which they were used. Chemigroundwood pulps were made that approached neutral sulfite semichemical pulps in strength and could probably be used for the same purposes. The darker chemigroundwood pulps were easily brightened with a single-stage hypochlorite treatment. Hyttinen and Schafer concluded that it might be possible to substitute chemigroundwood pulps entirely, or in part, for softwood groundwood in newsprint, book, and toweling papers. Severely treated sweetgum yielded chemigroundwood equal or superior to spruce groundwood in burst, tear, and tensile strength. A newsprint furnish made with 40 percent black tupelo chemigroundwood along with semibleached southern pine sulfate and southern pine groundwood pulps was comparable in strength and brightness to standard newsprint paper, but was somewhat stiffer; book paper of good quality was made using 60 percent black tupelo chemigroundwood and 40 percent semibleached pine sulfate pulp. The red oak sp. from Arkansas yielded pulp of high strength with low fines content when severely pretreated; the bursting and tensile strength of such red oak pulps were reduced by bleaching, but not sufficiently to lower usability in good quality paper.

Schafer (1961), in a review of wood factors affecting groundwood pulp quality, noted that the strength of hardwood groundwood can be improved by treating the pulp with a hot dilute caustic soda solution. Like chemigroundwood pretreatment, such caustic treatment of the pulp generally reduces bulk, opacity, and brightness of the paper.

Gavelin's (1966, p. 221) text on mechanical pulp manufacture describes two processes by which a few European groundwood mills have been able to utilize hardwoods. In the first of these processes, the logs are peeled, air dried to 30 percent moisture content, cut to 4-foot lengths, and then subjected to a vacuum-pressure cycle of 4 to 6 hours while being impregnated with hot liquor containing about 15 g of sodium sulfite/liter, buffered with sodium carbonate to a pH of 9.4. During the cook, 10 to 12 percent chemicals (based on ovendry weight of wood) are absorbed by the wood and the pH of the liquor drops to 8.2. At the end of the cook the liquor is withdrawn and fortified for re-use. Logs, discharged from the digester, are quenched in cold water and ground on conventional stone grinders. The specific power required is only about half that for ordinary grinding, and pulp yield is 88 to 93 percent. At a freeness of 200 ml such pulps had 40 percent higher bursting strength than hardwood groundwood of 150 ml freeness made conventionally. Gavelin noted that *Poplus* sp. and *Betula* sp. responded well to this treatment, while *Fagus* sp. gave less satisfactory results. Brecht (1958) provided additional data on the process.

In another process (ALB Semicell) used by some European groundwood mills, hardwood logs are treated at 260° to 280°F in horizontal digesters with sodium sulfite solution buffered with sodium carbonate to a pH of 7.5 to 9.4, depending on species. After the digestion cycle, all waste liquor is reclaimed, fortified, and reused. When stoneground, the treated logs yield pulp for use in newsprint and as a replacement for conventional softwood groundwood in printing papers (Barker 1962).

These approaches applied to sweetgum and oak, although shown promising in some laboratory experiments, have not been commercially viable; chemical penetration throughout a whole log is unpredictable causing nonuniformity of the groundwood in woods with specific gravity in excess of 0.50 to 0.55 (Swartz 1962).

PRESSURIZED STONE GRINDING

Because stone grinding requires only about two-thirds the energy per ton pulp required by thermomechanical pulping (TMP) of chips in disk refiners, researchers seek ways to improve the strength of stoneground pulp to more nearly equal that of TMP. One of the possibilities is to steam pressurize the stone-grinding operation and to soften the wood being ground. Experiments on softwoods indicate such pressurization significantly improves stoneground pulp properties with no change in power consumption (Aario et al. 1980). Work by R. Marton (TAPPI 1980) with fairly dense hardwoods, e. g. *Betula* sp., indicates that addition of caustic soda and hydrogen peroxide to the pressurized stone grinding process yields excellent pulps for corrugating medium and cardboards. No data are published on southern hardwoods pulped by this process.

Readers interested in process control of stone grinding will find useful Paulapuro (1977ab), Dornfeld et al. (1978), and DeVries et al. (1978). See also references page 2238.

REFINER MECHANICAL PULP (RMP)

Resource managers seeking commodity uses for pine-site hardwoods are frequently thwarted by the small size and low quality of the stems, and by the diversity of density, anatomy, and color of wood of these species. One method of homogenizing the raw material involves chipping the wood (sometimes with bark included) and defibrating the chips in a disk refiner (see sec. 23-6 and fig. 18-282 and related discussion). Metering wet chips of the major species groups to **disk refiners** in carefully controlled species proportions can produce mechanical fiber with predictable properties.

Southern hardwood fibers prepared by disk refiners are much used to make hardboard, medium density fiberboard, and insulation board. The technology of making refiner mechanical pulp for such products is described in section 23-6.

Even with control of species mixes, however, dense hardwood chips mechanically pulped in a disk refiner may be difficult to use in paper and paperboard because of their short thick-walled fibers, high proportion of parenchyma cells and vessels, and color. The vessel elements of hardwoods—especially the short, wide, barrel-shaped type present in oaks—do not bond readily into a fiber network, and when present on the surface of print-grade papers cause picks on the printing press from tacky inks (Byrd et al. 1967).

THERMOMECHANICAL PULP (TMP)

Thermomechanical pulps are produced by heating wet woodchips prior to disk refining (fig. 25-21 and sec. 23-6). Under proper conditions, the chips are softened, defibrating more completely and with less power (fig. 25-20) than if defibrated cold; the resulting pulp is not discolored (West 1979). Most often, heating and refining are conducted under pressure; some systems, however, heat chips under pressure and refine them at atmospheric pressure. Additional atmospheric refining stages are generally, but not always employed. Even with these process improvements, however, dense southern hardwoods require excessive power to defibrate and generally do not yield paper grades of pulp equal in strength to refiner groundwood from preferred softwoods.

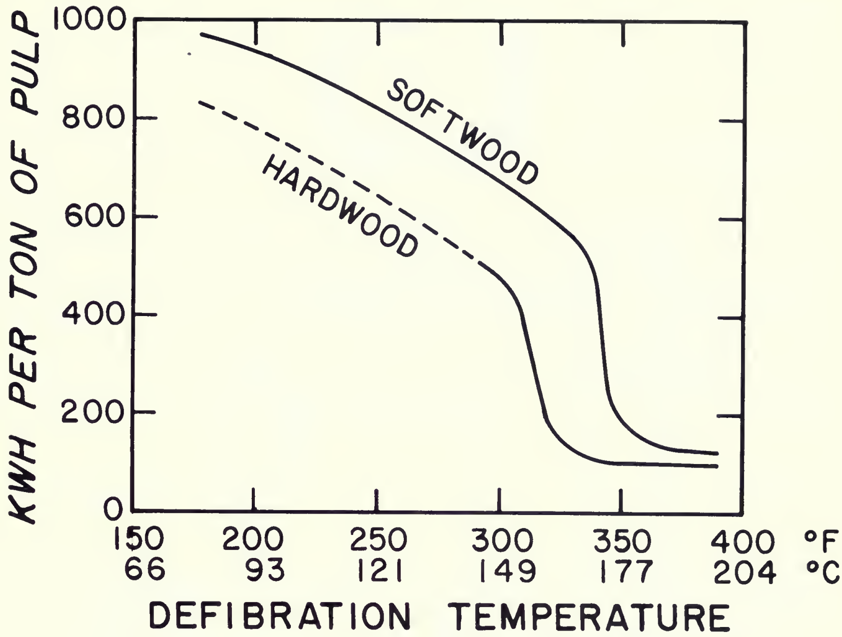

Figure 25-20.—Relationship between wood temperature and energy consumption for defibration of hardwoods and softwoods. (Drawing after Asplund 1939.)

A pilot plant to investigate the pulping of southern hardwoods by the thermomechanical process for paper grades was announced in 1975 (Dillen et al. 1975), but hardwood TMP is little used by southern paper mills.

CHEMI-MECHANICAL PULP (CCMP)

Because in many areas of the world hardwood is locally available at lower cost than preferred softwoods, much research is aimed at production of paper-grade hardwood pulp on a disk refiner. No results applying directly to pine-site hardwoods have been published. With certain hardwoods, notably *Populus* sp., pretreatment of chips with sodium hydroxide and sodium sulfite to produce a **chemi-mechanical** (CCMP) pulp, can yield a high quality pulp which is used in specialty papers and base stock for coating. Meinecke (1972) found that alkali alone causes a pronounced discoloration of CCMP pulps, but the addition of H_2O_2 or Na_2O_2 yields an extremely bright fibrous hardwood pulp.

Paper birch (*Betula papyrifera* Marsh.), a northern hardwood of medium density, has been reported to respond well to chemimechanical pulping (Leask 1968).

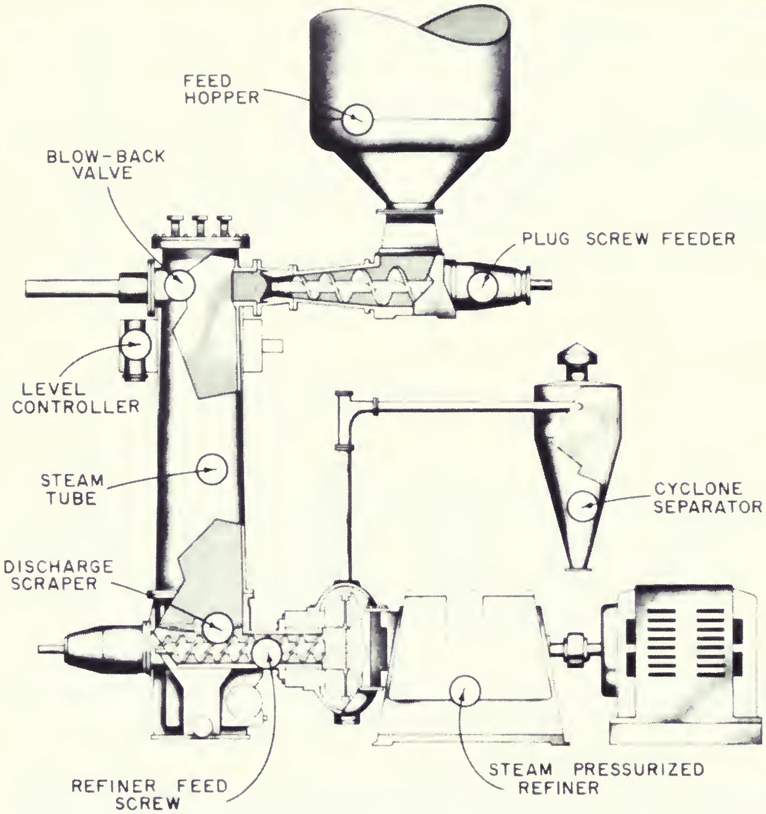

Figure 25-21.—Pressure refining system for TMP. (Drawing courtesy of Sprout Waldron Div., Koppers Co., Inc.)

CHEMI-THERMOMECHANICAL PULP (CTMP)

Nyblom and Levlin (1981) found that a good quality mechanical pulp can be produced from birch if chips are pretreated with alkaline sulfite liquor and then disk-refined; they observed that such pulp, for use as a substitute for groundwood pulp in printing papers, is often bleached with peroxide in the refiner, and finally acidified. The birch **chemi-thermomechanical** (CTMP) pulp, prepared on a pilot scale was intended for use as a magazine paper, and was favorably compared with a spruce (*Picea* sp.) TMP of the same freeness produced in the same refiner as the birch.

An acceptable newsprint can be manufactured from a pulp furnish containing 85 percent aspen (*Populus tremuloides* Michx.) chemi-thermomechanical pulp and 15 percent sulfite pulp (Keays and Leask 1973). McCarty (1973) succeeded in making a 100-percent aspen newsprint from CTMP. In Japan, one of the largest manufacturers of newsprint of the world incorporates a significant proportion of CTMP made from local hardwoods (Namiki 1973).

Kraft black liquor has also been used to pretreat birch chips prior to thermomechanical pulping; Kossoi et al. (1976) found that the black liquor plasticizes the chips and neutralizes acids formed during the cook, thus reducing hydrolysis of hemicelluloses and degradation of the fibers.

Also, *Eucalyptus* sp., is commercially pulped in Tasmania and elsewhere by chemimechanical processes (Higgins et al. 1977, 1978; Gavelin and Lunden 1980).

Northern red oak and five other hardwood species of varying morphology were pretreated by Marton et al. (1979) with sodium hydroxide and sodium sulfite prior to fiberization, or in the disk refiner with hydrogen peroxide in conjunction with second-stage refining. They found that the pretreatment improved strength properties at the expense of yield, brightness, and opacity; these shortcomings were eliminated by in-refiner hydrogen peroxide bleaching which, in addition, allowed savings in refiner energy.

COLD SODA PULP

In their review of mechanical and semichemical pulping of hardwoods growing on southern pine sites McGovern and Auchter (1976) noted that chemimechanical pulping of hardwoods (yields of 85-95 percent) of a wide range of densities started in the mid-1950's and grew to operations in about 20 mills. The process has tended to be superseded by other processes as operation economics and fiber use requirements have changed. Although the development was mostly applied in the North, two **cold soda chemimechanical** installations were made in the South. One of these making a pulp for bleached paperboard was discontinued because of a paper-grade change (Paper Trade Journal 1974). The other, making a brightened news-grade pulp from southern hardwoods, primarily oak, continues successfully; the chemimechanical pulp makes up about 15 percent of the newsprint pulp furnish, and the spent pulping liquor is recovered in the plant's kraft mill system (McGovern and Auchter 1976).

Brown (1958) estimated the following requirements for the manufacture of one ton of cold soda pulp for newsprint:

0.7 cord of oak	86 pounds of lime for bleaching
155 pounds of caustic soda	72 pounds of chlorine for bleaching
40 hp days of energy for fiberizing	

The cold soda process, as developed by the U.S. Forest Products Laboratory consists of steeping hardwood chips in a sodium hydroxide solution at ambient temperature and atmospheric pressure, draining the liquor, and fiberizing the softened chips in a disk refiner. It is a simple process, with high yield, and is applicable to many hardwoods otherwise difficult to pulp. The pulps are characteristically low in brightness, and if the wood is particularly dense incomplete penetration of solution results in a nonuniform pulp—chips being softened on the outside but uncooked at the center. These disadvantages often outweigh the advantages of cold soda and have limited use of the process (Cabella 1963).

Readers interested in the cold soda process as applied to water oak, willow oak (*Quercus phellos* L.), and sweetgum will find Brown's (1959) work useful. Cabella (1963) investigated cold soda pulping of such dense southern hardwoods as southern red oak, white oak, water oak, black tupelo, sweetgum, ash sp., and bitter pecan (*Carya aquatica* (Michx. f.) Nutt.). She concluded that liquor concentrations above 45 to 50 g/liter do not improve pulp strength and tend to darken the pulps. High digestion temperatures give the best strengths, but produce pulps difficult to bleach. For complete liquor penetration at low temperatures, small chips and 2 to 3 hours of retention time are necessary. Of the species studied, only ash was totally unacceptable because of low strength.

As previously noted, cold soda pulps are characteristically low in brightness. Ahlen et al. (1979) found, however, that *Gmelina arborea*, a medium-density tropical hardwood, can be used to produce a pulp for newsprint without bleaching if sodium sulfite is added to the cold-soda impregnating liquid. They also found that cold-soda hardwood pulps are easily bleached with peroxide as well as hypochlorite, but the latter results in lower yield and higher yellowness.

ENERGY TO MANUFACTURE MECHANICAL PULP

At wood temperatures in the range from 300°-350°F, lignin in the middle lamella softens and permits individual wood fibers to be separated from each other with less energy than in cold wood (fig. 25-20). TMP processes exploit this property of wood in a reduction system that involves heating and fiberizing in a revolving-disk mill. Even for heated wood, however, energy required by disk refiners is significantly greater than for other pulping processes. Large disk refiners may be driven by motors totaling 12,000 hp or more. Energy costs for TMP (about $40/air dry ton in 1977) are about 50 percent greater than those for stone groundwood. Chemi-thermomechanical pulp, however, can be fiberized with less energy than that required for stone groundwood. The unbleached kraft pulping process can be almost self sufficient in energy; only in the lime kiln is the use of some fossil fuel necessary. When energy required to manufacture bleaching chemicals is taken into account, energy consumption is somewhat greater for bleached pulp, but is still very low compared with that for mechanical pulping (Poyry 1977). A comparison of energy requirements and yields of various hardwood pulping processes, from stone groundwood to extensive chemical, are shown in table 25-11.

The dense southern hardwoods not only have fiber morphology less well suited than preferred softwoods to the manufacture of mechanical pulps, but their density leads to unusually large expenditures of energy for fiberizing. Readers interested in energy aspects of mechanical pulping with disk refiners, and control of large-horsepower thermal mechanical pulping systems will find useful Poyry (1977), Carty (1977), Koenig and Thompson (1978), Loly (1978), Otis (1978), and Kurdin (1979).

TABLE 25-11.—*Yields and electrical energy requirements of four hardwood pulping processes* (Swartz 1962)

Process	Pulp Yield[1]	Electrical energy requirement[2]
	Percent	*Hp days/ton*
Mechanical stone groundwood, conventional[3]............	90-95	65-75
Chemi-groundwood and chemi-thermomechanical pulp, including cold soda pulp..........................	85-92	40-70
Semi-chemical, including neutral sulfite semichemical.....	60-85	10-20
Extensive chemical, including hot soda, kraft, and acid sulfite and bisulfite	43-52	5-10

[1]Percent of ovendry weight of wood.
[2]Per ton of ovendry pulp.
[3]Thermomechanical pulp disk-refined from chips requires about 50 percent more energy than conventional groundwood.

One possibility for decreasing energy required for production of TMP is use of natural lignin-degrading organisms to loosen lignin bonds in chips before they are fiberized.

In spite of high energy costs, mechanical pulps have low total manufacturing costs because of their high pulping yields and low capital requirement.

Readers interested in further study of the technology of pulping chips with disk refiners will find useful the review of Franzen (1985).

25-6 SEMICHEMICAL PULPING

Semichemical pulping consists of a mild chemical treatment (but more severe than in chemi-mechanical pulping) to remove sufficient of the ligno-cellulose fiber encrustants to allow mechanical treatment to complete fiberizing. Pulps produced from southern hardwood by semichemical pulping are principally used for corrugating medium (fig. 25-18 top).

TRENDS IN MECHANICAL AND SEMICHEMICAL PULP PRODUCTION[7]

Production of mechanical pulps (steam-gun exploded fiber[8], stone groundwood, and disk-defibrated fiber) and semichemical pulps in the southern United States in 1974 was 5.25 million tons, but 2.20 million tons were conventional groundwood pulp which contained little hardwood. The remaining 3.05 million tons were 56 percent semichemical and 44 percent coarse fiber (exploded and disk defibrated) pulps which amounted to 10 percent of the total production of

[7]Text under this heading is condensed from McGovern and Auchter (1976).
[8]For a discussion of this technology see sections 18-27 and 23-6.

pulp in southern United States, i.e., 31.4 million tons. Production of these semichemical and coarse-fiber pulps doubled between 1960 and 1973 at a growth rate of 5.8 percent annually. Products made from these pulps were mainly corrugating medium (i.e., **nine-point**) and fiberboard (hard-board, medium-density fiberboard, and insulating board). There was also a small production of roofing and other felts.

Production trends in the manufacture of **fiberboards** made from mechanical pulps are described in section 23-1 and 23-2, and by figures 29-11 through 29-13.

Felts for roofing, sound deadening, and other purposes were produced in 5 Mid-South plants and 2 Southeast plants having total daily capacities of 234 tons and 100 tons in the two regions in 1974. These felts are made primarily of coarse mechanical pulps.

From 1967 to 1973, southern production of semichemical paperboard grew over 50 percent, for an annual increase of about 7.3 percent (table 25-12). In 1973 about 2.2 million tons of **semichemical paperboard** were produced in the 12 southern states, comprising 12 percent of all paperboard manufactured in the South.

Daily capacity of semichemical plants in 1977 was less in the six Mid-South states (9 plants) than in the six Southeastern states (11 plants), totaling about 2,400 and 3,700 tons respectively.

Two semichemical processes are particularly applicable to southern hardwoods, i.e., the neutral sulfite semichemical (NSSC), and green liquor semichemical (GLSC) processes; see table 25-13 for a comparison of the two processes. In Schroeder's (1976) survey of southern pulp mills, 17 produced NSSC pulp with yields of 63 to 80 percent (average 74.5 percent), all for use in corrugating medium; one mill was using the GLSC process, with interest expressed by several others.

TABLE 25-12.—*Semichemical paperboard production and total paperboard production in the southern United States* (McGovern and Auchter 1976)

Year	Semichemical	Total
	.......*Thousand tons/year*	
1967	1,415	12,333
1970	1,675	15,197
1971	1,854	15,905
1973	2,166	18,040
1974	2,122	17,464

TABLE 25-13.—*NSSC[1] and GLSC[2] pulping of southern hardwoods and properties of corrugating board made from the pulps* (Dawson 1974)

Statistic	NSSC	GLSC
Chemical, percent of ovendry weight of wood		
Na_2SO_3	6.4	—
Na_2CO_3	2.2	5.0
Na_2S	.3	1.8
NaOH	—	.6
Total	8.9	7.4
Yield, percent of ovendry weight of wood	76.7	75.8
Caliper, mils	11.2	10.4
Concora, pounds[3]	68	68
IPC runnability index	74	72

[1]Neutral sulfite semichemical process
[2]Green liquor semichemical process
[3]Flat crush strength

NEUTRAL SULFITE SEMICHEMICAL PULPING[9]

Neutral sulfite semichemical (NSSC) pulping was first developed in 1925 for utilization of tannin-extracted chestnut chips in corrugating medium. After World War II, NSSC pulping for corrugating medium was extended to southern hardwoods; this application continues to be commercially viable.

In neutral sulfite semichemical pulping, a solution of sodium sulfite and bicarbonate is used, usually in the ratios from four to six parts of sulfite to one of carbonate. Pulping with a slightly alkaline solution prevents acid hydrolysis, without removing a major portion of the hemicellulose. Swartz (1962) described batch cooking conditions for hardwoods as 1 to 3 hours at 170°C, depending on end-product requirement.

In a continuous cooking process for 9-point corrugating medium (fig. 25-22), hardwood chips may be presteamed, impregnated with hot NSSC liquor and cooked to about 80-perent yield in a continuous digester, and fiberized in a double disk refiner (see Kato (1961) for more complete process diagram). In this mill, duplicate production lines allow dense hardwoods to be pulped separately from low-density hardwoods.

Cooking chemical requirements are 10 to 15 percent, expressed as sodium carbonate to wood, but the relationships of amount and ratio of chemicals, pH, temperature, and cooking time are not simple. Low-density hardwoods generally produce better pulps than denser woods. For the manufacture of newsprint, NSSC pulps may be produced whose characteristics are between those of regular groundwood and the long-fibered part of the furnish. To produce maximum strength, mechanical treatment is necessary, which reduces opacity and results in "tinniness"; the degree of treatment must be adjusted according to the other components in the furnish to produce the desired result (Swartz 1962). Southern hardwood pulp yields by the process average near 75 percent of weight of ovendry wood (Schroeder 1976).

[9]With some additions related to process description, text under this heading is taken from McGovern and Auchter (1976), with permission of the authors.

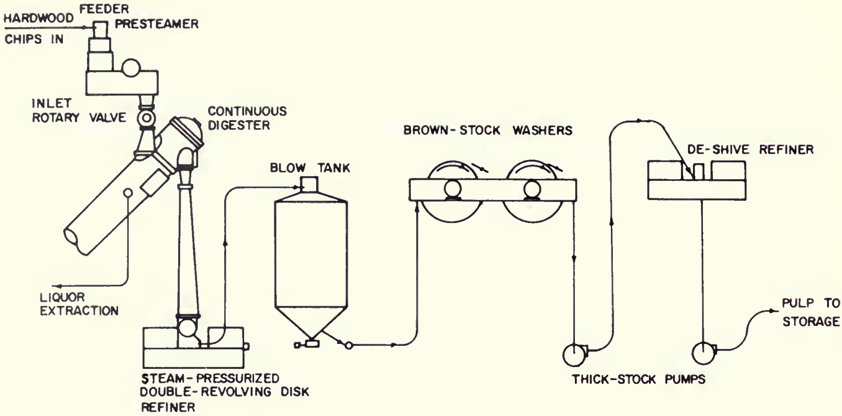

Figure 25-22.—Continuous digester system for NSSC pulping of hardwood chips. (Diagram from the Bauer Bros. Co.)

Unbleached NSSC pulps.—Individual species of southern hardwoods that are commonly found on southern pine sites produce unbleached NSSC pulps with different pulp properties (table 25-14). Sweetgum, black tupelo, and yellow-poplar made stronger pulps than other southern hardwoods; they were lower in bursting and tensile strengths, but higher in tearing resistance than quaking aspen (*Populus tremuloides* Michx.). Data on properties of bleached NSSC pulp are given in table 25-15, but not in units that permit direct comparison with those of table 25-14.

A tendency for chip quality to decrease under stress of procurement has led to the introduction of chip cleaning systems in mills employing continuous digesters. Most southern mills using the NSSC process have both. Whole-tree chips have been used extensively in the manufacture of unbleached NSSC pulps, a development that has greatly increased utilization of southern hardwoods.

TABLE 25-14.—*Yield, strength properties, and sheet density of neutral sulfite semichemical (NSSC) pulps of six southern hardwoods and* Populus tremuloides Michx. (McGovern and Auchter 1976)

Species	Yield	Burst	Tear	Tensile strength	Sheet density
	Percent	*Points/lb per ream*	*g/lb per ream*	*lb/in width*	*g/cm³*
Aspen	78	0.61	0.90	22	—
Ash, white	77	.41	.80	17	.44
Oak, southern red[1]	73	.41	.75	15	.54
Oak, white[2]	74	.31	.75	9	.46
Sweetgum	77	.40	1.07	15	.47
Tupelo, black	80	.40	1.14	16	.39
Yellow-poplar	78	.48	.98	19	.49

[1]Data from Keller and Fahey (1956)
[2]Data from Keller et al. (1959)

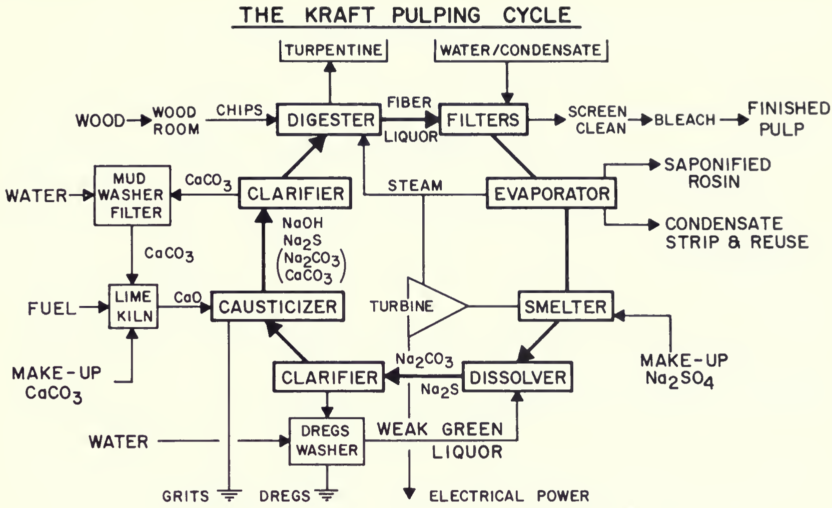

Figure 25-23.—Kraft pulping cycle. Turpentine and rosin yielded during southern pine digestion, are not a product of hardwood kraft pulping. (Drawing after B. K. Mayer; see text footnote 15.)

Bleached NSSC pulps.—Bleached semichemical hardwood pulps were produced in two southern mills in 1960. These and a number of northern mills made pulps from a wide range of hardwoods at higher yields, and about the same or higher pulp strength, than bleached kraft pulps (tables 25-15 and 25-16). These pulps were used in fine papers. The high chemical requirements for pulping and bleaching made the process uneconomical and the last such mill in the United States converted in the 1970s to bleached alkaline-type pulping. The two southern bleached NSSC mills converted to bleached kraft mills.

GREEN LIQUOR SEMICHEMICAL PULPING[10]

The use of kraft green liquor (see figure 25-23 for source of green liquor) in semichemical pulping was practiced as long ago as 1930 in at least one southern mill. Green liquor semichemical pulping (GLSC), utilizing green liquor alone as the pulping agent or as a buffer for sodium sulfite (Dawson 1974), is increasing. Chemical requirements of the NSSC and GLSC processes, and properties of corrugating board made from the pulps are compared in table 25-13. Board property differences are insignificant. The advantage in chemical recovery in GLSC pulping is substantial, especially because it adds less load to recovery systems than NSSC pulping.

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[10]Text under this heading is condensed from McGovern and Auchter (1976).

TABLE 25-15.—*Strength and yield of bleached NSSC pulps from four southern hardwoods sampled on the Arkansas Delta* (McGovern and Auchter 1976)[1]

Species	Burst	Tear	Breaking length	Yield
	Points/lb per ream	*g/lb per ream*	*Meters*	*Percent*[2]
Ash, green	0.25	0.61	1,400	75
Elm, American	.30	.78	1,550	80
Pecan, bitter[3]	.24	.62	1,200	75
Sugarberry.	.45	.82	2,400	75

[1]Data from U.S. Forest Products Laboratory Report No. 1292, dated April 1942.
[2]Percent of ovendry weight of wood
[3]Water hickory (*Carya aquatica* (Michx. f.) Nutt.)

TABLE 25-16.—*Freeness, strength, and yield of bleached and unbleached NSSC and kraft pulps made from mixed southern oaks*[1] (McGovern and Auchter 1976)[2]

Pulp process and bleach	Freeness[3]	Burst factor	Tear factor	Tensile strength	Sheet density
	ml			*lb/inch of width*	*g/cm*[3]
NSSC[4]					
Unbleached	366	44	91	25	0.62
Bleached.	356	67	98	32	.73
Kraft.					
Unbleached	388	56	98	31	.69
Bleached.	359	54	84	30	.72

[1]Sixty percent red oak sp. and 40 percent white oak sp.
[2]Data from Chesley (1959)
[3]Canadian Standard
[4]Neutral sulfite semichemical

NON-SULFUR SEMICHEMICAL PULPING

Lowe et al. (1969) described a proprietary non-sulfur semichemical process that has been applied commercially in two mills pulping northern hardwood mixtures. If the process proves economically advantageous, it could probably be applied to southern hardwoods.

25-7 CHEMICAL PULPING[11]

The kraft chemical pulping process accounts for most hardwood pulped for paper and paperboard in the South. Schroeder (1976), in his survey of pulp mills in the southern United States, found that 79 percent of total hardwood admitted to pulp mills was for bleached kraft pulp (36 mills), 7 percent for unbleached kraft linerboard (21 mills), and 14 percent for NSSC pulp (17 mills) mostly for corrugating medium. About one-quarter of all the kraft pulp produced in the South was from hardwoods.

Schroeder's (1976) survey further showed that one southern mill pulps by the cold soda process producing 220 tons daily at approximately 79 percent yield; the pulp is bleached to 58 GE brightness and used in newsprint as 15 percent of the furnish. One mill pulped by the hot soda process producing 270 tons daily at an approximate yield of 47 percent; after bleaching to 85 GE brightness the pulp is used in fine papers as 63 percent of the furnish. The hot soda process, like the kraft process, is an alkaline delignification process. The Owens-Illinois non-sulfur process is currently used by two northern mills to produce pulp for corrugating medium; one produces about 550 tons per day at a yield of 78 percent, and the other about 1,000 tons daily.

Since hardwoods are easier to delignify than softwoods some newer developments in pulping are more readily adaptable to hardwoods providing wood density is not a limiting factor. Alkaline oxygen pulping of hardwoods should be feasible without encountering the same difficulties presented by southern pines (Nicholls et al. 1975; Fugii and Hannah 1977; McKelvey et al. 1978). Acid sulfite pulping of most southern hardwoods is technically not feasible because of their high phenolic extractive content. Two-stage sulfite pulping, in which the first stage of relatively high pH (Stora process), or alkaline sulfite pulping of hardwoods to obtain a full chemical pulp is possible but perhaps not commercially viable. There would be no advantage over kraft pulping.

The discovery that additions of small amounts of anthraquinone increases the rate of delignification during alkaline pulping (Holton[12], Holton and Chapman[13]) holds promise of increasing pulp yields, and reducing cooking time and temperature. Anthraquinone has been used in a sulfur-free process to pulp birch (Lachenal et al. 1979), and in kraft pulping of Canadian hardwoods (Goel et al. 1980).

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[11]Text under this heading is, with minor changes, taken from Schroeder (1976), by permission of H. A. Schroeder and the Forest Products Research Society.

[12]Holton, H. H. Paper presented at 63rd CPPA-TS Annual Meeting, Montreal, 1977.

[13]Holton, H. H., and F. L. Chapman. Paper presented at TAPPI Alkaline Pulping Secondary Fibers Conference, Washington, D. C., 1977.

SPECIES PROPORTIONS FOR KRAFT PULPING

Unbleached kraft linerboard.—Schroeder (1976) found that the 21 southern mills that incorporated some hardwood pulp in their manufacture of unbleached kraft linerboard daily produced 16,900 tons of pulp, of which 1,515 tons (9 percent) was from hardwood. One mill used as little as 2 percent and others up to 15 percent. Three mills used 4 to 6 percent hardwood pulp in sack or bag paper.

Schroeder's (1976) survey indicated a definite trend to increase the amount of hardwood pulp in unbleached kraft linerboard. Fifteen percent was considered the maximum practical hardwood content, the balance being southern pine. (See sect. 25-4 for a discussion of press drying, a technology that may increase maximum acceptable proportions.) Almost all mills pulped hardwoods together with southern pine primarily because they have only one or two continuous digesters for pulping unbleached kraft linerboard. The few mills that have batch digesters apparently pulp hardwoods and pine separately and blend resulting pulps. Schroeder found that the average yield for unbleached kraft linerboard was 53 to 54 percent with range from 45 to 56 percent.

Pilot scale tests suggest that hardwood content of kraft linerboard furnish could be considerably increased without impairing product quality. Fahey and Setterholm (1960) found that linerboard containing up to 25 percent of sweet-gum kraft pulp could meet standard requirements. Bormett et al. (1981), testing linerboards incorporating 25, 50, and 75 percent red oak kraft pulp blended with southern pine kraft, found that with up to 25 percent hardwood, all carrier strength requirements were met. Linerboards with 50 percent hardwood furnish provided boxes with satisfactory compression strength.

Bleached kraft pulp.—One mill surveyed by Schroeder (1976) produced 1,000 tons of hardwood kraft pulp daily at 32 percent yield—all for dissolving pulp. Thirty-five mills daily produced 15,132 tons of bleached hardwood kraft pulp at yields of about 47 or 48 percent; reported yields ranged from 42 to 63 percent. These pulps were generally bleached to brightness values between 79 and 90+ GE brightness. The bleaching sequences used most often are CEH, CEHD, CEHED, CEDED, and CEHDED[14]. The more stages used, the higher the final GE brightness value, and the more efficient the use of bleaching chemicals.

Schroeder (1976) found that the products produced from bleached hardwood pulps and the percent of hardwood pulp in these products varied considerably. Market pulp usually had the most hardwood fiber; output from a few mills was 100 percent hardwood. Other products usually were in one of three categories depending upon which properties of hardwood pulp were to be exploited. Products such as tissues utilize the softness and absorbency of these pulps. Fine papers utilize the good surface texture and high opacity attainable with the pulps. A considerable amount of the hardwood pulp, however, is used primarily as an

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[14]C is chlorine stage, E is alkaline extraction stage, H is hypochlorite stage, and D is chlorine dioxide stage.

easily bleached filler in such items as food board, white linerboard, milk carton, and cup stock. For most uses of bleached hardwood pulp the amount of hardwood fiber in the product is between 25 and 75 percent.

Preferred species.—Schroeder's (1976) survey indicated that the oaks, except for live oak (*Quercus virginiana* Mill.) avoided because of its high density, were preferred hardwood species for kraft pulping; they accounted for 53 percent of all hardwood pulped. Sweetgum and tupelo sp. were next in importance, comprising 33 percent. All other species accounted for only 14 percent of hardwood pulped. Some mills, in addition to reluctance to accept live oak, also restricted use of hickory, dogwood (*Cornus florida* L.) and locust *Gleditsia* sp.)—probably because of their high density.

KRAFT PROCESS

Pulping cycle and chemical recovery furnace.—The kraft pulping cycle (fig. 25-23) requires wood, water, fuel (usually fossil fuel for the lime kiln plus bark residue for steam and electricity generation), calcium carbonate ($CaCO_3$) in the form of **lime rock,** and sodium sulfate (Na_2SO_4) in the form of **salt cake.** Manufacture of 1 ton of ovendry unbleached southern red oak kraft pulp at 54 percent yield might consume the following raw-materials.

Raw material	Quantity
Southern red oak wood, pounds (ovendry)	3,700
Water makeup, gallons (see text below)	9,000 - 13,000
Electrical energy, horsepower-days (see text below)	5-10
Process heat, million Btu (see text below)	9,000 - 13,000
Lime rock makeup, pounds (see text below)	55
Salt cake makeup, pounds (see text below)	125

The water requirement for producing a ton of unbleached kraft pulp is difficult to determine. A significant and highly variable amount of water which is not considered as makeup water is the moisture in the green chips. Water makeup value given is for all process water, including that for steam generation, brown stock washing, dissolving smelt, lime mud washing, and employee needs. The trend is toward efficient recovery and recycling of water; makeup water needed will therefore continue to decrease.

About 700 pounds of bark (ovendry) would accompany 3,700 pounds of southern red oak (ovendry); in an energy efficient mill this bark, together with the black liquor, can provide about 68 percent of the total electrical and heat energy tabulated above. As mills continue to adopt more energy conservation measures they will approach self sufficiency. If furnace and generating capacity is adequate, the shortfall can be supplied by forest residues (except possibly for the lime kiln).

The lime rock and salt cake makeup quantities indicated are for a mill which is capable of recycling 90 percent of both lime for the lime cycle, and chemicals for pulping. Here also mills are becoming more efficient and the ability to recycle a higher percentage is being realized. At high recycling rates of the pulping chemicals there tends to be a reduction in sulfidity. To correct this situation it may be necessary to add elemental sulfur as a makeup chemical. The cost of lime rock and salt cake makeup, tabulated above, is approximately $3.50 (1981) per ton of pulp.

The chemical recovery furnace is the heart of a kraft pulp mill. Mayer[15] summarized its function as follows:

> "The furnace is fired with spent cooking liquor (**black liquor**) after concentrating it to 65-percent solids. Some combustion takes place immediately in the furnace, but liquor droplet size is regulated to assure its falling on the hearth, where it forms a pile of char. Primary air is introduced under this bed sufficient only to burn the carbon to monoxide. The CO then reduces the salt cake in the char to Na_2S. The char bed is at 1,700°F, enough to melt all the salts and cause them to puddle on the bottom on the hearth. This puddle [**of green smelt**] is allowed to overflow to the outside into a dissolving tank. The non-sulfur salts are all converted to sodium carbonate by the furnace.
>
> "The CO above the hearth is oxidized to CO_2 by secondary air. Its heat content is then extracted by superheaters and the water-cooled walls. Maximum steam temperatures and pressures are 900°F and 1500 psi. Ruptured water wall tubes often cause serious damage if sufficient water is released to react with the hot hearth materials. The superheater tubes must be cleaned on a regular schedule to remove fume deposits that may slag. Heavy entrained fume falls out at the rear of the furnace and is returned to the incoming liquor. Light fume is recovered by electrostatic precipitators with guaranteed 99.5 percent efficiency. This fume is also returned to the feed liquor along with make-up chemical. To minimize the generation of obnoxious mercaptans in the furnace, the black liquor is oxidized with air or oxygen to convert residual sulfides to thiosulfide or sulfites"

Green liquor from the dissolver, primarily $NaCO_3$ and Na_2S, is added to calcium hydroxide (formed by water-slaking calcium oxide from the lime kiln) yielding **white liquor** comprised chiefly of NaOH, Na_2S, and Na_2CO_3. This white liquor is used to digest the wood chips, yielding pulp fibers and the spent **black liquor** which goes to the chemical recovery furnace.

Process references, southern pine.—Texts listed at the beginning of this chapter contain descriptions of the kraft pulping process. Readers needing a succinct review of southern pine kraft pulping will find useful Kleppe's (1970) work summarized in Koch (1972, p. 1431-1446). Kleppe (1978) supplemented this description with a review of high-yield kraft pulping published in the proceedings of the symposium "Complete-tree utilization of southern pine." For process details, readers are referred to these reviews and the literature cited therein.

Process references, hardwoods.—Forman and Niemeyer (1946) made the first comprehensive review of kraft pulping southern hardwoods. Another study published nearly 20 years later, included data on bleaching kraft pulps from southern hardwoods (MacLaurin and Peckham 1955). Bibliographies of hardwood kraft pulping were assembled by Weiner and Roth (1967) and Weiner and Pollock (1972). Other papers on kraft pulping of southern hardwoods include the following:

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[15]Mayer, B. K. 1979. Pulping—A state-of-the-art review. Paper presented at 1979 Fall Meeting, TAPPI/API Coll. Relations Comm. Conf., Houston. 12 p.

Reference	Subject
Perkins (1958)	Kraft pulping and bleaching of southern hardwoods
Schroeder (1976)	Review of techniques, properties, and markets
McGovern (1977)	Oak kraft pulp in offset printing papers
Rushton and Howe (1978)	Wood utilization by the southern pulp and paper industry
Worster (1978)	Hardwood potential for kraft linerboard
Hart (1980)	Potential for expanded hardwood use

The following subsection, which is condensed from Schroeder's (1976) review, contrasts kraft pulping of southern hardwoods to the pulping of southern pine, and compares resulting pulps.

HARDWOOD KRAFT PULPING VERSUS SOFTWOOD KRAFT PULPING

Pulping.—The advantages tend to be with the hardwoods, with a few notable exceptions. An advantage of high density southern hardwoods is that digesters filled with dense wood have greater output capacity than if filled with low-density wood. Digesters charged with oaks will produce more pulp than if charged with southern pine. Outputs from digesters charged with sweetgum and tupelo sp. are about equal to, while those with yellow-poplar are less than, those charged with southern pine.

Energy required by a digester filled with dense wood is not greatly different than that needed to pulp one filled with low-density wood; thus dense wood requires less energy per ton of pulp than low-density wood.

Required liquor-to-wood ratio during digestion is lower for dense than for low-density woods. Chemical requirement is based on wood weight and a lower liquid-to-wood ratio permits use of a more concentrated solution, which uses the chemical more effectively, thereby reducing overall chemical requirement. With a lower liquid-to-wood ratio the solids content of the spent liquor is higher, and the energy required to recover the contained chemicals is lower.

As with dense latewood of pines, exceptionally dense hardwoods, such as live oaks, present a complex diffusion problem, involving penetration of the chemicals into the chip and the cell wall, localized depletion of alkali and outward diffusion of cell wall constituents, especially solubilized lignin. As shorter pulping cycles are adopted, this problem may become critical because reject proportion increases as the pulping cycle is shortened.

The differences in chemical constitution of hardwoods and softwoods give the hardwoods a very distinct advantage in chemical pulping processes, especially in alkaline processes. There is less lignin in hardwoods, it occurs in the cell wall, is less highly condensed than that in southern pine, and it has less tendency to condense under alkaline pulping conditions. Lessened condensation of hardwood lignin is the primary reason why hardwoods are more easily pulped than softwoods, and why it is possible to produce acceptable pulps from hardwoods by the hot soda process but not from softwoods. This is also why it is possible to delignify hardwoods further in chemical pulping than softwoods and why it is easier to bleach hardwood pulps. Kraft hardwood pulps normally have **permanganate or Kappa numbers** (numbers proportional to lignin content) of one-half or less that of comparable softwood pulps. As an example, hardwood pulps are often compared at a permanganate number of 12 ml. (25 ml. basis), whereas softwood pulps are compared at a permanganate number of 25 ml. (40 ml. basis).

Kraft pulp yield (pulp weight as a percent of ovendry wood weight) from hardwoods is higher than from softwoods even though their pulp retains less lignin and screening rejects. Pine-site southern hardwoods have 1.1 to 9.6 percent extractives and these lower pulp yields. Since southern pines have slightly more extractives (3 to 9 percent), their yield is reduced proportionately. The higher hardwood yield stems not only from their lower extractive content, but from their 1 to 2 percent higher average content of cellulose and their higher content of xylan hemicellulose retained in kraft pulping. Yields of bleachable pulp from southern pine are typically 45 to 46 percent as compared to about 48 to 49 percent for oak, sweetgum, and tupelo sp. (ovendry-weight basis).

Pulping costs for hardwoods are less than those for southern pine because kraft pulping conditions are less drastic for hardwoods than for softwoods; depending upon species and type of pulp sought, either the time can be reduced or the temperature lowered or both modified. Whereas southern pines are often pulped at 170-175°C for 75 to 90 minutes, most hardwoods are adequately treated at 160-170°C in 45 to 75 minutes.

Hardwoods can be pulped with a lower liquor-to-wood ratio, a more concentrated liquor solution, and a more effective use of chemical than is possible with southern pine. The amount of active (or effective) alkali required and the sulfidity can be reduced several percentage points. For most hardwoods an active alkali content of 15 percent (13.5 percent effective alkali) and a sulfidity of 20 percent will suffice to give a full chemical kraft pulp with acceptable rejects.

Disadvantage of kraft pulps from pine-site hardwoods include lack of the valuable byproducts (rosin and turpentine) typical of southern pine, and resistance of hardwood pulps to diffuser washing; they are, however, well suited to filter washing.

Beating and bleaching.—Hardwood chemical pulps require less energy for beating than comparable softwood pulps, probably because of their high hemicellulose (specifically xylan) content. The presence of polar groups, especially ionizable carboxyl groups, such as the uronic acids attached to xylan, has a favorable influence on beatability of pulp. The availability of these uronic acids account for most of the differences between sulfite and kraft pulps, and between hardwood and softwood kraft pulps. The power requirement for beating pulps to a given degree of hydration is usually 25 to 40 percent less for hardwood than for softwood pulps. Hardwood pulps, however, must be beaten to much lower freeness values than softwood pulps to obtain anywhere near equivalent values for tensile and burst strength. Commercially, hardwood pulps are not usually beaten to these freeness values to avoid slow drainage on the paper machine due to fragmentation of thin-walled vessels and parenchyma.

Hardwood and softwood chemical pulps are bleached under similar conditions and bleaching sequences. Hardwoods require less chemical for equal brightness. Shrinkage (reduction in yield) during bleaching is usually less for hardwood kraft pulp due to less residual lignin and lower alkaline solubility.

Strength properties.—Hardwood pulps are inferior to softwood pulps in strength, especially tear, and particularly so in comparison with the high strength values for southern pine. As noted in section 25-3, strength properties of pulps are related to fiber length, strength, and morphology. Short fibers, averaging about one-third the length of softwood fibers, are the primary cause of the poorer strength properties of hardwood pulps (figs. 25-11 through 25-13).

Hardwood pulps are rarely used where strength is of importance unless they are fortified with appreciable amounts of kraft softwood fiber. However, additions of hardwood pulps to southern pine pulps in amounts up to 20 percent can improve paper formation without severe strength reduction. In admixtures to 10 percent even a slight increase in tensile and tear strength can result. Mixing the softwood and hardwood chips prior to pulping can achieve similar results in the production of wrapping and sack paper and in food board and linerboard although it is more advantageous to pulp them separately and blend during or after beating (Worster and Bartels 1976).

Press drying of hardwood high-yield kraft pulps holds considerable promise of imparting strength sufficient for their use as linerboard. For a discussion of press drying see section 25-4.

Hardwood kraft pulps possess many desirable characteristics offsetting their low strength properties. Good sheet formation and surface texture, low porosity and high bulk, opacity, softness, and absorbency qualify them for high-grade products for which hardwood pulps are best used bleached and only slightly beaten. They often compete with softwood sulfite pulps for the same uses (Casey 1980). Being absorbent and softer than softwood sulfite pulps, hardwood kraft pulp is well suited for use in tissues. The smooth surface of paper from hardwood kraft pulps gives it good printability, which together with its high opacity makes it ideal for fine papers, although additives may be required to prevent picking, especially in pulps prepared from ring-porous woods. Hardwood pulps with poorer strength properties are often used for bleached facing on linerboard, or more usually as filler in food board, where strength is not critical.

Reaction wood.—In kraft pulping as a means of whole tree utilization, hardwoods possess an advantage over softwoods. Reaction wood of hardwood, such as that found in limbs, is poorer in lignin and considerably richer in cellulose than normal wood. In softwoods the reverse is true, and their reaction-wood lignin appears to be more highly condensed than that of normal wood. The pulping of hardwood limbs should present no difficulties and the yield should be higher than that from stemwood at comparable lignin contents. The resultant pulp, however, should have poorer physical properties because of coarser, shorter fibers. Also the extra cellulose in tension wood is present as a gelatinous layer adjacent to the lumen and therefore not normally involved in interfiber bonding during papermaking (Clermont and Bender 1958).

25-8 DISSOLVING PULP

The art of converting native cellulose fibers into solutions from which other cellulose forms are regenerated has been known since the late 1800s; large-scale use of wood cellulose for man-made fibers began in 1916, 1919, and 1921 by application of the **acetate, cuprammonium,** and **viscose** processes, respectively. From these beginnings, uses for **dissolving pulp,** the dry, loosely matted sheets of refined fibers used for chemical processing (also termed chemical cellulose) have grown along with other uses for wood fiber. Four southern mills manufacture dissolving pulp—at least one of which uses southern hardwoods—and in 1969 they produced about 40 percent of all **market pulp** made in North America, that is, pulp manufactured by one organization and used by another.

The technology of dissolving pulp manufacture and its conversion into regenerated cellulose products such as fiber and film (cellophane) by the viscose process, and fiber, film and tow (in cigarette filters) by the acetate process is complex. For a summary the reader is referred to Durso (1969), reproduced with minor revisions in Koch (1972, p. 1454-1463).

Rayon is produced by dissolving cellulose and then reprecipitating it under conditions favoring orientation and crystallization. Rayon, like cotton, can have moisture absorbent properties that make it highly desirable for certain textiles and non-woven fabrics, a characteristic not shared by other synthetic fibers such as polyester and nylon. Limited world cotton supplies at economic prices may afford a market for expanded production of improved rayon if new methods for its manufacture were invented to reduce capital costs to a range commensurate with plant costs required for synthetic fibers, and to reduce pollution problems. Hergert et al. (1978) reviewed technology for rayon manufacture, and concluded that the ideal system is yet to be discovered, but that a major new system will likely be developed.

Most southern dissolving pulp is made from southern pine by the prehydrolysis kraft process, but hardwoods are also used (Logan 1952, Simmonds et al. 1955; Makukha et al. 1976; and Kosaya et al. 1978). Literature specific to conversion of dense pine-site hardwoods to dissolving pulp is scarce.

CELLULOSE ETHER DERIVATIVES

Cellulose ether derivatives are traditionally made from chemical cellulose (mostly from wood), pulped and bleached by conventional operations that chemically remove lignin and hemicelluloses, then dried at high temperature. These operations, particularly drying, alter molecular structure and significantly reduce accessibility of cellulose to etherifying reactions. Carboxy methyl cellulose (CMC) is produced when chloroacetic acid is the etherifying reagent.

To increase accessibility of the cellulose during etherifying reactions, to simplify the process, and to broaden the potential raw material source for cellulose derivatives, Durso (1976, 1978, 1981) invented a system of producing

CMC from whole tree chips of southern hardwoods which eliminates the intermediate drying step. By his process, whole-tree hardwood chips are fiberized in a disk refiner; a caustic reagent is applied as a mist sprayed into the disk refiner at a point approximately half the distance between the center of the disk and the outside periphery. The etherifying reagent is introduced separately by spraying it into the refiner between the point the caustic was introduced and the disk periphery. Both reagents contact the wood while it is being fiberized and while it is in a fluid state. Durso (1981) found that once the etherifying reaction is initiated, the fiberized wood material can be conveyed to any suitable vessel until the reaction is completed. Reaction time is temperature dependent, ranging from about 100 to 5 minutes with reaction temperatures from 55 to 95°C, respectively.

After the reaction, the ether derivative can be dissolved from the unreactive wood components and recovered by precipitation with alcohol, if a pure derivative is desired. For a technical-grade derivative, one typically containing salt, the entire reaction mass may be dried and ground to suitable particle size.

25-9 PULPING OF WHOLE-TREE HARDWOOD CHIPS

Forest managers in the southern pine region need economic commodity uses for the pine-site hardwoods to facilitate intensive silviculture and thereby increase yield from their lands. Moreover, they need markets that will accept the mixture of species and diameter classes that naturally occur. Fiberboards (Chapter 23), structural flakeboards (Chapter 24), and energy wood (Chapter 26) are commodities that can provide these needed markets. Pulp and paper products, however, probably have most promise.

For any particular species mix, a pulping procedure can probably be devised; one of the most difficult problems facing a potential user of southern hardwoods, however, is maintenance of a stable mix of species. Eschner (1977) identified the biggest problem in the paper industry as follows: "How can the mill get uniform stock to the wet end of the machines?"

Most of the economic systems for harvesting cull pine-site hardwoods call for chipping trees entire, to yield whole-tree chips with bark in place (figs. 16-18, 16-45, and 16-49 through 16-56). In summer, these whole-tree chips cannot be stored for any appreciable length of time. If stored even for a short time in the chip van, the chips start to blacken. For this reason, mills should unload whole-tree chips on arrival for direct delivery to the mill. Removal of fines during field chipping slows chip deterioration while in storage.

The progress of weight loss in piles of whole-tree chips is similar to that in piles of bark-free wood chips, except that in piles of whole-tree chips incorporating leaves and bark, deterioration is more rapid and problems with heat buildup are more severe. Moran[16] reported that the decay rate for mixed hardwood

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[16]Moran, J. S. 1975. Kraft mill experience with whole-tree chips. Presentation at TAPPI Annual Meeting, New York, Feb.

whole-tree chips (mainly oak) stored in an outside pile was approximately three times that for clean debarked chips. Weight loss, and changes in temperature, moisture content, heat of combustion, and pH are all manifestations of incompletely understood reactions within piles of whole-tree chips. For a discussion of these factors see figures 11-21 through 11-24 and related text.

For a summary of effects on the pulping process of including bark with wood of hardwood chips to be pulped, see section 13-18 INDUSTRIAL UTILIZATION, under the subsection PAPER; also see table 13-48.

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26

Energy, fuels, and chemicals

This chapter is slightly condensed, with some revisions, from J. Karchesy and P. Koch's (1979) General Technical Report SO-24, "Energy production from hardwoods growing on southern pine sites," available from the U.S. Department of Agriculture, Forest Service, Southern Forest Experiment Station, New Orleans, La.

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Chapter 26

Energy, fuels, and chemicals

CONTENTS

Chapter 26

Energy, fuels, and chemicals[1]

26-1 INTRODUCTION

The United States uses about one-third of the total energy produced in the world. Since the 1973 oil embargo, we have become aware that our energy sources are not inexhaustible and they are no longer cheap. We are compelled, therefore, to assess our energy needs for the future and to seek new sources.

The amounts of energy consumed today are very large and are therefore measured in millions of barrels per day oil equivalent or in quads. A barrel of oil has a heat content of 5.55 million British thermal units (Btu) (Exxon Company 1978). One quad is equal to 10^{15} Btu's or about 494,000 barrels of oil per day for a year, as follows:

$$1 \text{ quad} = \frac{10^{15} \text{ Btu}}{5.5 \times 10^{6} \text{ Btu/barrel} \times 365 \text{ days}} = 493{,}644, \text{ barrels}$$

The U.S. Department of Energy (1978a) has projected that by 1990 the total consumption of energy by the United States could range from 100.7 to 109.4 quads per year.

In another projection of demand (Exxon Company 1978), the United States is forecast to increase its energy consumption from 38 million barrels per day oil equivalent (just under 77 quads annually) in 1977 to 51 million barrels per day oil equivalent (103 quads annually) by 1990. The assumptions made in this projection include the following: the growth rate of the gross national product will be just under 3.6 percent annually; environmental goals will be achieved at a rate comparable with economic growth; and oil imports will be available at a price that will increase at about the same rate as inflation.

Historically, U.S. energy consumption per unit of gross national product has been declining and forecasts of energy demand in the year 2000 have also been steadily declining since 1972. Forecasts which were among the lowest when made in 1972 are comparable to the highest forecasts made in 1978. The MITRE Corporation (1981) concluded that an energy demand of 50.5 million barrels of oil equivalent per day in the year 2000 is probably a high estimate.

Oil is expected to remain the predominant fuel through 1990 (fig. 26-1). Oil and gas are expected to supply a smaller proportion of total energy, 43 and 17 percent respectively in 1990, as compared with 48 and 27 percent in 1977, although oil consumption is expected to increase from about 18 million to about 22 million barrels per day. Nuclear energy (which is limited to electric utility use) may increase to 10 percent of our energy base. Hydroelectric and geother-

[1]Text and illustrations in chapter 26 are taken, with minor revisions, from Karchesy and Koch (1979).

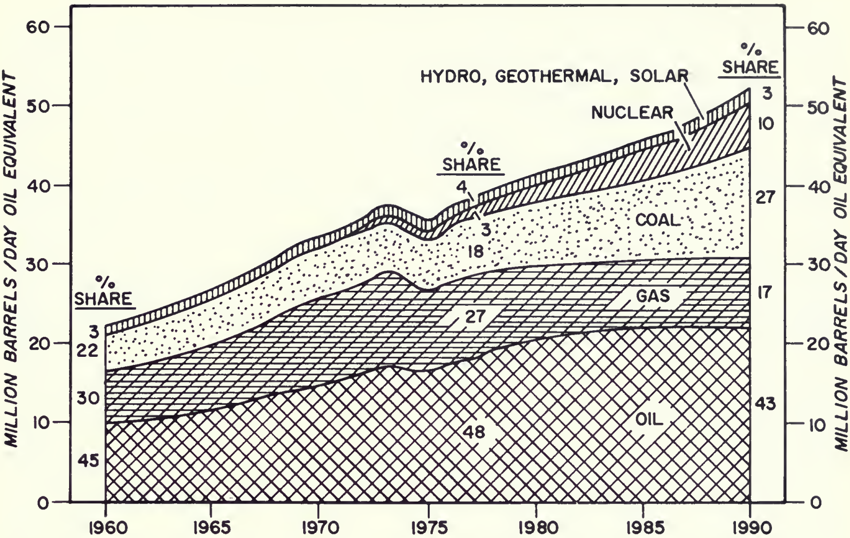

Figure 26-1.—U.S. energy supply projected to 1990. Top line represents 100 percent of the energy supply which is broken down into contributing percentages from oil, gas, coal, and nuclear energy, and hydro, geothermal and solar energy. (Drawing after Exxon Company 1978.)

mal energy have small growth potentials due to the limited number of sites where such energy is available.

The Department of Energy estimates the proven domestic reserve of coal in the United States at about 4,000 quads (fig. 26-2). However, logistical and

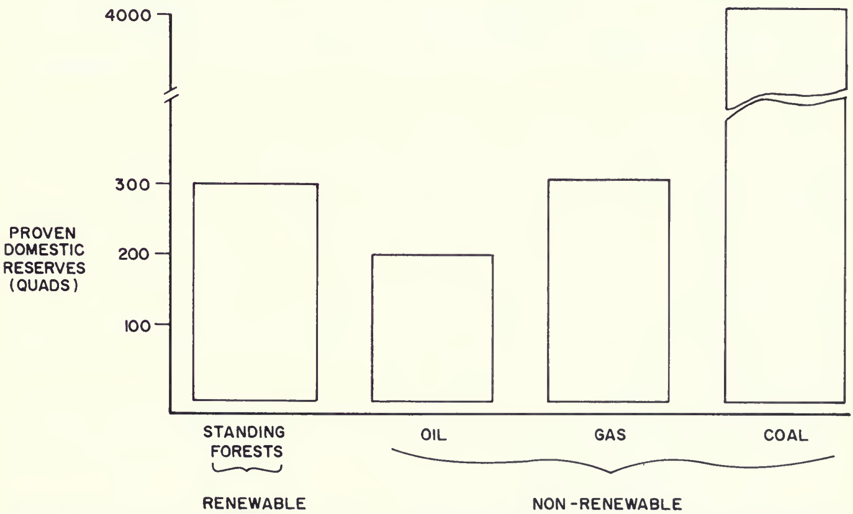

Figure 26-2.—Proven reserves of energy in the U.S. Renewable reserves are considered to be 730 million acres of standing forests with an annual production of 7 to 8 quads. Oil, gas, and coal are the non-renewable resources. Coal is the largest reserve with about 4,000 quads, about 8 times the oil plus gas total. (Drawing from Department of Energy.)

technological gaps prevent us from fully using this potential now. Extensive research and development are underway to find methods for converting coal into fuels that are economically acceptable and environmentally clean. Coal usage is expected to more than double in quantity and to provide 27 percent of our energy base in 1990 as compared to 18 percent in 1977.

Among potential sources, one that has generated considerable interest—mainly because it is renewable—is **biomass,** that is, living matter. For example, the U.S. Department of Energy and others are assessing the technical and economic feasibility of using intensively managed, short-rotation tree farms as a source of energy for the future (Inman et al. 1977; U.S. Department Energy 1979ab; Dawson et al. 1978; Inman and Salo 1978; Krinard et al. 1979). Malac and Heeren (1979) provided an economic evaluation of intensive hardwood plantation management yielding 50 percent more volume at one-third the cost of natural regeneration.

Essentially biomass is a form of stored solar energy. Green plants use sunlight as energy in **photosynthesis** to convert carbon dioxide (CO_2) and water (H_2O) to higher energy carbohydrates $(CH_2O)_n$ and oxygen (O_2), together with other compounds such as hydrocarbons, fats, and proteins in the process (Calvin 1976; Bassham 1980). Overall photosynthetic conversion efficiency for plants in the temperate zone ranges from 0.1 to 1 percent of the total available sunlight. Calvin (1976) envisions that eventually synthetic systems will be developed to simulate plant photosynthesis in producing renewable fuel.

Estimates of the annual storage of solar energy in the U.S. biomass system are as high as 80 quads a year (Falkehag 1977). The U.S. Department of Energy estimates 7 to 8 quads are produced annually in our forests (Del Gobbo 1978). Standing available forests contribute about 300 quads to the proven reserves of energy in the U.S. (fig. 26-2).

The equivalent of about 4 quads of our forests are harvested annually for lumber and paper products. These products are more valuable than fuel. However, the residues from these resources can be, and many of them are, utilized for energy.

The forest products industry already produces (1983) about 1.5 quads of energy from its residues. In the near term, an additional 0.5 to 1.0 quad could be realized from combined forestry and agricultural residues. The projected contribution of biomass to our national energy requirements by the year 2000 ranges from 3 to 8 quads. (Del Gobbo 1978; Zerbe 1977). To aid in achieving this goal, the Department of Energy has established a Fuels from Biomass Program. Its objective is to develop technologies for the preparation, harvest, and conversion of renewable biomass into clean fuels, petrochemical substitutes, and other energy-intensive products (Del Gobbo 1978).

In the South, hardwoods growing on pine sites are a virtually unused source of biomass. Over the years attempts to use these hardwoods have been thwarted by the diversity of species, scattered occurrence, smallness and shortness of boles, branchiness of crowns, and prevalence of knots. Therefore, most of these hardwoods are destroyed during site prepartion for pine—a destruction that is wasteful and costly (perhaps $100 per acre in 1981). Economic uses for these hardwoods would be desirable and several utilization schemes have been proposed (Goldstein et al. 1978; Koch 1978, 1982). In the energy self-sufficient Koch approach featuring tree pullers, swathe-felling mobile chippers, and shaping-lathe headrigs to make diverse products including structural flakeboard, over 50 percent of complete-tree biomass of all species could be recovered as solid wood products. In the Goldstein et al. approach, entire hardwood trees are chipped in the woods. Such chips can be used for fuel, production of chemicals, or for fiberboard.

Chapter 16 reviews methods for harvesting hardwoods growing among southern pines; many of the methods discussed are appropriate for energy wood. Also, sections 28-7 and 28-9 analyze the economic feasibility of several systems of harvesting pine-site hardwoods for energy.

Sections that follow summarize the potential of using the pine-site hardwoods, or their residues from manufacturing processes, as a source for energy, fuels and chemicals. Conversion processes that are available or near at hand are described, and potential uses and economics of the conversion products are discussed.

In gaining a perspective of the potential for converting wood to heat energy, fuels, and chemicals, it is useful to summarize conversion efficiencies by major processes (table 26-1). Maximum energy recovery is attained by combustion, with recovery by other processes ranging downward to 25 percent or lower. For example, boilers burning green hardwoods to produce steam may be about 63 percent efficient, but overall energy recovered by converting green hardwood to steam and then to electrical energy may be only 25 percent. Interpretation of the Btu yields shown in table 26-1 also requires knowledge of the values of different products; e.g., a Btu in the form of heat energy (hot combustion gas) has significantly less market value than a Btu of pipeline-grade gaseous fuel, a Btu of ethanol liquid fuel, or a Btu of electrical energy.

These energy recovery data require considerable interpretation, and will be discussed in more detail in following sections.

TABLE 26-1.—*Yield of heat energy, fuels, and chemicals from a ton of hardwood, ovendry basis*[1]

Wood conversion process	Charcoal	Oil	Low-Btu gas	Methanol	Ethanol	Other chemicals	Animal food	Total[2]
Destructive distillation, small scale								
Pounds	600	—	137[3]	40[4]	—	700	—	1,477
Million Btu	7.2	—	0.5	.4	—	7.0	—	15.1 (50-89%)[5]
Gasification, small scale (to gas)								
Pounds	—	—	3,960	—	—	—	—	3,960
Million Btu	—	—	14.4	—	—	—	—	14.4 (60-85%)
Pyrolysis, small-scale								
Pounds	330	660	660	—	—	—	—	1,650
Millon Btu	4.0	7.2	2.4	—	—	—	—	13.6 (45-80%)
Gasification, large-scale (to methanol)								
Pounds[4]	—	—	—	670	—	—	—	670
Million Btu	—	—	—	6.5	—	—	—	6.5 (38%)
Fermentation to ethanol, small scale								
Pounds	—	—	—	—	397[4]	—	[6]	397
Million Btu	—	—	—	—	5.1	—	[6]	5.1 (22-33%)[7]
Conversion to electricity, via steam turbine								
Million Btu	—	—	—	—	—	—	—	4.3 (25%)[8]

[1]Assumes 100 percent of the heat content of an ovendry ton of hardwood totals 17 million Btu.

[2]The number in parentheses following the Btu value is the percentage of 17 million Btu heat content of the wood.

[3]One pound of low-Btu gas is equivalent to 36.4 standard cubic feet of low-Btu gas, is equivalent to 3,640 Btu.

[4]Both methanol and ethanol weigh about 6.6 pounds per gallon.

[5]The 89-percent upper efficiency for destructive distillation is perhaps misleading becuase the low-Btu gas produced would probably be used (possibly with some additional wood or coal) to heat and recover and purify the chemicals. Accounting for these heat expenditures, 50 percent efficiency may be more realistic.

[6]A small amount of yeast.

[7]Some authorities estimate heat recovery efficiency of the dilute-acid hydrolysis process for ethanol only at 22 percent, but if ethanol and electricity are co-produced efficiency may be 33 percent.

[8]One kWh is equivalent to 3,412 Btu.

The literature describing utilization of biomass for energy is large and expanding rapidly. Readers needing information additional to that summarized here will find useful the following texts, proccedings, and bibliographies:

References	Subject
Forest Products Research Society	
1975	Wood residue as an energy source
1977	Energy and the wood products industry
1979	Hardware for energy generation in the wood products industry
1980	Energy generation and cogeneration from wood
1981	Industrial wood energy forum—'81
1983	Industrial wood energy forum—'82
Current, continuing	Energy bibliography
Corder (1975)	Wood and bark residues for energy
Shelton (1976)	The woodburner's encyclopedia
Tillman (1978)	Wood as an energy resource
Bio-Energy Council (1978)	Bio-energy directory
Jones and Radding (1978)	Conversion by advanced thermal processes
Sarkanen and Tillman (1979)	Progress in biomass conversion
Robinson (1980)	Fuels from biomass
Bente (1981)	International bio-energy directory
Goldstein (1981)	Organic chemicals from biomass
Kirk et al. (1980)	Lignin degradation
Technical Insights, Inc. (1980)	Biomass process handbook
Wise (1981)	Fuel gas production from biomass
Solar Energy Research Institute (1981)	Alcohol fuels bibliography
Klass (1981)	Biomass as a fuel source

Additionally there are a number of computerized data bases available that specialize in energy from biomass. The U.S. Department of Energy (1978b) published a guide to such data bases produced by the DOE Technical Information Center. The Forest Products Research Society, Madison, Wis., offers an information retrieval service (FOREST) specializing in energy from wood. The U.S. Department of Commerce, National Technical Information Service (1978) also has energy-related data bases available. There are others, too numerous to mention.

Also, several institutions regularly publish information bulletins reporting current developments in the field of energy from wood. Among these are: *Quads* published by the Forest Service, U.S. Department of Agriculture, Madison, Wis.; *Biomass Digest* published by Technical Insights, Inc., Fort Lee, N.J. An "Annotated bibliography of wood energy periodicals" is obtainable from the Resource Policy Center, Thayer School, Dartmouth College, Hanover, N.H.

In this text, chapter 28 contains economic analyses of eight enterprises for conversion of pine-site hardwoods into energy-related products, as follows:

Section	Capital investment and enterprise
28-1	$13,000.—Cost of owning and operating a 65-hp (drawbar) diesel tractor on wood gas.
28-5	$292,550.—Small-scale production of ethanol and furfural.
28-6	$350,000.—Wood gasifier retrofitted to existing gas/oil-fired boiler.
28-7	$336,838.—Modification of conventional harvesting systems to recover forest residue in bales.
28-9	$603,000 to $975,00.—Chip harvesting by three systems.
28-10	$700,000.—Manufacture of charcoal, oil, and gas with a portable pyrolysis plant.
28-20	$4.5 to $13.0 million.—Charcoal and fuel gas production with a Herreshoff carbonizer.
28-33	$93.6 million.—Production of ethanol, furfural, and lignin products by hydrolysis.

26-2 THE RAW MATERIAL

THE RESOURCE

In chapter 2, it was noted that the total hardwood resource of the South recently was estimated at 113.7 billion ft^3 which amounts to 2,051 million tons of ovendry wood and bark. This resource spread over 12 states, can be divided into that on southern pine sites and that on hardwood sites. Christopher et al. (1976) found that hardwoods on pine sites total about 49.2 billion ft^3 of wood (888 million tons of wood and bark, ovendry) or 43 percent of total hardwood inventory (from summation of tables 2-7 through 2-18).

The inventoried hardwoods (table 26-2) are only about one-half of the total hardwood biomass (excluding foliage) grown on these sites; the other half is in roots, stumps, and branches of inventoried stems and in trees smaller than 5 inches d.b.h.

Oaks comprise 47 percent of the 12-state **inventoried volume** of hardwoods on pine sites. Sweetgum and white oak are the leading species, each with an inventory of more than 6 billion ft^3. The hickories, third in abundance, are widespread. The five most abundant pine site hardwoods, sweetgum, white oak, hickory, southern red oak, and post oak, and the seventh, black tupelo, are well respresented in all 12 states. Yellow-poplar, scarlet oak, and chestnut oak are scarce or absent west of the Mississippi and in Florida. Black oak is plentiful except in Florida, Texas, Louisiana, and Oklahoma. Among other species making up 2 percent or more of the hardwood on pine sites, red maple is well distributed except in Oklahoma, water oak is scarce only in Tennessee and Oklahoma, and northern red oak is scarce in the Gulf states.

TABLE 26-2.—*Species volume on pine sites in the 12 southern states*[1]

Species	Volume	Proportion of pine site hadwood volume
	Million cubic feet	*Percent*
Sweetgum	6,508	13.2
Oak, white	6,058	12.3
Hickory, spp	4,173	8.5
Oak, southern red	3,994	8.1
Oak, post	3,444	7.0
Yellow-poplar	3,421	7.0
Tupelo, black	2,710	5.5
Oak, water	2,332	4.7
Oak, chestnut	2,102	4.2
Oak, black	1,949	4.0
Oak, scarlet	1,799	3.6
Maple, red	1,751	3.6
Oak, northern red	1,169	2.4
Oak, laurel	683	1.4
Elm, spp	668	1.4
Oak, cherrybark	579	1.2
Ash, spp	441	.9
Sweetbay	300	.6
Oak, Shumard	120	.2
Hackberry, spp	57	.1
Other hardwoods	4,978	10.1
Total hardwoods	49,236	100.00

[1]From tables 2-7 through 2-18.

Carpenter (1980) estimated that from eastern and southern forests, 138 million tons per year (ovendry-weight basis) of **forest residues** of all species could be used for fuel if conditions and technology existed for their economic harvest. About two-thirds of this forest residue is in the South, where it is about equally divided between hardwoods and softwoods. Thus Carpenter's data indicate that annually in the South, about 46 million dry tons of hardwood logging residue and rough, rotten, and salvable dead trees from which products were not taken, could possibly be used for fuel.

Harvesting the hardwoods found where southern pines grow is difficult and expensive as described in Chapter 16. Data on distribution of tree biomass weight are provided in section 16-1 and information on quantities of logging residues in section 16-2. Section 16-3 provides some information on tract size and volume. For data on energy expended during harvesting, see section 16-4.

PHYSICAL AND CHEMICAL CHARACTERISTICS

To assess the energy potential of pine-site hardwoods, it is necessary to know their specific gravity, moisture content, heat (energy) content, and chemical makeup.

Tree wood specific gravity (based on ovendry weight and green volume) ranges from 0.40 in yellow-poplar to 0.66 in post and white oaks. Tree bark, which constitutes about 18.8 percent of above-ground biomass (foliage excepted) in 6-inch trees, ranges in specific gravity from 0.34 in winged elm to 0.64 in blackjack and northern red oaks (table 7-7). In-place densities of wood are given in table 7-2 and those of bark in table 13-40. Bulk densities of particulate fuels in various forms are given in section 16-13, in table 13-42, and in related discussion.

Moisture content of stemwood of 22 of the species arithmetically averages 73.5 percent of ovendry weight (42 percent wet basis); bark averages 67.2 percent moisture content on a dry basis and 40 percent on a wet basis (table 8-2). Stemwood of sweetgum has highest moisture content at 120.4 percent of ovendry weight (55 percent on a wet basis) and stembark of yellow-poplar has highest moisture content at 125.8 percent of ovendry weight (56 percent on a wet basis). Moisture content of bark residues is discussed in section 13-4.

In general, large piles of wood chips or bark stored outside in the South gain moisture content (see sections 16-16, 16-17, and 13-4). Shallow piles, a foot or less in depth, can be airdried, however, if under cover and turned frequently (figs. 20-18AB).

Heats of combustion of stemwood, stembark, branchwood, and branchbark all range between 6,840 and 8,183 Btu per ovendry pound (table 9-12). The averages are as follows:

Tree portion	Heat of combustion (higher heating value)
	Btu/ovendry pound
Stembark	7,593
Branchbark	7,623
Branchwood	7,784
Stemwood	7,827

Additional data on heat of combustion of wood of the pine site hardwoods are found in section 9-3 under the subsection HEAT OF COMBUSION; data on bark are found in section 13-6 under the subsection HEAT OF COMBUSTION. Figure 11-3 relates heat of combustion in wood-bark residue piles to time in storage, and indicates that heat content per ovendry pound increases during 4 months of storage.

About 50 percent of the wood and bark of these hardwoods is comprised of the element carbon, from 30 to 44 percent is oxygen, and about 6 percent is hydrogen. Together, ash and nitrogen amount to about 1 percent of wood weight; ash content of bark is higher than that of wood (table 26-3).

The proximate analyses for wood and bark also fall within a rather narrow range of values (table 26-4). In general, when wood and bark are burned, 75 to 80 percent will burn in the gaseous state while about 20 to 24 percent will burn as fixed carbon (Arola 1976).

Summative chemical analyses of stemwood of 18 of the principal pine-site hardwoods are given in table 6-1. Percentages of the components range as follows:

Component	Percent
Cellulose	33.8-48.7
Hemicellulose	23.2-37.7
Lignin	19.1-30.3
Extractives	1.1- 9.6
Ash	.1- 1.3
	100

Chemical constituents of bark are discussed in section 13-5; mineral contents are summarized, by species, in table 6-19.

TABLE 26-3.—*Typical ultimate analysis for hardwood species*[1]

	Wood	Bark
	Percent	
Carbon	50.8	51.2
Oxygen	41.8	37.9
Hydrogen	6.4	6.0
Nitrogen	.4	.4
Ash	.9	5.2

[1]Data from Arola (1976).

TABLE 26-4.—*Typical proximate analysis for hardwoods*[1]

Component	Wood	Bark
	Percent	
Volatile matter	77.3	76.7
Fixed carbon[2]	19.4	18.6
Ash	3.2[3]	4.6

[1]Data from Arola (1976).
[2]Differs from value in ultimate analysis due to different purpose and method of determination.
[3]The high ash content of the wood was probably due to dirt adhering to the wood residues analyzed.

Data on ash content of stemwood, stembark, branchwood, and branchbark from 6-inch-diameter pine-site hardwoods of 22 species sampled throughout their southern ranges are presented in table 6-18.

26-3 DIRECT COMBUSTION

Today, as in the past, the most common way to use wood and bark for energy is to burn it for heat. In the United States the use of wood for fuel peaked about 1875 and has dramatically declined with the availability of fossil fuels (Corder 1973). Internationally, however, about half of all harvested wood is still used for fuel.[2] With the depletion of fossil fuels, there is renewed interest in using wood and bark as fuel for residences (figs. 29-9AB), and industry.

WOOD AS FUEL

Heating value, ultimate analysis, proximate analysis, moisture content, and size are some of the important characteristics that influence the value of wood as a fuel. Some of these characteristics will not vary signficiantly, while others, such as moisture content and size, can vary greatly. Often, fuel preparation will be required to minimize variations and to provide a more homogeneous material for efficient combustion.

The combustion process.—Combustion is the rapid chemical combination of oxygen with the elements of a fuel that will burn (Babcock and Wilcox Company 1972). Chemically it is an oxidation process that results in the release of heat energy. The major combustible elements in wood are carbon and hydrogen (table 26-3). The complete oxidation of carbon forms carbon dixoide (CO_2), and heat energy; complete oxidation of hydrogen (H_2) yields water (H_2O) and heat energy.

$$C + O_2 \longrightarrow CO_2 + 14{,}100 \text{ Btu/lb of C} \qquad (26\text{-}1)$$

$$2H_2 + O_2 \longrightarrow 2H_2O + 61{,}100 \text{ Btu/lb of } H_2 \qquad (26\text{-}2)$$

Combustion of wood is not always complete, which results in the release of lesser amounts of carbon monoxide (CO), hydrocarbons, and other substances.

The burning of wood involves three consecutive stages. In the first stage the moisture is evaporated to dry the wood, which requires about 1,100 Btu per lb of water. In the second stage, the temperature of the fuel rises to the point where volatiles are driven off and combusted. In the third stage, the fixed carbon (carbon remaining after the volatiles are driven off) is combusted as fast as oxygen can be brought in contact with it (Fernandes 1976).

In most combustion processes, air is the source of oxygen. For the purpose of calculating the amount of air required for combustion, air can be considered to be 23.1 percent oxygen and 76.9 percent nitrogen by weight. Thus, for every lb of oxygen required, 4.32 lb of air must be supplied. As carbon has an atomic weight of 12 and oxygen a molecular weight of 32, it is seen from equation 26-1 that 12 pounds of carbon require 32 pounds of oxygen to produce 44 pounds of carbon dioxide (molecular weight 44). To burn 1 lb of carbon will require 2.67 lb of oxygen. By similar calculations, it can be shown that 8 lb of oxygen are required to burn 1 lb of hydrogen (equation 26-2). The amount of air required to burn a fuel can be calculated from its ultimate analysis. The average hardwood contains about 50.8 percent carbon, 41.8 percent oxygen, and 6.4 percent hydrogen (table 26-3). The nitrogen and ash do not play a significant role in the combustion calculations and can be left out. In calculating the minimum air required to burn wood, the percentage of elements can be based on any weight; here let us use 1 lb of wood.

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[2]Saeman, J. F. Energy and materials from the forest biomass. Institute of Gas Technology Symp. on Clean Fuels from Biomass and Wastes. (Orlando, Fla., Jan. 1977.)

The oxygen required to burn the carbon equals

$$1 \text{ lb wood } (0.508 \text{ lb C/lb wood})(2.67 \text{ lb } O_2/\text{lb C}) = 1.36 \text{ lb } O_2$$

The oxygen required to burn the hydrogen equals

$$1 \text{ lb wood } (0.064 \text{ lb H/lb wood})(8.00 \text{ lb } O_2/\text{lb H}) = 0.512 \text{ lb } 0_2$$

Thus, total oxygen required equals 1.87 lb.

The molecular structure of the average hardwood is already 41.8 percent oxygen (table 26-3). This oxygen as well as oxygen from air will be involved in the formation of CO_2 and H_2O and must be accounted for in the combustion calculations. Thus, the oxygen already in 1 lb of wood = 0.418 lb. The oxygen needed from the air = total oxygen required − oxygen already in wood = 1.87 lb − 0.42 lb. = 1.45 lb. Therefore, total air required = (1.45 lb O_2)(4.32 lb air/lb O_2) = 6.26 lb air.

This minimum amount of air is called **theoretical air** and does not depend on the moisture content of the wood. In theory, combustion of wood generally requires about 6 lb of air per lb of wood (Wiley 1976). In practice, **excess air** is provided to ensure complete combustion. This usually runs from 25 to 150 percent over the theoretical air.

We have seen how the ultimate analysis can be used to calculate the air required for burning wood. The proximate fuel analysis is an indication of the relative amounts of volatile material that will be evolved and burned in the second stage of the combustion process. The amount of carbon left after the volatiles leave is called the fixed carbon, and burns in the solid state. Seventy-seven percent of the average hardwood will burn as volatile matter and 19 percent will burn in the solid state as fixed carbon (table 26-4). This kind of analysis can suggest the best locations for combustion air inlets in a furnace.

Moisture content and available heat.—The **heat of combustion** of wood and bark can vary considerably with chemical content. Resin waxes, lignin, and such compounds with high carbon and hydrogen contents have higher heating values than carbohydrates which have a high oxygen content. Softwoods, because they generally have a higher resin and lignin content, have a higher heat of combustion than hardwoods. For example, loblolly pine stemwood has a heat of combustion of 8,600 Btu per ovendry pound (Howard 1973), while pine-site hardwoods average 7,827 Btu per ovendry pound of stemwood and about 7,593 Btu per ovendry pound of stembark (table 9-12).

Heats of combustion are determined with an oxygen bomb calorimeter. Values obtained are somewhat higher than those recovered in practice because the calorimeter is closed and the products of combustion are contained. Thus, on cooling, water vapor is condensed and releases its heat of vaporation. In an industrial furnace, this heat is normally lost to the atmosphere. The heat combustion measured by a bomb calorimeter is called the **higher heating value.** The **lower heating value** is obtained by subtracting the heat of vaporization of the water formed in combustion. The average lower heating value for pine-site hardwoods is 7,261 Btu per pound for stemwood and 7,027 Btu per pound for stembark.

There are two ways to express moisture content of wood. The ovendry method is most commonly used by people in the forest products industry.

$$\text{M.C. (dry)} = \frac{\text{(weight of water)}}{\text{(weight of ovendry wood)}} \times 100 \qquad (26\text{-}3)$$

People in the field of fuels and combustion and most engineers use the wet basis moisture content.

$$\text{M.C. (wet)} = \frac{\text{(weight of water)}}{\text{(total weight of wood and water)}} \times 100 \qquad (26\text{-}4)$$

A material that is half water and half wood would have M.C. (dry) = 100 percent and M.C. (wet) = 50 percent. The two moisture contents can be converted by the following formula:

$$\text{M.C. (wet)} = 100\ \text{M.C. (dry)}/[100 + \text{M.C. (dry)}] \qquad (26\text{-}5)$$

$$\text{M.C. (dry)} = 100\ \text{M.C. (wet)}/[100 - \text{M.C. (wet)}] \qquad (26\text{-}6)$$

In keeping with most of the literature referenced, the wet basis moisture content will be used in the following discussion unless otherwise noted.

The economic value of a fuel will depend both on its heating value and moisture content. High moisture content is detrimental in two ways. First, it reduces the **available heat** of the fuel. The higher heating value of a fuel does not change with increasing moisture content, but the available heat does change (equation 26-7) because there is simply less fuel per unit weight (table 26-5, Ince 1977).

$$\text{Available heat} = \text{(percent wood)(higher heating value)} \qquad (26\text{-}7)$$

TABLE 26-5.—*Available heat versus moisture content for pine-site hardwoods*[1]

Moisture content (percent, wet basis)	Available heat (Higher heating value)
	Btu/lb
0 (ovendry)	7,827
10	7,044
25	5,870
42	4,540
50	3,914

[1]Average value for stemwood (table 9-12).

High moisture content also reduces furnace efficiency, because heat energy is lost up the stack in vaporizing the moisture in the wood. Vaporization of fuel moisture is the first stage in combustion; thus heat energy must raise the moisture temperature from ambient (70°F) to the boiling point (212°F). Additional heat energy is required to vaporize the water to steam at 212°F. Heat energy is also lost in raising the steam temperature to that of the furnace stack gases. Steam tables can be readily used to calculate the amount of energy required to heat and evaporate water. For example, if the stack temperature is 500°F, the calculated heat energy lost in changing the water at 70°F to steam at 500°F and 14.7 psi is 1,250 Btu/lb of water (Wiley 1976).

Fuel preparation.—High moisture content, bulkiness, dirt, and heterogeneous size are undesirable properties of some wood fuels. As with refined petroleum fuels, wood can be upgraded in value for various burning situations (Johnson 1975). Wood-burning furnaces, for example, are designed to burn chip size or smaller material. This permits automation in feeding and more efficient burning. But of course the size of pieces can range from slabs and logs to sawdust and shavings. To reduce and size wood for easier handling and burning, it usually is passed through an attrition mill or **hog.** In a typical hammer hog (fig. 18-277) large pieces enter at the top and are forced down and through spaced bars by the rotating action of hammers. The size of the particles leaving the hog depends on speed of the hammers and clearance between the hammers and the spaced bars. Optimum particle size depends on the burner. In some grate-type furnaces, for example, an excess of fines and sawdust inhibits efficient combustion. See figures 18-276 and 18-278 through 18-280 for other types of hogs and shredders.

Hogged fuel is wood waste having no higher recovery value than that of fuel; such fuel contains no municipal refuse (Johnson 1975). Under this broad definition, which is in common use today, a fuel would not have to be passed through a hog to be called hogged fuel. Common hogged fuels include sander dust, shavings, sawdust, bark, log yard clean-up, clarified sludge, forest residuals, and fly carbon.

Drying hogged fuel increases steam generation efficiency and reduces emissions (Johnson 1975; Hall et al. 1976). Even furnaces designed for wet wood operate best at fuel moisture of 50 percent or less on a wet basis. At moisture contents exceeding 60 percent, most furnaces operate poorly, if at all.

Wood fuel can be dried in several ways. Mechanical pressing squeezes water out with simple equipment that requires no heat; moisture content can be reduced to 50-55 percent by this method (Porter and Robinson 1976; Haygreen 1981). Air drying (figs. 20-15 through 20-18) is slow but can reduce the moisture content to about 20 percent and if climate permits, even less. Perhaps solar dryers will be developed for this purpose. Today, fuel dryers which use hot gases are in widespread use. The most common type is the rotary drum. Other types of fuel dryers, such as the hot hog and hot conveyor system (American Logger and Lumberman 1978; Johnson 1975) have not been as widely used.[3]

In a typical **rotary drum dryer system,** fuel that is to be dried is first screened to remove and rehog oversized pieces. Hot gases and the fuel enter one end of the drum or cylinder and are brought into contact with each other by cylinder rotation and horizontal gas flow (fig. 26-3). An induced-draft fan draws the hot gases through the dryer, and this gas flow pushes the dried fuel toward the outlet. Two- to four-inch pieces can be adequately dried in 20 minutes or less. Fuel is separated into different sizes at the dryer outlet. Airborne fines go to the cyclone separator with the gas flow (Thompson 1975; Johnson 1975).

[3]Personal communication with David C. Junge, Oregon State Univ., Corvallis.

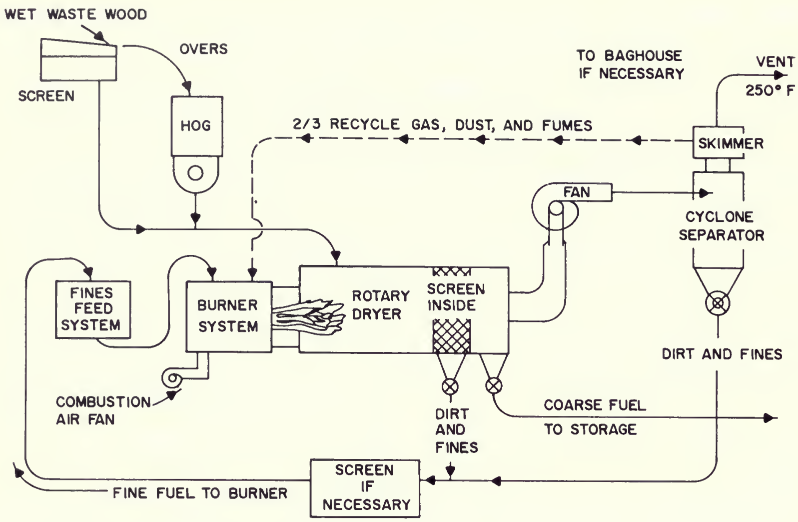

Figure 26-3.—Typical rotary dryer system. (Drawing after Johnson 1975.)

Rotary drum dryers are suited for handling large quantities of wet fuel. The inlet temperature can go as high as 1600°F if the moisture in the fuel is high enough to absorb the heat without scorching the wood. A major environmental concern for the forest products industry, however, is blue haze, caused by distillation of organic material such as terpenoids into the air while drying wood. Douglas-fir dried above 750°F creates blue haze. Optimum drying conditions for pine-site hardwoods are not known.

Bark or hogged wood for fuel can also be dried in a **vertical dryer** (fig. 26-4) in which flue gases from combustion provide required heat. Before entering the dryer, the flue gas is divided. One part enters the unit through a centrally located slot in the bottom. The other part is supplied thorugh peripheral slots in the conical bottom. It conveys the bark from the periphery into the center. Here a continuous cascade of flue gas and bark goes up from the bottom and reverses at the deflector in the dryer's top.

After deflection, the bark drops and rejoins the cascade while the flue gases, now cooled, leave the dryer through the outlet above the deflector. Wet bark is supplied through a rotary air lock located in the upper part of the unit. An adjustable outlet slot in the conical bottom of the dryer discharges bark to another rotary air lock. By adjusting the slot area, the bark retention can be controlled and adjusted to various operating conditions.

The flue gas leaving the dryer carries both ash from the boiler and the combustible dry fines from the bark which must be collected. Collection and separation takes place in two stages. First, combustible material is extracted in a precollector, then pneumatically conveyed and either mixed with the bark or burned separately in a suspension burner. Second, ash is collected in a multi-cyclone unit and then conveyed for deposit.

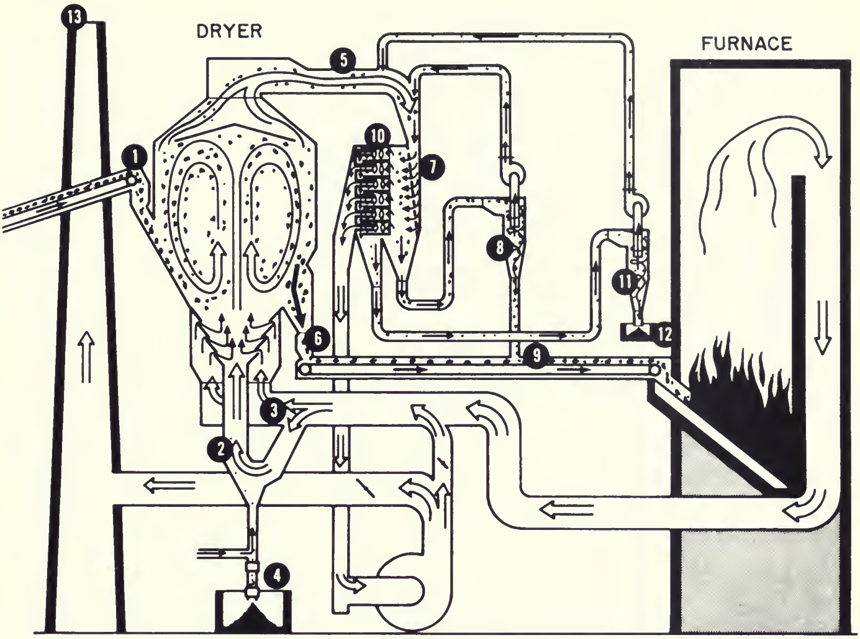

Figure 26-4.—Bark dryer in which flue gases from combustion supply required heat. (1) Wet bark conveyed to dryer. (2) High velocity gas stream. (3) Main gas stream. (4) Stone and scrap discharge. (5) Gas and combustible fines leave dryer. (6) Dried bark conveyed to boiler. (7) Pre-collector separates combustible fines. (8) Secondary cyclone for combustible fines from pre-collector. (9) Combustible fines join dried bark enroute to boiler. (10) Multicyclone for final separation. (11) Secondary cyclone for fly ash from multicyclone. (12) Fly ash removed from system. (13) Stack emission cleaned to code. (Drawing from BAHCO Systems, Inc.)

Some burners will operate only on dry fuel. Others are designed to burn wet fuel; opinion is not unanimous on the economic virtues of drying fuel in a separate operation before admitting it to wet-fuel burners. Some furnace designers contend that the most economical place to dry wet fuel is in the combustion chamber of a wet-fuel burner; others disagree.

Bulkiness of wood fuel can be circumvented to some extend by compressing it into more dense material of various shapes and sizes. Such compressing makes storing, handling, and shipping easier and promotes uniform burning.

There are several ways to densify wood for fuel. Tops and limbs can be baled (fig. 16-53). Compression bailing of wood chips can reduce volume to one-fifth their loose bulk while squeezing out 12 to 15 percent of their moisture (American Hoist and Derrick 1976). Dry particulate wood and bark can be formed into log or pellet shape by compressing in a die under heat and pressure sufficient to break down the elasticity of wood or bark, so that the densified form will have permanence (Hausmann 1974). It is possible that polyphenolic compounds (especially in bark) play a role in successful densification. The compounds may act as natural binding agents or glues when subjected to heat and pressure. Fire logs for home use can employ a wax or other binder (Braun 1975).

The technology for densifying particulate wood and bark has been around for over 50 years (Sprout Waldron and Co. 1961; Hausmann 1974; Currier 1977; Farnsworth 1977). The famous "pres-to-logs" used for hand-firing fireplaces and stoves were first made about 1933. In the 1950's machines were developed to extrude wood residue rods suitable for fueling coal stoker furnaces. Generally, the rods are about 1 inch in diameter and can be cut to desired lengths. In 1959 a company in Tennessee first pelletized bark for fuel. These oak bark pellets were used with coal to fire a steam boiler and reportedly gave burning rates equivalent to soft-coal. Since the late 1960's extensive research on pelletization of wood and bark residues for fuel and other uses has been caried out by Currier (1977) at Oregon State University and Steffensen (1973) at Georgia-Pacific.

Pelletization can be accomplished with standard agricultural pellet mills (Currier 1977). The product is generally 3/16- to ½-inch in diameter and ½-inch long. The compression rate in pelletizing is usually about 3 to 1. Because of their uniform density, fuel pellets are easier than hogged fuel to meter into a furnace and can be burned at more closely controlled rates. Wet fuel cannot be pelletized unless it is first dried to 6-10 percent moisture content, at a considerable energy cost. Because of this, those industries whose wood wastes are dry, such as furniture and cabinet manufacturers, may find pelletizing most economically attractive.

A company in Alabama pelletizes sawdust and bark after pre-drying it in a rotary dryer fired by some of the pelletized product. The pellets are sold to a power plant. Estimated total investment is about one-half million dollars including land. The pelletizer sells for around $32,000. Similar estimates of cost have been reported by Farnsworth (1977). A company in Oregon markets pelletized Douglas-fir bark (Blackman 1978). Reportedly, the product sells for about half the price of coal of equivalent Btu's. Plant operations use the equivalent of 12 percent of the energy contained in the pelletized product. Costs of densification are dependent on degree of comminution and drying required (estimated at $2 to $6 per ton in 1978).

North American manufacturers of equipment to make densified pellets or logs include the following:

Extruders	Agnew Environmental Products, Inc., Grants Pass, Ore. California Pellet Mill Co., San Francisco, Calif. Universal Wood Ltd., San Diego, Calif.
Pellet mills	California Pellet Mill Co., San Francisco, Calif. Sprout Waldron, Muncy, Pa.
Wood and wax extruders	Bonnot Co., Kent, Ohio
Cubers	Warren & Baerg Manufacturing, Dinuba, Calif.

Residues.—Ash and incompletely combusted carbon are the solid residues from burning wood. In boiler furnaces, where high burning temperatures are achieved, slag and clinker are formed from the melting and fusion of ash. Ash content of wood and bark of the 22 principal hardwoods found on southern pine sites are shown in tables 6-1 and 6-18. Data from table 6-18, which describes trees 6 inches in dbh, are summarized as follows:

Tissue	Average	Minimum	Maximum
	Percent of unextracted ovendry weight		
Wood			
Stemwood	0.75	0.43 (northern red oak and yellow-poplar)	1.33 (hackberry)
Branchwood	.94	.60 (sweetbay)	1.45 (hackberry)
Bark			
Stembark	7.87	4.08 (yellow-poplar)	12.12 (winged elm)
Branchbark	6.76	4.12 (yellow-poplar)	11.75 (winged elm)

Thus, variation among the species is significant. Even among the 11 oak species, ash content in all components varies significantly with species. For example, the stem bark of white oak and post oak have about 11 percent ash content, while that of scarlet oak has less than half this amount (5.18 percent).

Mineral analyses of the ash of above-ground wood and bark are shown in table 6-19.

See tables 14-9 and 14-10 for ash and mineral content of wood and bark in stump-root systems of pine-site hardwoods.

Studies of other species indicate that wood ash is generally high in CaO (50 to 60 percent) and high in Na_2O and K_2O (4 to 7 percent). Stemwood of southern hardwoods has about equal content of K and Ca (about 2,000 ppm of each); bark of these hardwoods has a much higher content of Ca than K. Percentages of ash components probably vary significantly among species and with fuel types, i.e., stems, branches, wood, or bark. Some values for wood and bark are shown in table 26-6, but these values do not represent averages specifically applicable to hardwoods grown among pines.

TABLE 26-6.—*Chemical composition of ash from bark and wood*[1,2]

Component	Southern bark #1	Southern bark #2	Oak bark	Wood[3]
	Percent of ovendry weight			
Silicon as SiO_2	34.0	62.0	11.1	33.8
Aluminum as Al_2O_3	5.5	4.0	.1	2.6
Titanium as TiO_2	.3	.3	.1	.2
Iron as Fe_2O_3	2.7	1.6	3.3	1.6
Calcium as CaO	48.0	23.0	64.5	56.5
Magnesium as MgO	3.5	2.2	1.2	4.7
Sodium as Na_2O	.4	.5	8.9	.5
Potassium as K_2O	4.2	3.5	.2	.1
Sulfur as SO_3	2.6	2.8	2.0	—
	101.2	99.9	91.4	100.0

[1]Data from Babcock and Wilcox Company (1972) and personal correspondence with Babcock and Wilcox Company, January 1982.

[2]Component percentages will vary significantly with wood species and between wood and bark fuels; analytical techniques may not permit summing to 100 percent.

[3]Species not known.

Wood ash generally has been considered inert (Hall et al. 1976), but this may not be chemically true. In at least one case, wood ash has been shown to be an effective catalyst in the gasification of wood (Feldman 1978).

Increased use of wood for fuel might make ash disposal a problem (Hall et al. 1976). Perhaps ash could be used as a soil conditioner to break up clay, and the alkalinity of ash could help raise the pH of acid soil. If supplemented with nitrogen compounds ash also has the potential for use as a fertilizer. Host and Pfenninger (1978) found that flyash has a natural timed release of nutrients over an extended period of time; field tests showed tree growth response still evident 3 years after application. One mill in central Louisiana uses clinkers for road-bed surfaces around the plant.

Emissions.—Both gaseous and particulate emissions occur when wood is burned (table 26-7). Carbon dioxide and water vapor (equations 26-1 and 26-2) combined with nitrogen and oxygen from the combustion air comprise 98-99 percent of the total material emitted from an efficient combustion process.

In terms of potential air pollution, the United States Environmental Protection Agency (EPA) is concerned with the amounts of particulate matter, sulfur dioxide, carbon monoxide, nitrogen oxides, and unburned hydrocarbons that are emitted into the atmosphere. In wood combustion, sulfer dioxide emission is very low, and carbon monoxide and hydrocarbon emissions present no problems in most situations. The situation with nitrogen oxides is less certain, and particulate emissions from wood-fired boilers require attention.

TABLE 26-7.—*Emissions from combustion of hogged fuel* (Junge 1975a)

Gases		Particulate matter
Nitrogen	98-99% of total	Inorganic flyash
Carbon dioxide		Fixed carbon
Oxygen		Traces of metals and salts
Water vapor		
Carbon monoxide		
Unburned hydrocarbons		
Sulfur dioxide		
Oxides of nitrogen		
Inert gases		

There are no published data on the sulfur content of bark from individual species of southern hardwoods. The National Council of the Paper Industry for Air and Stream Improvement, Inc. (1978) sampled sulfur content of bark fuel at four pulpmills in the Southeast (Alabama, Georgia, and Florida) and found contents of 0.010, 0.060, 0.068, and 0.134 percent; although most of the bark was from southern pines, substantial amounts of hardwood bark were also in the mixtures. It was found that just over 5 percent of the sulfur contained in bark was emitted from the mill boilers as SO_2, i.e., about 0.0001 to 0.0020 pound of SO_2 per million Btu in the bark fed to the boilers. (Stembark of small pine-site hardwoods has a heat of combustion—higher heating value—of about 7,593 Btu/ovendry pound; emissions in these tests therefore suggest about 0.76 to 15.19 pound SO_2 per million pounds of dry bark.)

When combustion is poor, hydrocarbon[4] emissions are increased. In extreme cases, these emissions may be 55-85 lb/ton of fuel (Junge and Kwan 1974). High hydrocarbon emissions could present a twofold pollution problem. First, polycyclic aromatic compounds can be produced through the incomplete combustion of solid carbonaceous fuels such as coal (Hall et al. 1976). Certain polyclyclic aromatic compounds are suspected carcinogens. However, it is not certain to what extent these compounds occur in the incomplete combustion of wood. The second problem is the production of peroxy compounds that react with sunlight as part of the complex process resulting in photochemical smog. Formation of carcinogenic compounds or photochemical smog should not be problems in wood burning if combustion is efficient (Hall et al. 1976).

Nitrogen oxides (NO and NO_2) are instrumental in smog formation. At present, the automobile engine is by far the largest source of nitrogen oxides. In high concentrations, these compounds not only harm life but destroy material as well. Fortunately, the ambient concentration of nitrogen oxides is low enough in most areas that emission control for them from wood burning should not be required. However, if the need arises, modification in the combustion process rather than the use of a cleaning device at the stack would be necessary (Hall et al. 1976).

Particulate emissions can be controlled by any of four basic devices. These are cyclone separators, scrubbers, baghouse filters, and electrostatic precipitators (Junge 1975a). Most wood-fueled boilers are equipped with cyclone separators; however, some are equipped with scrubbers.

Comparison to fossil fuels.—The higher percentages of oxygen in the molecular structures of wood and bark gives them lower heating values than coal and oil (table 26-8). In comparison with coal, wood has a low ash content and little or no sulfur. The chief drawback of woody fuels is their naturally high moisture content and bulkiness.

Arola (1975) has a graph (fig. 26-5) that is a useful tool for comparing the cost of heat or steam produced from wood-based and fossil fuels. The graph has three sets of lines which correspond to three classes of fuel considered: (1) oil; (2) coal, bark, wood, and municipal solid refuse; and (3) gas. A fourth set of lines represents efficiency values to allow for losses when converting heat energy to steam. Heating values used for the solid fuels are "as fired", that is, the available heat at the moisture content (wet basis) as fired (equation 26-7).

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[4]The term hydrocarbon is used rather loosely in the literature, sometimes denoting oxygen-containing organic compounds as well as hydrocarbons.

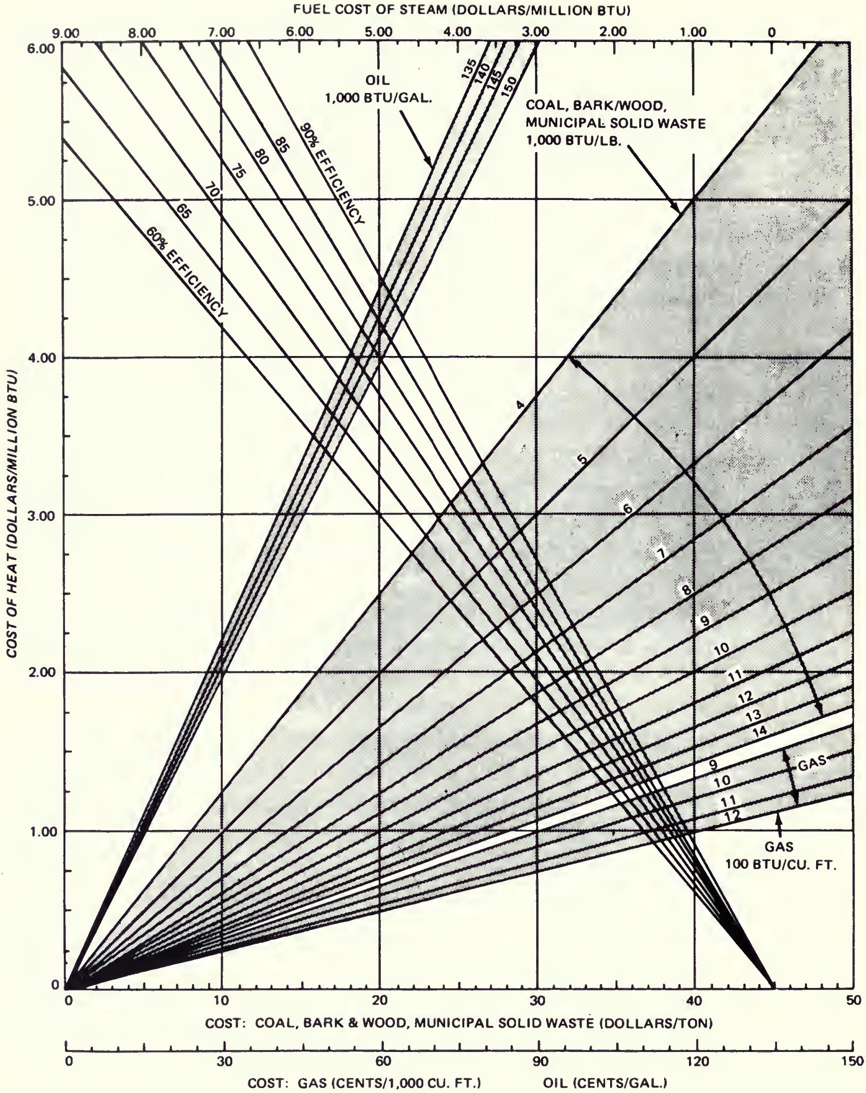


Figure 26-5.—Graph to compare fuel value for wood-based and fossil fuels. (Drawing after Arola 1975.)

TABLE 26-8.—*Ultimate analyses and heating values of some fossil fuels compared with hardwoods*

	Coal[1]		Hardwood[2]		
	Western	Pennsylvania	Wood	Bark	Residual fuel oil[1]
	Percent				
Ultimate analysis					
Hydrogen	6.4	5.0	6.4	6.0	9.5-12.0
Carbon	54.6	74.2	50.8	51.2	86.5-90.2
Oxygen	33.8	7.1	41.8	37.9	—
Sulfur	.4	2.1	—	—	.7- 3.5
Nitrogen	1.0	1.5	.4	.4	—
Ash	3.3	10.1	.9	5.2	.01-.50
Heating value, Btu/lb.	9,420	13,310	7,827[3]	7,593[3]	17,410-18,990

[1]Data from Hall et al. (1976).
[2]Data from Arola (1976).
[3]Data from table 9-12.

Arola (1975) provided the illustration reproduced in figure 26-6 as an example of how to use the graph.

Given: The fuel is bark which costs $10/wet ton and has a higher heating value of 9,000 Btu/lb when ovendry. Process efficiency is 65 percent. The bark is fired at 50 percent moisture content (wet basis).

Problem: What is the cost of steam?

Solution: Available heat at 50 percent moisture content is 4,500 Btu/lb, i.e., (1.00 − 0.50) x 9,000 Btu/lb. From the $10/ton point along the upper scale at bottom of chart, extend a line vertically to the 4,500 Btu/lb point for bark (interpolation required). Extend a horizontal line from this intersection to the 65 percent efficiency line and then a vertical line to the top of the graph to read the cost of steam.

Answer: About $1.70/million Btu.

INDUSTRIAL BURNING SYSTEMS

Today industrial wood burning furnaces are commonly incorporated into boiler systems to produce steam. Nearly 1700 such wood-fired boiler systems are in operation in the United States (Environmental Protection Agency 1977), and the number is increasing. They range in size from shop-fabricated units, with steam capacities up to about 100,000 pounds per hour, to large field-erected units that can generate up to 600,000 pounds of steam per hour on hogged fuel (USDA Forest Service 1976; Bliss and Blake 1977). Wood-fired boilers producing 15,000 to 100,000 pounds per hour are the most common among recent installations (Hall et al. 1976). In some furnace systems the hot combustion gases produced are used to direct-fire kilns and dryers without the intermediate step of steam generation. In addition, certain furnaces could be used to drive gas turbines whose exhaust heat could then be used in a conventional boiler to produce added steam power.[5]

[5]H. G. Hagen. 1977. Wood fueled combustion cycle gas turbine power plant. 38 p. Paper presented at the California Energy Comm. Energy-From-Wood Workshop. See also: Hamrick, J. T. and T. M. Hamrick, 1981. Development of wood as an alternative fuel for large power generation systems, Part I - Research on wood burning gas turbines. Final Report DOE/ET/20058-T2(Pt.1) (DE82002034) prepared by Aerospace Research Corp., Roanoke, Va. for U.S. Dept. of Energy. 80 p.

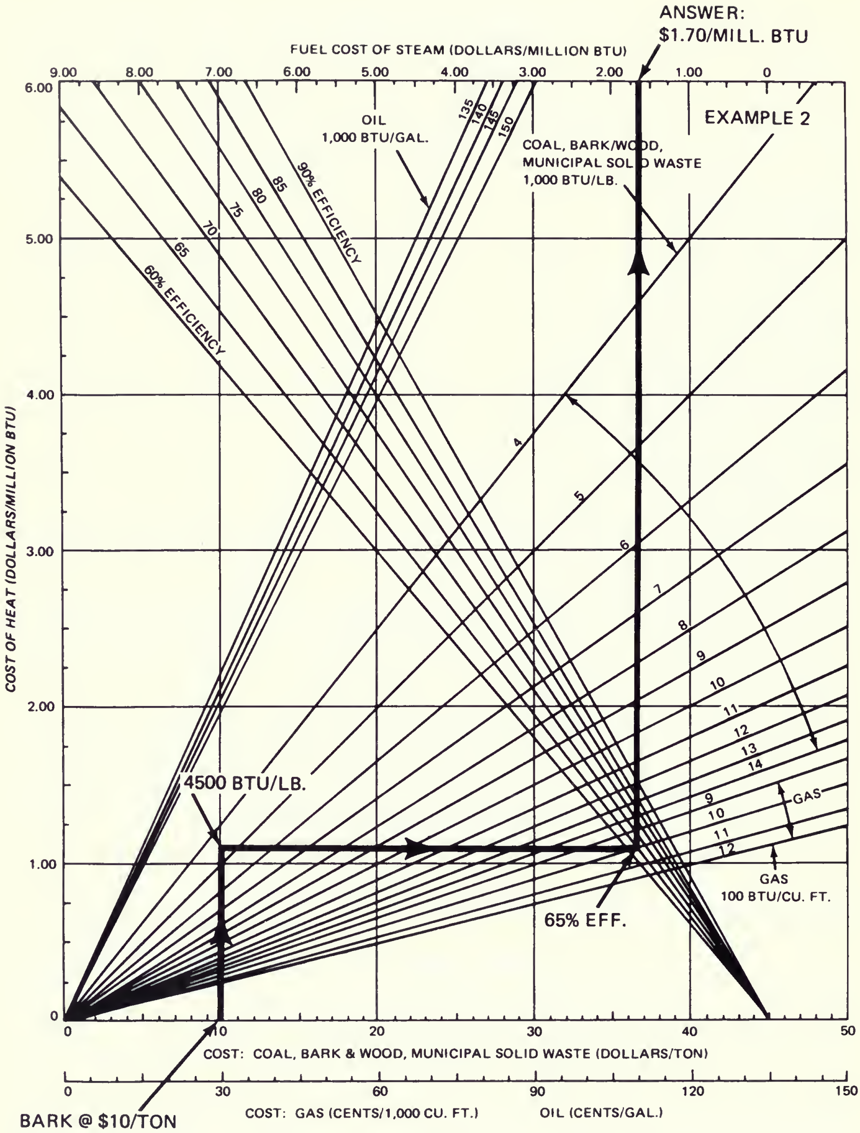


Figure 26-6.—Example of how to use the fuel value comparison graph. See test paragraphs *Comparison to fossil fuels.* (Drawing after Arola 1975.)

Basically there are two classes of furnace design in use for wood burning—**grate burners** and **suspension burners.** Dutch ovens, inclined grate furnaces and spreader stokers burn the fuel on a grate, either in a pile or spread into a thin bed. In suspension burning, the fuel is supported by air during its combustion. Within these two classes of furnace design are a variety of furnace types which can differ markedly in basic operation, largely in adjusting to the various forms that wood fuel can take. A few of the most important types are described in this text. Readers needing additional information on hardware for industrial burning systems will find useful the proceedings on this subject published by the Forest Products Research Society (1979).

Dutch ovens.—Historically, Dutch ovens (fig. 26-7) provided steam for many industries in this country. They are now considered obsolete for new installations, because they are expensive to maintain and respond poorly to load changes.

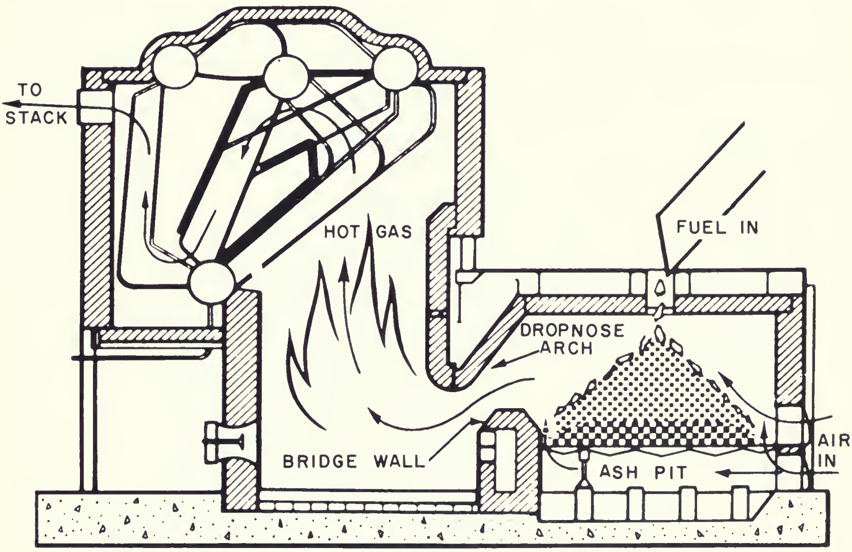


Figure 26-7.—Dutch oven furnace and boiler. (Drawing after McKenzie 1968.)

The Dutch oven is a two-stage refractory (firebrick-lined) furnace. Fuel is fed through a chute in the oven roof and forms a conical pile on the grate in the oven or primary furnace. Here the fuel is dried and partially combusted. The system is designed so that there is insufficient air for complete combustion in the primary furnace. Combustible gases emerging from the fuel pile pass into the secondary furnace, or combustion chamber, where air entering through the overfire ports completes combustion. On their way to the stack, the hot combustion gases pass through water-carrying heat exchangers to generate steam. Removal of ash is done by either manual rake-out or dumping grates. Combustion rates of about 600,000 Btu per ft^2 of grate per hour have been attained with air and wood having 45 percent moisture content, but combustion rate drops off rapidly above that level. Excess air at the stack is usually between 30 and 40 percent (Babcock and Wilcox Company 1972; Junge 1975a).

Fuel cell burners.—Fuel cell burners (fig. 26-8) are an adaptation of the Dutch oven design; drying and gasification of the fuel occur in the primary furnace, and combustion is completed in the secondary furnace. Fuel is metered into the primary furnace, which is a vertical, refractory-lined cylinder with a water-cooled grate. Here the fuel is partially combusted, the volatiles pass into

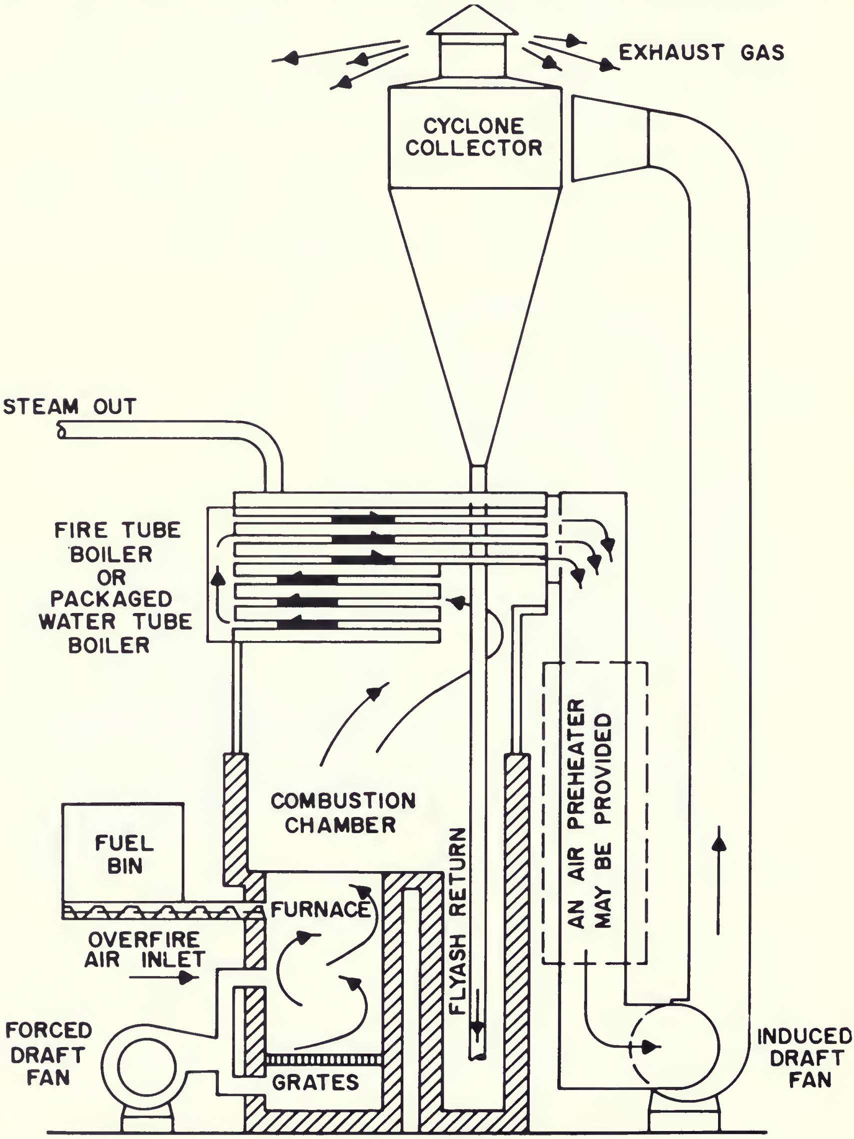


Figure 26-8.—Fuel cell furnace system. (Drawing after Junge 1975a.)

the upper chamber where burning is completed. Boilers of this type are common in the Western United States, where they are used for kiln-drying lumber. They generally have capacities of 10,000 to 30,000 lb of steam per hour when operated at pressures below 150 psi. Dryers have to be incorporated when fuel moisture content is above 50 percent (Junge 1975a; Corder 1973).

A new variation of a fuel cell furnace is the wet cell burner (Anonymous 1978). This unit employs a cyclonic-type furnace for the upper, secondary combustion chamber (fig. 26-9). Hogged fuel with a moisture content up to 65 percent is metered by a hydraulic ram at a rate controlled by Btu demand. The

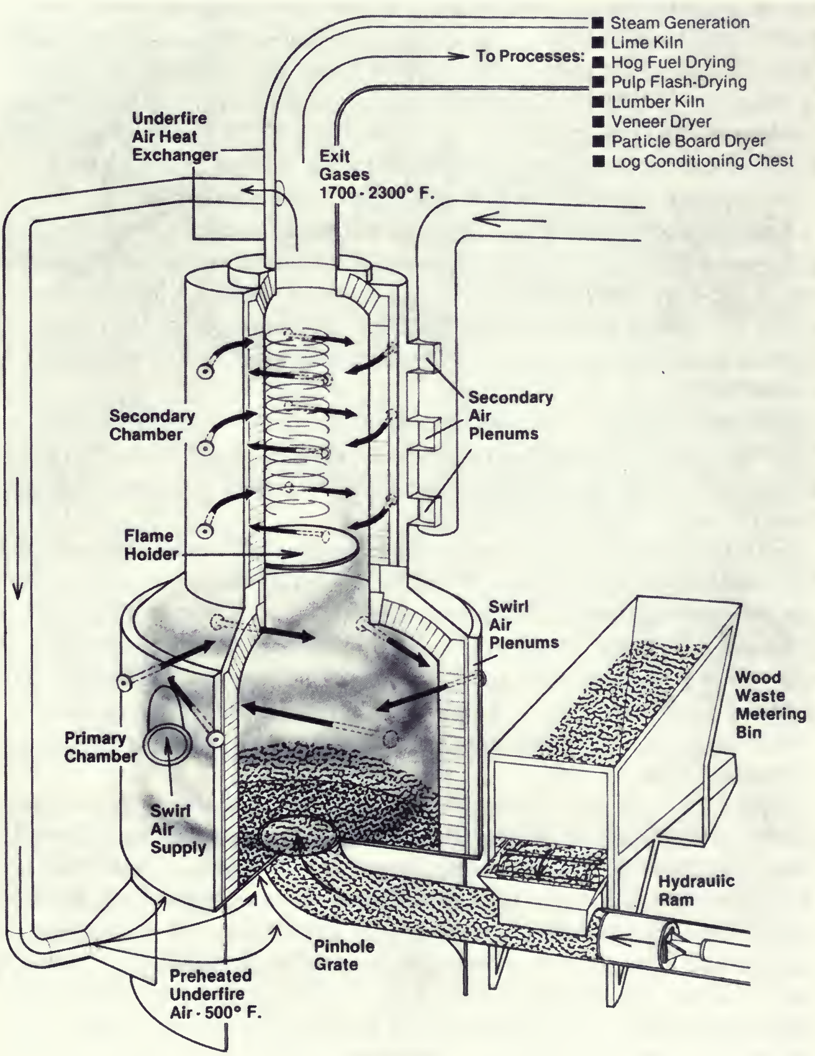


Figure 26-9.—Wet cell burner. (Drawing from Hugh Dwight Advertising.)

hydraulic ram then forces the fuel up through a large-diameter cylinder under the base of the burner, depositing the fuel through an opening in pinhole grates that form the floor of the lower chamber. The fuel forms a slightly conical pile over the grate as more fuel is pushed up from below. An automatic gas burner ignites the pile, but shuts down after it is burning. Preheated air is forced up through the pile as well as through swirl air plenums above it. Air supplied is insufficient for complete combustion so that the fuel is mostly dried and gasified. Swirling airflows near the top of the primary combustion chamber subject the hot distillates to a scrubbing action that separates particulates to the outer wall by centrifugal action. The fixed carbon particulates complete oxidation as they are swept away. As the volatiles rise to the upper combustion chamber, they are met by cooler air that is vortexing downward. This action mixes and combusts the gases in a cyclonic air flow. Excess combustion air is limited to 10-15 percent by this mechanism. Exhaust gases leave the burner at 1,700 to 2,300°F and can fire a boiler or can be blended with cooler air to use in kilns and dryers.

For another example of a fuel cell burner, see figure 24-25.

Inclined grate furnaces.—This type of furnace usually has a water-cooled grate and water-cooled furnace walls (fig. 26-10). Fuel enters the furnace at the top of the grate and is dried as it slides down to the lower horizontal section where it is burned. Ash is removed intermittently through discharge doors. The inclined grate furnace is one of the more popular types in Europe (Astrom and Harris 1975).

Spreader stokers.—The spreader stoker is probably the most commonly used wood and bark burning furnace (Fuller 1976; Bliss and Blake 1977). These furnaces can burn large amounts of wood and bark alone or in combination with coal, oil, or gas with little difficulty.

In spreader stokers, fuel is spread either pneumatically or mechanically into a thin even bed across the grates. When the fuel is added above the grate, smaller particles and volatiles burn in suspension while the large pieces of fuel fall to the grate and burn in the fuel bed. Flames from the particles suspended above the grate radiate heat that aids in combustion of the fuel bed. Furnace walls are normally lined with heat exchange tubes (water walled). Because there is no refractory surface to reflect heat back to fuel, combustion air is sometimes preheated (Junge 1975a).

Figure 26-11 shows a closeup sectional view of a **traveling grate** spreader stoker with front ash discharge; in figure 26-12 the stoker is attached to a large steam generator. Fuel is conveyed continuously and distributed into the furnace through an air-swept spout. High-pressure overfire air jets provide turbulence to aid the suspension burning of small particles and volatiles. Air for combustion in the fuel bed is admitted from the plenum chamber through holes in the grate bars. The fuel bed moves with the grate at a rate adjusted to allow complete combustion of the fuel before the ash is dumped into a hopper. Other types of grate are also used with spreader stoker furnaces (Fuller 1976). These include a vibrating-grate where the fuel bed moves toward the ash hopper as the bed is intermittently vibrated by an eccentric drive mechanism (fig. 26-13). In dumping-grate stokers (fig. 26-14) the grate bars are rotated 90° to dump the ash into a combined ash hopper-air plenum.

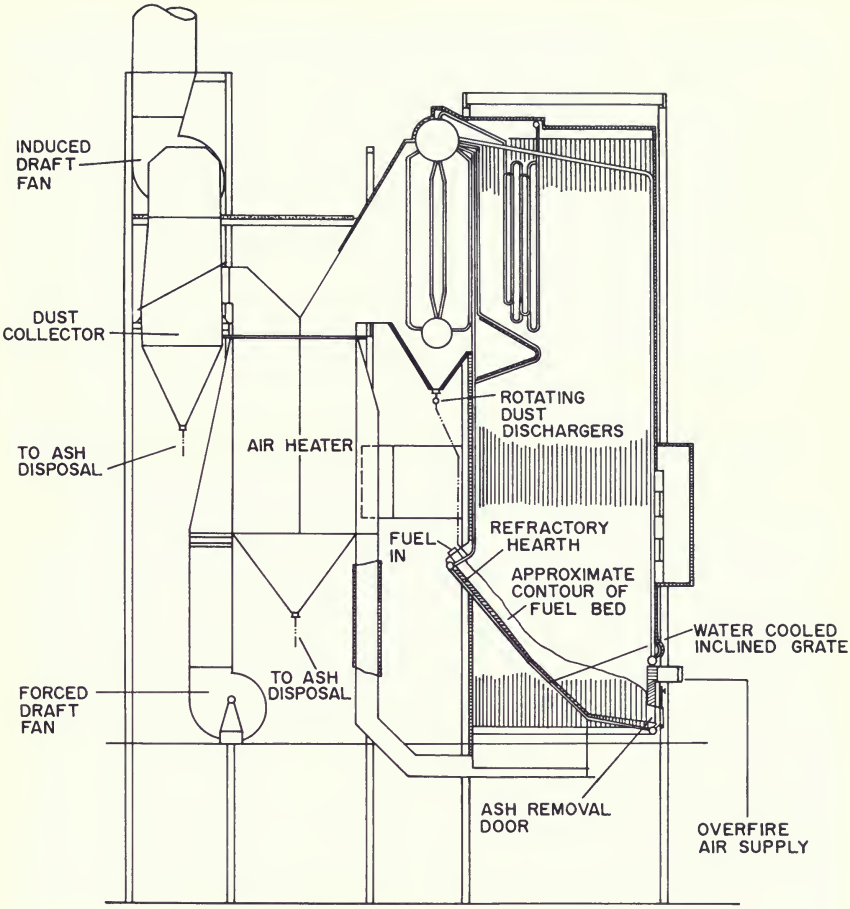
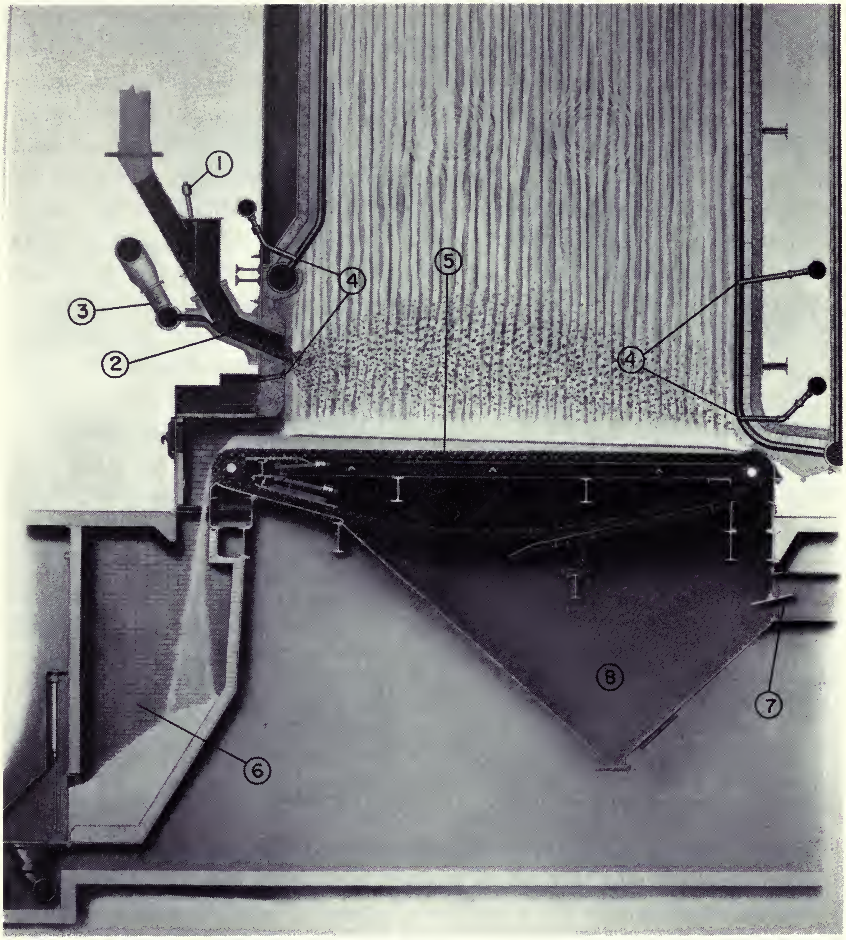


Figure 26-10.—Inclined grate furnace system. (Drawing after Corder 1973.)

Spreader stokers can burn hogged fuel containing 45 to 50 percent moisture at 1 million Btu per hour per ft^2 of grate area while using 35 to 45 percent excess air. However, most boilers in operation use more than 75 percent excess air.[6] Spreader stokers are used with boilers that generate from 25,000 to 600,000 lb of steam per hour (Babcock and Wilcox Company 1972; Corder 1973; Bliss and Blake 1977).

Suspension-fire boilers.—Suspension firing of wood and bark in large boiler furnaces is similar to the firing of pulverized coal (Hall et al. 1976). Most often bark, hogged to small size and pneumatically injected into the furnace, is the fuel. If injection is high enough in the furnace and the fuel particles are small enough, then the fuel will be completely combusted before it falls out of the combustion zone.

[6]Personal communication with David C. Junge, Oregon State University, Corvallis.



(1.) BALANCED DAMPER ASSEMBLY
(2.) AIR SWEPT FUEL DISTRIBUTOR SPOUT
(3.) ROTARY AIR DAMPER
(4.) HIGH PRESSURE OVERFIRE AIR JETS
(5.) TRAVELLING GRATE (6.) ASH HOPPER
(7.) BLAST GATE (8.) AIR PLENUM

Figure 26-11.—Sectional view of a traveling grate stoker with front ash discharge. (Drawing from Detroit Stoker Company.)

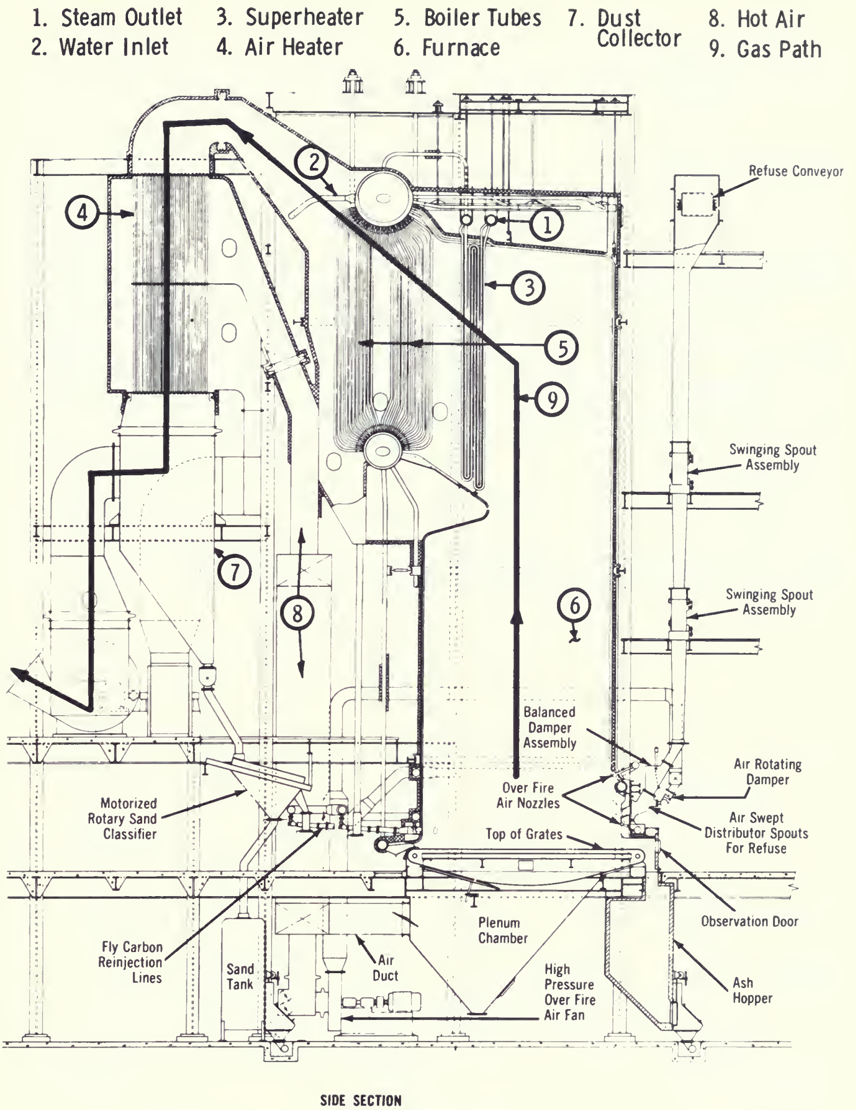


Figure 26-12.—Components of a typical large steam generator equipped with a spreader stoker. (Drawing from Detroit Stoker Company.)

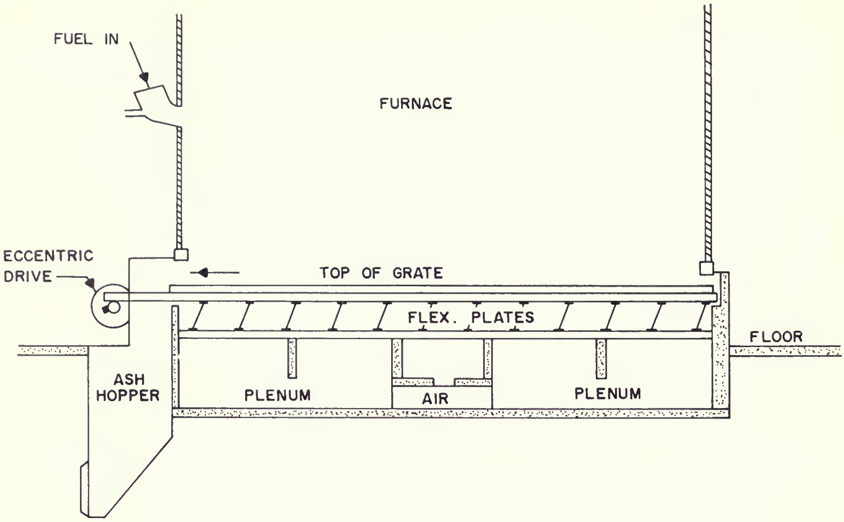


Figure 26-13.—Vibrating grate stoker. (Drawing after Fuller 1976.)

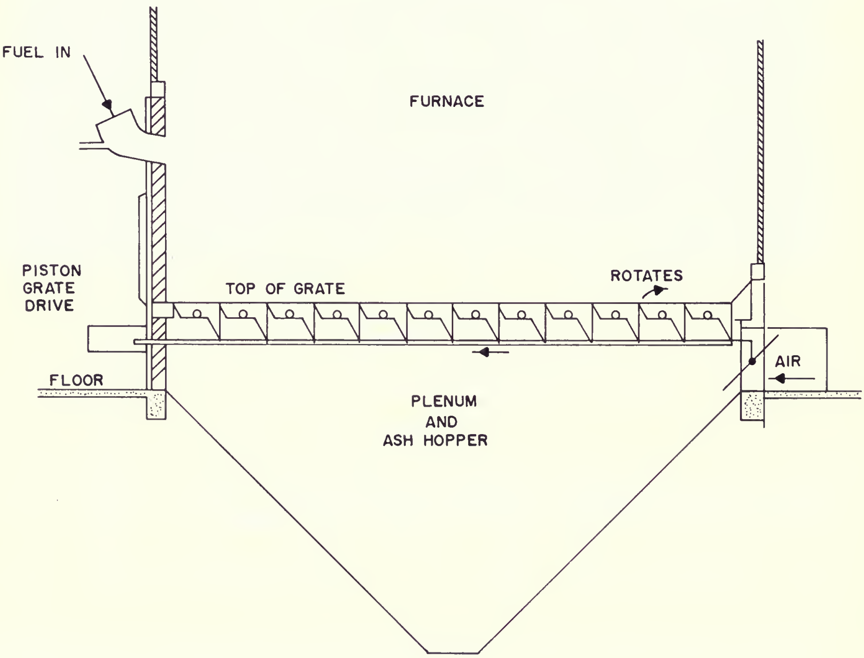


Figure 26-14.—Dumping grate stoker. (Drawing after Fuller 1976.)

Hamrick (1978, 1980) found that large-scale furnaces to burn wood in suspension at rates comparable to those achieved with powdered coal require finely ground wood particles fired with primary combustion air at 500°F and secondary combustion air at about 1,000°F.

In the system shown in figure 26-15, turbulence is provided by high velocity, tangentially injected flows of preheated air through nozzles at various heights in the furnace (Fernandes 1976). In such **tangential firing,** the air flows create spinning air masses or fire circles that hold the fuel particles in suspension while they burn (fig. 26-16). Figure 26-17 reproduces a photograph of the fire circle in a boiler furnace.

In the suspension burners, a small dump grate is located at the bottom of the furnace to catch and burn larger fuel particles that fall out of suspension (Fernandes 1976). Usually, suspension-fired boilers are simpler than spreader stokers, but fuel must be hogged to smaller sizes. Bark alone can be used as fuel but usually an auxiliary fuel, such as oil, pulverized coal, or gas is co-fired in suspension with the bark. Auxiliary fuel nozzels are usually located immediately above and below the bark nozzle. Suspension fired boilers are often large units, some capable of generating over 500,000 lb of steam per hour (Hall et al. 1976).

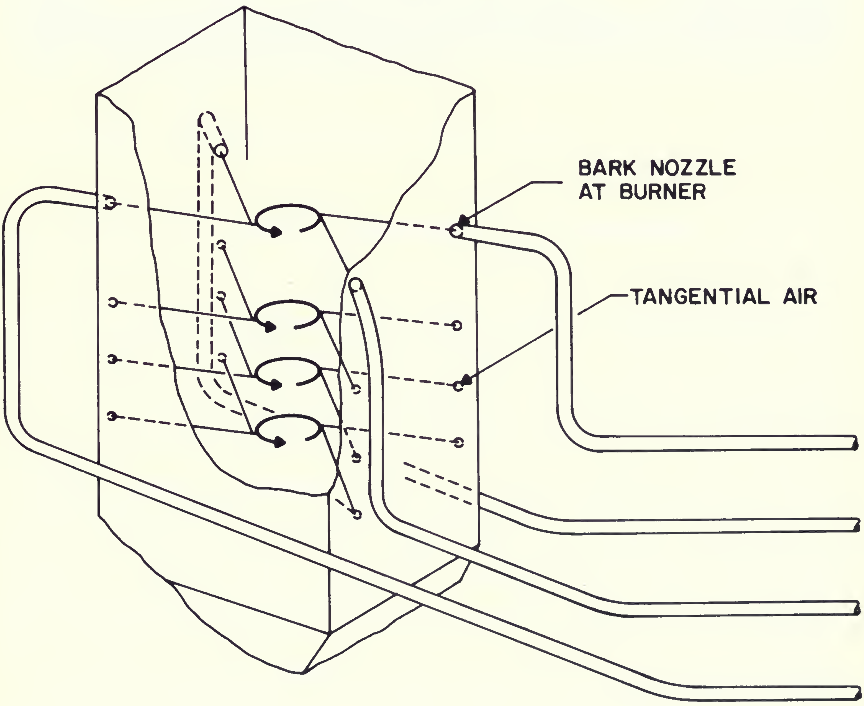


Figure 26-15.—Schematic of a suspension firing system used in large boilers. (Drawing after Fernandes 1976.)

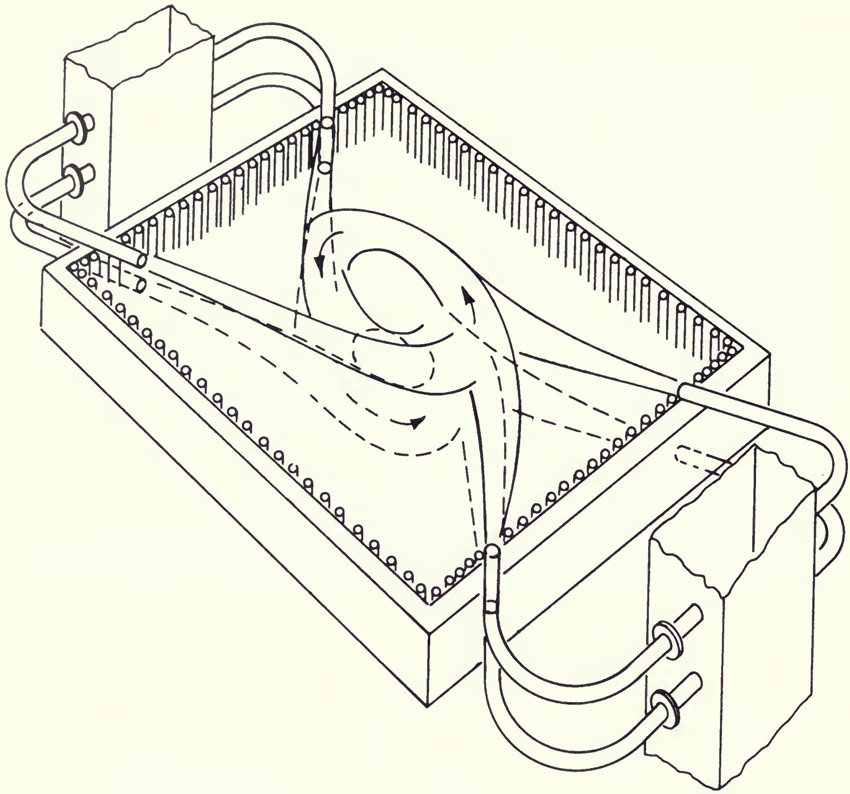


Figure 26-16.—Tangential firing concept. (Drawing after Fernandes 1976.)

Cyclonic furnaces.—Cyclonic furnaces also burn fuel in suspension. In early water-cooled models, cyclone burners were fueled with wood and bark in combination with coal (Fuller 1976). Today, refractory lined models are commonly used and do not require auxiliary fuel except at startup.

In the horizontally mounted cyclonic burner, a drumlike combustion chamber is closed at one end (fig. 26-18). Hot combustion gases are discharged from the opening in the other end called the choke. Combustion air is forced by a blower through the air manifold into tuyeres which admit the air tangent to the inner surface of the combustion chamber. The airflow pattern created is a double cyclonic action. Fuel is injected tangentially into the burner with a stream of high velocity air. Mixing of the fuel and air takes place around the periphery of the burner as they transverse toward the choke. Both the high turbulence of the cyclonic airflow and the time in the burner contribute to complete combustion as long as proper temperatures are maintained. Excess air can vary from 60 to 130 percent depending on the installation (Levelton and O'Connor 1978).

Fuel wood for this system must be dry (15 percent moisture content) and sized (⅛-inch or less). The fuel is metered from a bin to a mixing tee and then into the high velocity air stream for injection into the burners. An auxiliary burner is

Figure 26-17.—Photograph of fire circle produced by tangential firing inside a large boiler. (Photo courtesy of Combustion Engineering, Inc.)

required for startup and additional controls and components can be added for automation. A recirculation system can be incorporated to burn the volatile hydrocarbons associated with the blue haze produced by some veneer dryers (Cherewick 1975; Neild and Weyer 1975). A trap can be added to the basic burners for automatic removal of slag and grit.

Capacities range from 5 to 60 million Btu per hour. Applications for this type of burner include direct firing of lumber kilns, rotary and veneer dryers, and boilers.

Fluidized bed burners.—Particles such as sand contained in a vessel can be fluidized by passing a stream of gas upward through them with a certain velocity (Bryers and Kramer 1977; Wiley 1978). When the particles are fluidized, the bed has a hydrostatic head, and light objects float on its surface, while heavy ones sink. Individual particles undergo a high degree of mixing by moving about in the bed.

Particle size determines the rate of gas flow needed to effect fluidization. With a low rate of gas flow the bed of particles behaves as a porous medium, allowing the gas to pass through. As the rate of flow is increased, the point of incipient fluidization is reached where the pressure drop across the bed equals the weight per unit area of the bed. At this point, the particles start to float on the gas flow. Increasing the gas flows gives no further rise in the pressure drop across the bed. The extra flow passes through the bed as bubbles, and when 3-5 times the

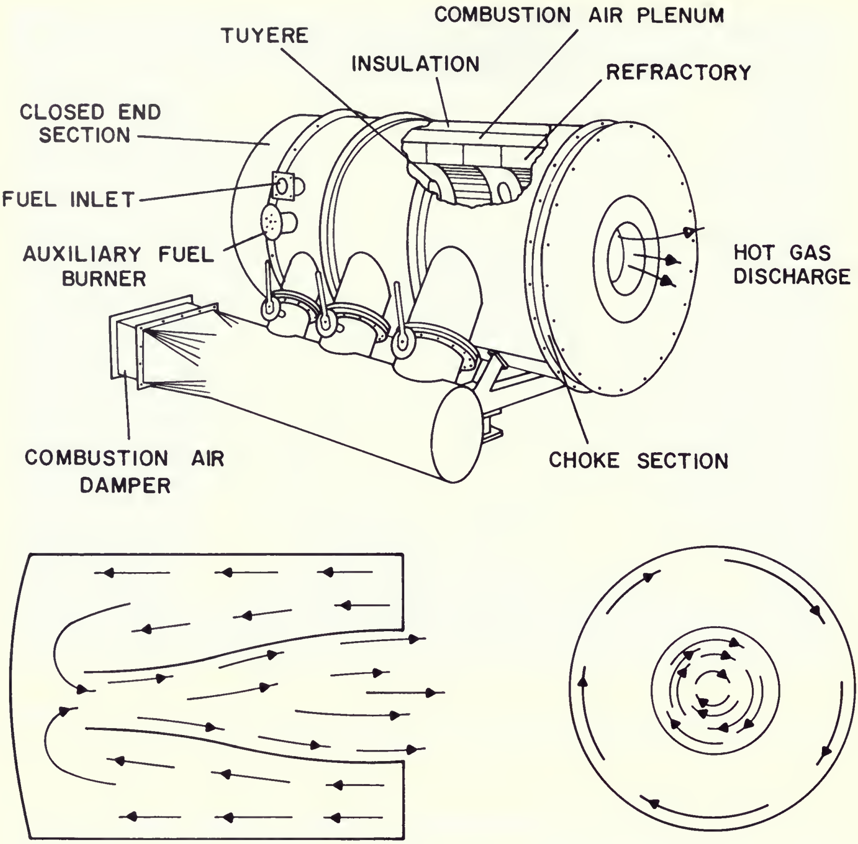


Figure 26-18.—Cyclonic burner and airflow pattern in cyclonic burner. (Drawing from Energex Company.)

minimum fluidization velocity is reached, the bed rsembles a violently boiling liquid. On fluidization, the bed may expand to 1½ or 2 times its original static depth.

Fluidized beds have been used for many years in the petroleum and mining industries for catalytic and ore reactors (Keller 1975). Most recently, they have been adapted to combustion systems. Because of the large particle surface area in the fluidized bed, rapid heat transfer occurs between gas and solids. As the fluidized bed has high thermal inertia, fluctuations in heat input are dampened. This permits combustion of wet and low-quality fuels that vary in heating value. The mineral olivine has been found to be a suitable bed material as it is inert to combustion temperatures up to 2000°F. Bed material wears out by attrition and forms fines that are blown out of the system with the fluidizing gas flow.

Fluidized-bed burners may be used with existing boilers or water tubes can be inserted into the bed or placed in the wall of the burner. The hot combustion gases can also be used for direct heat drying applications (Bryers and Kramer 1977; Wiley 1978). A modified gas turbine cycle coupled to a fluidized bed burner has also been proposed. Such a system will fit into future mill energy needs by providing a higher ratio of electric power to steam power while utilizing a variety of low-grade fuels (Moody 1976).

In the fluidized-bed burner shown (fig. 26-19), the bed is preheated to 700 or 750°F with a non-fluidized airflow for startup. Then, a small amount of fuel spontaneously ignites as it is added to the bed. Once a flame is established, the bed is fluidized by increasing the airflow and then fuel feed is started. As combustion becomes self-sustaining, the temperature of the bed will rapidly rise into the operating range of 1,000 to 1,800°F. Preheat burners can then be turned off and no auxiliary fuel is required.

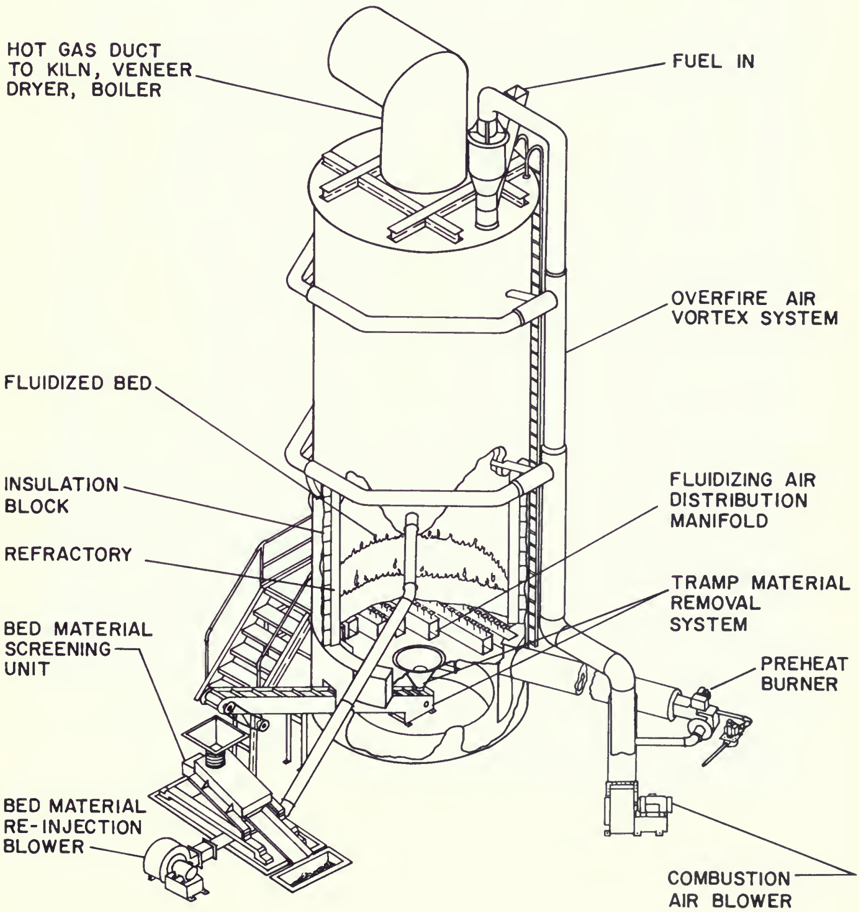


Figure 26-19.—Fluidized bed combustion unit. (Drawing from Energy Products of Idaho.)

Fuel moisture contents can be up to 65 percent. Exhaust gas temperatures are normally up to 2,200°F and bed temperatures around 1,750°F. The largest units being constructed will handle 250 tons per day of hogged fuel and generate 55,000 pounds of steam per hour. Some authorities do not expect large units comparable to the spreader stokers to be built in the near future (DeArmond et al. 1975; Keller 1975), but this opinion is not unanimous (Daman 1979).

Jasper-Koch burner.—The Jasper-Koch burner (fig. 26-20) takes a new approach to suspension burning. The unit is designed to burn wet wood or bark efficiently in a small furnace with output of about 6 million Btu per hour that costs less than grate-type furnaces of comparable capacity.

As noted previously, bark or sawdust that is half water by weight burns very poorly and must be partially dried before combustion occurs. This drying can take place in a separate dryer before burning, in a pile on the floor of the furnace combustion chamber, or in an integral dryer that pases through the combustion zone. The Jasper-Koch burner works on the latter principle.

In the Jasper-Koch design, the combustion chamber is an annular space between two concentric vertical cylinders; particulate fuel burns in suspension in this chamber (fig. 26-21). In the commercial prototype, a stainless steel inner cylinder 29 inches in diameter with walls ¼-inch thick houses a vertical down-feeding screw that introduces fuel into the bottom of the chamber. The outer stainless steel cylinder that confines the upward-moving combustion gases is 49 inches in diameter and also has ¼-inch thick walls. This cylinder is flared to 72 inches at the top of the combustion zone. The fuel is nearly ovendried in its 15-minute transit to the combustion zone. Steam from the drying fuel exits through the combustion zone.

Surrounding the outer cylinder, along the entire 7-foot-high burning zone, is a heat exchanger that preheats air to about 500°F and introduces it at high velocity (1,000-1,300 fpm) into the bottom of the burner. This air conveys fuel particles upward into the combustion zone, where the temperature is about 1,600°F. A 30 hp blower is required for the preheated air to assure proper airfllow and velocity.

The burner has neither grate nor fuel bed. Combustion occurs throughout a zone in which particles are suspended in the air stream. The outer cylinder is flared at the top of the combustion zone. Since the inner cylinder has constant diameter, the flare increases flow area for upward-moving combustion gases, slowing their velocity. This causes particulate matter (other than fine ash) to fall back into the burning zone for continuous recirculation until completely burned. Neither the laboratory model (Jasper and Koch 1975) nor the commercial prototype (Koch et al. 1978) formed slag since combustion temperatures do not exceed 1,800°F. Ash formed during combustion is discharged upwards along with hot combustion gases for later separation. The burner is equipped with a gas jet of one million Btu/hour capacity to facilitate startup.

Nonuniformity of fuel particle size is a problem for designers of wood burning furnaces. Most grate-type furnaces operate best with particles of pulp-chip size and cannot tolerate more than 50% sawdust or fines in the fuel mixture. Because wood particles can be hammermilled to smaller size, but cannot be increased in size (unless pelletized), the operators of grate-type furnaces have difficulty with an oversupply of fines and sawdust.

Figure 26-20.—Photograph of the prototype of the Jasper-Koch burner.

In all suspension burners, small particles are needed. Tests on the Jasper-Koch prototype have shown that the burner runs well with particles sized through the screen (½-inch apertures) of a hammermill hog. Heat of combustion of the fuel was 8,500 Btu per ovendry pound. Ash content contents ranged from 1 to 4 percent of dry weight, and moisture content as admitted to the infeed screw was 53 percent (wet basis).

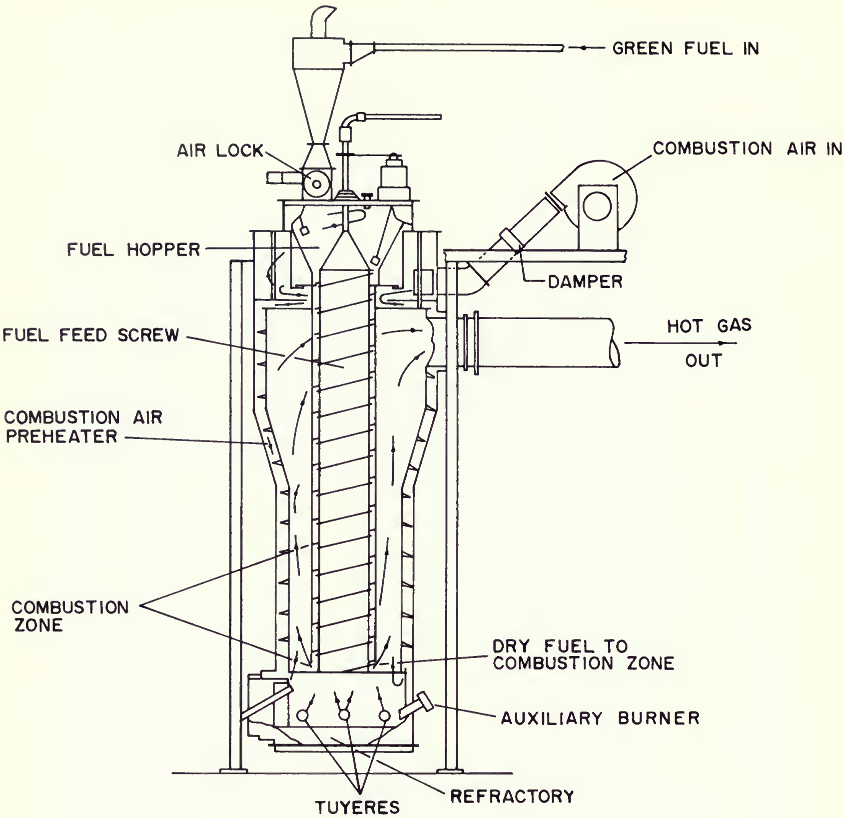


Figure 26-21.—Cross sectional view of the prototype of the Jasper-Koch burner.

STEAM AND ELECTRICAL GENERATION

Steam delivery from boilers can be expressed as kilo Btu's per hour, boiler horsepower, or pounds per hour (Miller 1976). **Kilo Btu** means 1,000 Btu and is a term commonly used by engineers.

Operators of small steam generating units sometimes express steam delivery in **boiler horsepower** (BoHP) a unit that bears no relationshiop to engine horsepower. Boiler horsepower was more commonly used in past decades when small steam plants were used to drive machinery. Boiler horsepower is the energy required for the evaporation of 34.5 lb of water per hour to saturated steam at 212°F at atmospheric pressure. The equivalent amount of heat energy in Btu's is 33,480 Btu/hr.

The amount of wood required to generate 1 BoHP can be calculated if boiler efficiency and fuel moisture content are known. The average green pine-site hardwood with 42 percent moisture content has an available heat of 4,540 Btu/lb (table 26-5). If we assume a boiler efficiency of 63 percent, then 11.7 lb per hour of green wood would be required to produce 1 BoHP:

$$1 \text{ BoHP} = \frac{33{,}480 \text{ Btu/hr}}{(\text{boiler efficiency})(\text{available heat of fuel, Btu/lb})} =$$

$$\frac{33{,}480 \text{ Btu/hr}}{(0.63)(4{,}540 \text{ Btu/lb})} = 11.7 \text{ lb/hr}$$

Today, in the forest products industry the most common expression of steam delivery is number of pounds of steam delivered per hour (**PPH**). The unit is not an absolute measurement as steam at different pressures and temperatures will have different amounts of energy. For example, steam at 165 psi absolute and 550°F contains heat energy of 1,118 Btu/lb more than feed water at 212°F. Under such a system, the amount of green pine-site hardwood (average available heat, 4,540 Btu/lb) required to deliver 50,000 lb of steam per hour with a boiler efficiency of 63 percent is equal to (50,000 lb steam/hr) (1,118 Btu/lb steam) ÷ (0.63) (4,540 Btu/lb wood), or 19,544 lb of wood per hour.

Overall **boiler efficiency** is expressed as energy output divided by energy input:

$$\text{Percent efficiency} = \frac{\text{output}}{\text{input}} \times 100 \qquad (26\text{-}8)$$

This energy input equals the dry weight of fuel multiplied by the higher heating value of the fuel:

$$\text{Input} = m_f \times q_h \qquad (26\text{-}9)$$

m_f = dry weight of fuel burned, lb/hr
q_h = higher heating value of fuel, Btu/lb

The output equals the steam generated multiplied by the difference in heat contents of the feed water and steam leaving the boiler:

$$\text{Output} = m_g (h_1 - h_2) \qquad (26\text{-}10)$$

m_g = steam generated, lb/hr
h_1 = heat content of steam leaving boiler, Btu/lb
h_2 = heat content of feed water, Btu/lb

The instrumentation and procedures required to measure efficiency can become complicated. However, the process of calculating overall efficiency can be greatly simplified by assuming that everything going into the furnace comes out as mass or energy (Hughes 1976). Then, boiler output does not have to be measured and overall boiler efficiency can be expressed as:

$$\text{Percent efficiency} = \frac{\text{input} - \text{losses}}{\text{input}} \times 100 \qquad (26\text{-}11)$$

Corder (1973) lists the sources of boiler heat loss as follows: (a) moisture in fuel; (b) moisture formed from hydrogen in fuel; (c) dry stack gas loss; (d) incomplete combustion, radiation, and unaccounted sources.

In equation 26-11 the sum of (a) through (d) equals losses. Losses due to (a) through (c) can be readily calculated if the moisture content, ultimate analysis (table 26-3), and higher heating value (table 9-12) for the fuel are known. The ultimate analysis is required to calculate the amount of air needed for combustion. Corder (1973) estimates that item (d) accounts for a 4 percent heat loss, but the loss could be substantially greater in poorly insulated boilers.

A procedure outlined by Wiley (1976) was used to calculate overall boiler efficiency for pine-site hardwoods at various moisture contents (table 26-9). It was assumed that the furnace used 40 percent excess combustion air and that the stack gas temperature was 500°F (Corder 1973); these are values that might be expected for efficient burning of hogged fuel. The overall efficiency for green stemwood of average moisture content (42 percent wet basis, table 8-2) is 63 percent, i.e., 63 percent of the heat content of a pound of green wood is converted to steam heat content.

High fuel moisture content is the most important factor in loss of boiler efficiency. The loss is a function of both the amount of moisture in the fuel and the stack gas temperature. Heat is lost both in vaporizing the water and in raising the temperature of the steam to that of the stack gases. At 50 percent moisture content, 16 percent of the fuel energy is lost up the stack (table 26-9). If the moisture content can be reduced to 10 percent, less than 1 percent of the fuel energy is lost and overall efficiency is 74 percent.

TABLE 26-9.—*Heat losses and overall boiler efficiency related to pine-site hardwood moisture content*[1]

Heat loss from	Moisture content[2]			
	10%	25%	42%	50%
	Percent loss			
Moisture in wood[3]	1	5	12	16
Moisture from hydrogen in fuel[3]	9	9	9	9
Dry stack gases[3]	12	12	12	12
Incomplete combustion, radiation and unaccounted[4]	4	4	4	4
Total heat loss	26	30	37	41
Overall boiler efficiency	74%	70%	63%	59%

[1]Boiler operating with 40 percent excess air and stack temperature of 500°F.

[2]Wet basis.

[3]Calculated by Wiley's method (1976); average stemwood value of 7,827 Btu/lb used (table 9-12).

[4]Estimated (Corder 1973).

Evaporation of moisture formed from the combustion of hydrogen in wood also causes loss in boiler efficiency. One pound of dry wood, of which 6.4 percent is H will produce 0.58 lb of water on combustion (equation 26-2) this results in a 9 percent loss in boiler efficiency.

Dry stack gas heat loss depends on both the amount of excess air and stack temperature. As either excess air or stack gas temperature increases, heat loss increases (Corder 1973). When pine-site hardwoods are used as fuel, the loss is estimated at 12 percent with 40 percent excess air and 500°F stack gases. After the gases have passed through the steam-generating heat exchangers, heat can be salvaged from the gases by passing them through a second set of heat exchangers called economizers. Economizers can be used to preheat boiler feed water. Some of the stack gases can also be used to predry incoming fuel and to preheat incoming combustion air.

The overall conversion efficiency for conventional steam generation of electricity from wood is about 25 percent (Benemann 1978; Love and Overend 1978). This estimate includes boiler efficiency, steam cycle efficiency, and auxiliary power requirements, all of which can vary. The amount of pine-site hardwood required to generate a kilowatt-hour (Kwhr) can be calculated as follows. For green pine-site hardwood of 42 percent moisture content (wet basis), the available heat is 4,540 Btu/lb (table 26-5). As 1 Kwhr = 3,412 Btu,

$$1 \text{ Kwhr} = \frac{3{,}412 \text{ Btu}}{4{,}540 \text{ Btu/lb } (0.25)} = 3 \text{ lb green pine-site hardwood}$$

The amount of wood required to fuel electrical generating plants, assuming 25 percent conversion efficiency, is as follows: (1 megawatt, Mw = 1,000 kilowatts):

Electrical generating plant size	Amount of green pine-site hardwood required for fuel
5 Mw	7.5 ton/hr
25 Mw	37.5 ton/hr
250 Mw	375 ton/hr
500 Mw	750 ton/hr

Co-generation of steam and electricity from a boiler plant is becoming an accepted practice in the forest products industry (Pingrey and Waggoner 1978). It is not a new process, but interest in it has been renewed in recent years. In the 1920's, co-generation was common in New England and on the West Coast as it was the only way to obtain electricity for mill operations. As electricity from utilities became available at low cost, most of the electrical generation systems were shut down.

Cogeneration of steam and electricity is economically most advantageous in plants having a large demand for process steam and also a need (or market) for electrical energy. One method of cogeneration finding favor utilizes a back-pressure type of turbo-generator. Steam is passed through the turbo generator to produce electricity, and the exhaust provides process steam for the mill. Since there is no cooling water or cooling tower, the turbo-generator takes only the amount of energy out of the steam necessary to generate electricity sufficient for the load, and the remaining energy is in the process steam. Exhaust gage pressures commonly vary between 25 and 200 psi depending on the usage. Under ideal conditions where demand for electricity and process steam are in the proper balance, no condenser is needed on the turbine and overall efficiency of the system may approach or exceed 60 percent. This is a significant improvement from the 25 percent overall efficiency commonly observed in plants producing only electricity.

Readers interested in cogeneration are referred to papers on the subject published by the Forest Products Research Society (1979, p. 10-36; 1980).

Pingrey and Waggoner (1978) estimated that in the United States the overall generating capacity of electrical generating plants using wood and wood derived fuels is about 4,500 MW (table 26-10). Many of the plants, however, use fossil fuels at the same time they are burning wood and wood derived fuels. For instance, it is estimated that on an annual basis, the pulp and paper industry burns 54 percent fossil fuels to generate electricity, while wood residues and pulping liquors supply the remaining 46 percent. On the other hand, solid wood products mills are estimated to use 98 percent wood fuel and only 2 percent fossil fuel.

But outside the forest products industry, few wood-fueled electrical utilities are in operation. They are located in Eugene, Oregon; Libby, Montana; Burlington, Vermont; Ashland, Wisconsin; and Kettle Falls, Washington. Others are under construction.

The Eugene utility has been using hogged fuel since the 1940's to generate electricity. The steam generated not only is used to run turbines, but is distributed to the central part of the city, where it is used to heat businesses and homes and provides process steam to plants such as laundries (Anonymous 1977).

Readers interested in construction costs and operating expenses of large steam-electric plants should find useful the comprehensive study by the U.S. Department of Energy (1978c) of major steam-electric plants of the electric utility business.

TABLE 26-10.—*Estimated generating capabilities of electric generating plants in the United States that use wood and wood derived fuels*[1]

Producers	Generation capability
	Megawatts
Pulp and paper mills	3,600
Solid wood products	800
Utilities	60
Other[2]	40
Total	4,500

[1]Data from Pingrey and Waggoner (1978).

[2]Miscellaneous users of small wood fired plants which included a rubber plant, sugar mills, and a resort.

DOMESTIC STOVES AND FIREPLACES

High oil, natural gas, and electricity prices have renewed the public's interest in home and shop space heating with wood. Wood is readily available and improvements in woodstove design and devices to make stoves and fireplaces more efficient have come about with the renewed interest in wood burning (Shelton 1976; and Lew[7]). Annual wood usage for such space heating is substantial—equivalent to perhaps 0.8 quads in 1983.

[7]V. Lew, "Wood Burning Stoves", a staff report to the Fuels Office, Alternatives Division, California Energy Commission, June 14, 1978, Sacramento, California)

Timber to be cut into firewood for personal use is usually available at low cost from both State and National Forests. Owners of small woodlots also sell culled hardwoods as domestic firewood. The pine-site hardwoods make excellent firewood for home use. They are more dense and burn with a longer lasting fire than resinous softwoods. Oak is probably best as it gives the most uniform flames while producing hot and long lasting coals (USDA Forest Service 1974).

Efficiency.—Fireplaces generally are not very efficient (10 percent or less) because much heat is lost up the chimney (Shelton 1976). One device to make fireplaces more efficient is a hollow grate through which air can be circulated. Glass doors with controlled air intakes can be placed on a fireplace to reduce the amount of air entering from the room. With reduced airflow the fire burns more slowly and less heat is lost up the chimney. In new fireplace installations, efficiency can be raised to about 40 percent by heating circulating fire boxes with outside air intakes.

Wood burning stoves are considerably more efficient than fireplaces; efficiencies can range from 25 to 75 percent;[7] 50 to 55 percent efficiency is commonly attained in airtight stoves of good design. Stove design is generally based on controlling combustion air and enhancing heat transfer to the room. Combustion air can be controlled with secondary air inlets, airtightness, and different airflow patterns through the stove. Secondary air, which is often provided in a secondary combustion chamber, is used to combust completely the volatile gases produced from the burning wood. In non airtight stoves air leaks through cracks around the door and at other places where parts are joined reduce efficiency because the leaked air is not involved in combustion and takes heat out through the chimney. Airtight stoves control combustion air more effectively because stove sections are welded or cemented together. This control over airflow gives airtight stoves longer burning times and causes them to use 25 to 50 percent less wood.

While operation of wood-burning stoves in an airtight mode increases their thermal efficiency, there are some dangers in such operation, i.e., combustion can occur with less than stoichiometric oxygen resulting in generation of intermediate combustion products which may condense in the chimney to form flammable liquids. These liquids, sometimes called creosote, can cause chimney fires if not periodically removed.

Air-flow patterns in stoves.—Many different wood stoves are on the market today. Most can be broadly categorized on the basis of the flow pattern of air through the stove (Shelton 1976). The five basic patterns are: up, diagonal, across, down, and "S" (fig. 26-22).

In the updraft pattern the combustion air enters below the burning wood and travels up through the grate. Secondary air may be necessary above the wood for complete combustion of volatiles. Example of updraft stoves include the potbellied stoves and the Shenandoah.

The diagonal flow pattern is found in the simple box stove. Air enters the stove at the bottom front of the combustion zone and travels diagonally through the burning wood, exiting at the top back corner. Secondary air inlets again may

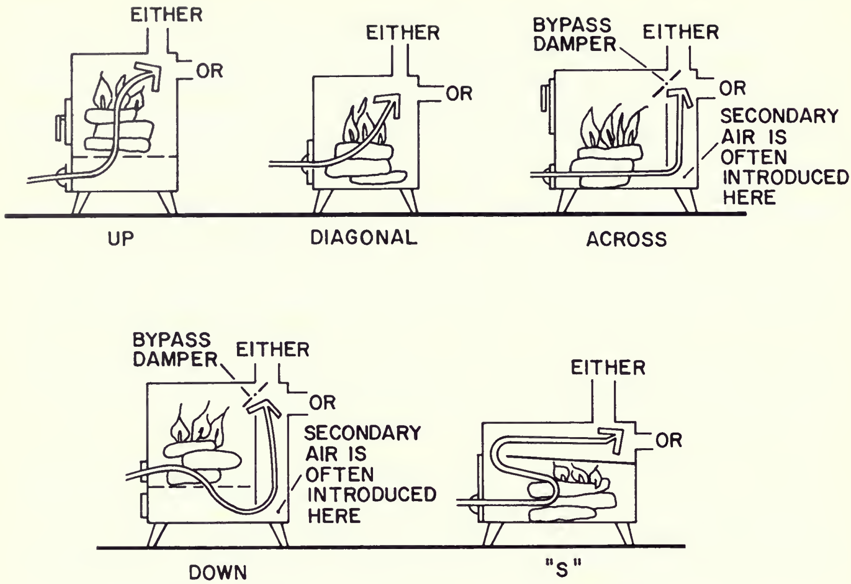


Figure 26-22.—The five basic airflow patterns found in domestic stoves. Stoves with both the across- and down-draft flow patterns usually require a bypass damper to prevent smoke from entering the room when the stove door is opened. (Drawing after Lew.[7]).

be supplied above the burning wood for more efficient combustion. Examples of this flow pattern include the Ashley 25HF, Fisher and drum stoves (Shelton 1976).

In the across pattern, air enters the stove at the bottom front but moves horizontally across the wood to exit at the lower back. Considerable turbulence occurs above the burning wood and volatile gases are forced through the hot coals or flames at the back of the combustion chamber. Secondary air is usually provided at this point. Stoves with both the across and downdraft flow patterns usually require a bypass damper to prevent smoke from entering the room when the stove door is opened. Many stoves using the across flow are airtight and have large fuel capacities so that refueling is not necessary for long periods (Shelton 1976).

In downdraft stoves, air enters the stove above the grate and passes down through the grate along with emerging volatiles produced from the burning wood. Secondary air can be provided at a number of points, often at the bottom of a baffle plate at the back of the stove. Combustion is then completed in a secondary chamber. This design is one of the better ones for efficient burning of wood. Downdraft stoves are usually airtight and can operate for long periods between fueling (Shelton 1976).

Wood usually rests directly on the firebox floor in the S-flow stoves. A horizontal baffle extends from the back of the stove and prevents air flow and volatile gases from leaving the combustion area directly. The S-flow provides extra turbulence and burning time for the volatiles, and the baffle also helps to increase heat transfer from the hot gases to the outside of the stove. Wood tends to burn from the front of the stove to the back. These stoves are noted for steadiness of heat output and high efficiency. Common examples of this type of stove are the Norwegian Jϕtul, Lange, and Ram woodstoves.[7]

Economics.—The economics of home heating are attractive if an efficient wood stove is used. Lew[7] has estimated that one cord of red oak (21 million Btu's per cord) burned in an airtight stove (50 percent efficiency) will yield heat equivalent to the use of 1.1 tons of coal, 115 gallons of number 2 fuel oil, 14,000 cubic feet of natural gas, or 3,074 kilowatt hours (kWh) of electricity. At 6¢ per kWh, the equivalent electricity cost would be $184. A cord burned in a box stove or Franklin fireplace (30 percent efficiency) would produce heat equivalent to 1,848 kWh or $111. In a fireplace with 10 percent efficiency, the heat realized would be equivalent to only 616 kWh, or about $37 per cord. It is thus apparent that savings will depend greatly on the efficiency of the burning system. Parker (1979) provided graphs for quick analysis of wood costs related to costs of fossil fuels or electric heat at various stove efficiencies.

Air pollution and trends.—Air-tight stoves that restrict inlet air to increase stove efficiency are now widely used in northern parts of the United States. When such stoves are operated with dampers nearly closed, particulate and condensable organic emissions can signifiantly contribute to national pollutant emissions (Butcher and Sorenson 1979; DeAngelis et al. 1980; Jaasma and Kurstedt[8]). When stove fires are burned hot with ample combustion air, pollution is lessened as is accumulation of condensed creosote in chimneys.

Installation of a catalytic combustor may increase stove efficiency and decrease both pollution and creosote buildup by burning, rather than discharging to the chimney, combustible gases distilled from the wood being burned. Gases coming in contact with a catalytic combustor burn even if the temperature of the gases is below 500°F. As made by Corning Glass Works, the device is a ceramic honeycomb 3 inches long by 5⅝ inches in diameter with 16 cells per square inch coated with a noble metal similar to the catalysts used in automative exhaust systems. Temperatures as high as 1,600°F can occur in a catalytic combustor, so it should be located inside the stove where the gases must pass through it.[9] Quick fouling of catalytic combustors and resulting short service life is a problem not yet fully solved by stove designers.

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[7]V. Lew, "Wood Burning Stoves", a staff report to the Fuels Office, Alternatives Division, California Energy Commission, June 14, 1978, Sacramento, California)

[8]Jaasma, D.R., and H.A. Kurstedt, Jr. (n.d.) The contribution of wood combustion to national pollutant emissions. Unpublished paper. Dept. Mechanical Eng., Virginia Polytech. Inst. and State Univ., Blacksburg.

[9]Personal communication from D.E. Nelson, U.S. Dep. Agric., Washington, D.C., May 1981.

An alternative way to burn wood cleanly is to burn it at very high temperature in a small refractory-lined combustion chamber with heated, turbulent, forced-flow combustion air. Heat from resulting complete combustion can be captured by a heat exchanger which transfers it to an insulated water storage tank with sufficient storage capacity to heat a home for 2 days or more. The homeowner monitors the water temperature and reheats it with a hot furnace fire when necessary. Such furnaces, developed by Hill (1979), are manufactured in Maine for firing with round or split wood.

Chips can be automatically stoker-fed to furnaces in response to thermostat signals and they are cheaper per ton than firewood in stick form.[10] These factors stimulated Riley et al. (1979) to develop at the University of Maine a residential furnace (fig. 26-23) fueled by wood chips via a top-feed stoker. In their design chimney temperatures are usually 250-300°F to allow natural draft to provide sufficient combustion air, eliminating need for safety chimneys or emergency blowers in the event of a power failure. The small chip bin holds a 1- to several-day fuel supply. A short conveyor carries chips to the firebox on call of a thermostat, with feed rates from 8 to 16 pounds of wood (ovendry weight basis) per hour resulting in heat outputs of 50,000 to 100,000 Btu per hour. Fuel is fed into the top of the firebox to provide a break in the fuel supply line and thus eliminate the possibility of pyrolysis occurring in the fuel supply line. An oil burner (with 6-second time delay to allow a chimney draft inducer to come up to

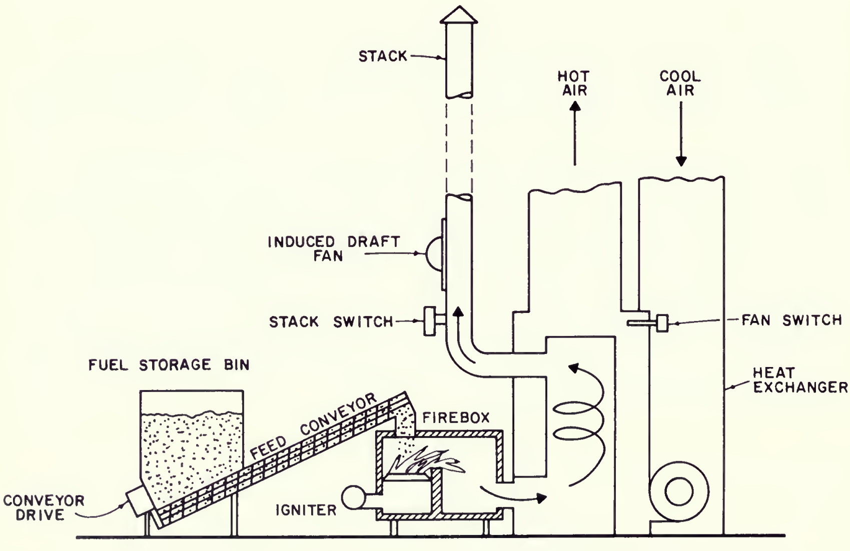

Figure 26-23.—Chip burner retrofitted to a conventional residential oil furnace; output is 50,000 to 100,000 Btu per hour. (Drawing after Riley et al. 1979.)

[10]American Fyr-Feeder Engineers. (N.d.) Wood chips—the rediscovered energy fuel source. American Fyr-Feeder Engineers, Des Plaines, Ill.

speed), firing directly below the fire grate lights the fuel as it falls on the grate and shuts off once the chips are ignited. Chip feed continues while the thermostat calls for heat and ceases when the thermostat is satisfied.

In the design of Riley et al. (1979) air supply is governed so that sufficient air is always supplied for complete combustion but excess is limited to maintain a firebox vacuum. As much of the combustion air as possible is passed through the grate to:

- Produce an intense hot fire which burns the chips, which must be previously dried to 30 percent, or less, moisture content
- Produce a high ratio of energy release/grate area
- Increase grate life by cooling the grate with air flow
- Cool ash on the grate below fusing and slagging temperature, thus leaving it particulate so it will fall through the grate into the ash pit.

The refractory-lined firebox has two chambers, one containing the grate and the other forming an afterburner tube to provide sufficient turbulence and retention time at high temperature to insure complete combustion before flue gases leave the firebox and commence cooling. Firebox operating temperatures are 1,400-1,800°F with fairly dry chips and 1,100-1,300°F with moister chips. The small amount of fuel remaining on the grate after the thermostat shuts off burns out in a few minutes. The unit is designed for hot-air, hot-water, or steam central heating systems. Wide application of chip-burning, top-feed central furnaces for homes is somewhat inhibited by the need to pre-dry the chips to below 30 percent moisture content and screen them to eliminate oversize chips. Also, distribution systems must be established to deliver 1-ton loads of chips to home fuel bins.

Chip-fired residential stoves and furnaces (usually of under-feed design) are common in Sweden; Thörnqvist and Lundström (1980) found that airborne fungal propagules were more numerous in Swedish homes so heated, than if heated by oil or stick firewood. They found that risk of fungal attack is minimized if chips are stored only short periods of time, if the roundwood from which the chips are cut is stored a long time before chipping, if the porportion of hardwood chips in the pile is reduced, and if trees are limbed and topped before chipping (to decrease content of leaves, needles, and bark). They recommend the following measures to avoid heavy air contamination by fungus propagules to which many people are sensitive and which cause allergies:

- Do not store chips in dwellings.
- Wear a protective mask when working with chips.
- Do not store clothes in a room where chips are stored.
- Keep furnace room and storage room as clean as possible.
- Remove old chips before introducing new chips to storage.
- Build storage room of durable materials to prevent decay.
- Make storage room spacious to allow large volumes of air above stored chips.
- Ventilate air from the storage room to prevent it from reaching living or working areas.

Miller et al. (1982) also suggested that dry storage of chips under conditions that do not allow fungal growth is important to avoid propagation of allergenic and pathogenic fungi; chips subject to biological heating, if loaded into a home chip-fuel furnace, may distribute fungal propagules throughout basement and upper floors.

26-4 GASIFICATION

Water slurries of wood and bark, or whole-tree chips, can be converted by anaerobic biodigestion to a gaseous fuel (methane); the process is not further described because yields of gas are too low, and the process too slow, to warrant economic consideration (National Aeronautics and Space Administration 1979; Pfeffer 1978).

Gasification, as discussed under this heading, is accomplished by thermal decomposition of organic material in the presence of controlled and limited amounts of air or oxygen to produce a combustible mixture of gases, often referred to as **producer gas.** When air is used, the producer gas contains mostly hydrogen, carbon monoxide, and nitrogen. Lesser amounts of carbon dixoide, methane, and hydrocarbons are formed. The mixture is generally referred to as a **low Btu gas** (table 26-11). Heating values range from 100 to about 200 Btu/sdcf (standard dry cubic foot) (Levelton and O'Connor 1978; California State Energy Commission[11]).

When oxygen is used for gasification, the producer gas is termed medium Btu gas, with heating values as high as 350 Btu/sdcf (Bliss and Blake 1977). Nitrogen dilution is eliminated so that the two major components of medium Btu gas are hydrogen and carbon monoxide. Lesser amounts of carbon dioxide, methane, and hydrocarbons are also produced (Table 26-11).

The exact chemical composition of either low or medium Btu gas depends on variables that include gasification temperature, pressure, time, and presence of a catalyst (Love and Overend 1978). In the crude state, both low and medium Btu gas contain high percentages of moisture which originates from the partial oxidation process and from moisture in the fuel. However, the moisture can be readily removed (Bliss and Blake 1977).

TABLE 26-11.—*Typical composition for low and medium Btu gases produced on gasification of biomass*[1,2]

Constituent	Low Btu gas	Medium Btu gas
	Percent	
Carbon monoxide (CO)	20	40
Hydrogen (H_2)	15	30
Carbon dioxide (CO_2)	10	20
Hydrocarbons (CH_x)	5	10
Nitrogen (N_2)	50	—

[1]Data from Benemann (1978).
[2]Composition varies.

[11]California State Energy Commission, "Commercial Biomass Gasifier at State Central Heating and Cooling Plant", Feasibility Study prepared by Fuels Office, Alternatives Division, April 1978, 63 p.

The constitution of **synthesis gas** (hydrogen and carbon monoxide), which can be used to produce several important chemicals, is closely approximated by medium Btu gas from wood gasification.

The basic processes in gasification are similar to those in combustion except that complete oxidation of carbon to carbon dioxide is avoided. Only sufficient air or oxygen is provided to the gasifier bed for (1) gasification of the carbon char by partial oxidation to carbon monoxide and (2) for generation of enough heat to support drying and pyrolysis of the fuel (Eggen and Kraatz 1976). Drying and pyrolysis of the fuel occur much as they do in combustion except the volatile gases produced are not oxidized. In pyrolysis, water vapor, carbon monoxide, and carbon dioxide are formed first. Then further decomposition gives tars which finally yield hydrogen and hydrocarbons leaving only a carbon char. The carbon char is partially oxidized to carbon monoxide by oxygen, water, or carbon dioxide. The carbon dioxide then is reduced to carbon monoxide. While the addition of air or oxygen to the fuel bed is necessary to sustain this complex oxidation-reduction scheme, no air or oxygen can be allowed to mix with the gases produced as they would readily combust.

Researchers are investigating the use of catalysts in gasification of wood (Feldman 1978; Walkup et al. 1978; Garten et al. n.d.). A primary reason for catalyzing gasification would be to lower gasification temperature and to improve reactivity. The best catalysts found so far are calcium oxide and wood ash. Catalysis may also be used to selectively form one product. If such a catalysis system can be developed, gases that are predominantly methane, hydrogen, or carbon monoxide or optimum mixtures for a specific purpose might be produced. These products would be of much higher value than producer gas and would make gasification a more competitive conversion process.

Gasification is not new; coal was gasified in the nineteenth century.[11] Early gasification units operated by blowing air up through the fuel bed and allowing gases to exit the top (updraft operation). The producer gas was used to fire boilers and furnaces.

After cooling and cleaning, producer gas has been used to fuel internal combustion engines. In fact, about 600 Crossley gas plants (fig. 26-24) were constructed for that purpose between 1912 and 1940 (Levelton and O'Connor 1978). Reportedly some are still in working order.

Portable gasification units were developed during the 1940's.[11] About 700,000 vehicles were adapted to use producer gas in Europe during World War II. Coal, coke, and charcoal were commonly gasified; wood and crop residues had limited use. Although development of portable gasifiers mostly ceased after World War II, Swedish researchers produced a successful wood-fueled downdraft gasifier for use on agricultural vehicles. For an extensive account of the Swedish experience in developing generation gas for motor vehicles, see Solar Energy Research Institute (1979a). See section 28-1 for discussion of the cost of owning and operating a diesel tractor operated on wood gas. For description of producer-gas-fueled spark-ignition engines for low power systems (to 20 kW) using charcoal, see Hollingdale et al. (1983). See also: Kaup, A. and J.R. Goss.

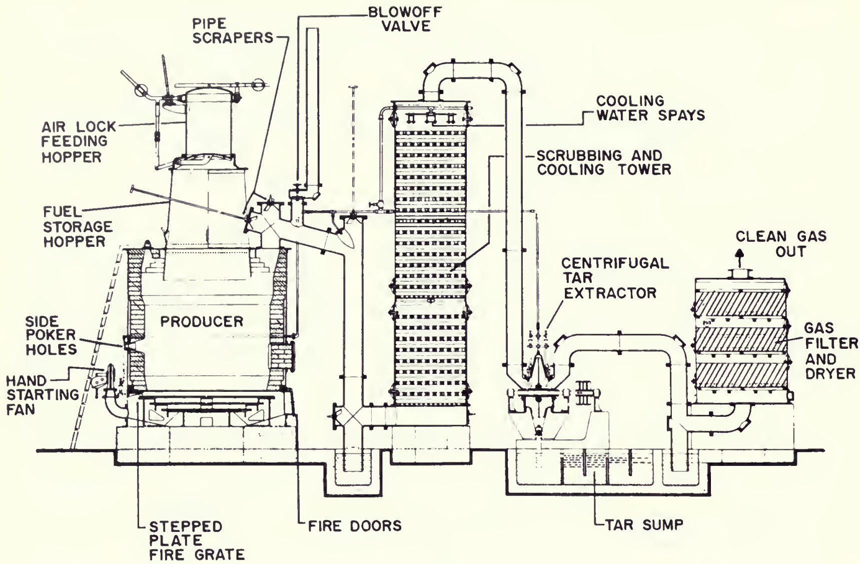

Figure 26-24.—Original Crossley gas plant. (Drawing after Levelton and O'Connor 1978.)

1981. State of the art for small (2-50 kW) gas producer engine systems. Final Report to U.S. Dept. of Agric. Forest Service, Wash., D.C. 278 p.

While not a completely proven technology in all applications, wood gasification offers wide versatility (fig. 26-25). In North America, many types of wood gasifiers are in various stages of development (Levelton and O'Connor 1978, Solar Energy Research Institute 1979b). In general, wood gasifiers are smaller than the coal gasification units now under development and would be suitable primarily for smaller scale applications. Capacities of present wood gasifiers are usually 10 million Btu/hour or less, and seldom exceed 100 million Btu/hour.

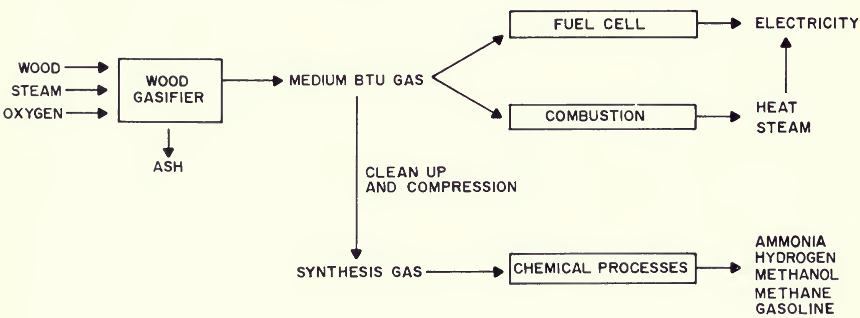

Figure 26-25.—Gasification scheme for the production of energy, chemicals, and synthetic fuels from wood.

ENERGY PRODUCTION

Gasifier types.—Reed (1980) described four general types as updraft, downdraft, fluidized-bed, and suspension gasifiers (fig. 26-26). In **updraft gasifiers** (fig. 26-26 top left) air or oxygen is injected under a grate supporting charcoal causing combustion and reduction of the gases. The resulting hot gases then rise through the incoming biomass at the top of the furnace, producing oils and water by pyrolysis and drying. The resulting gas must be close-coupled to the burner and burned directly because suspended tars are difficult to remove. Updraft gasifiers are especially appropriate for retrofitting existing gas- or oil-fired boilers.

In the **downdraft gasifier** (fig. 26-26 top right) air or oxygen is injected above the char mass, causing pyrolysis of incoming biomass and producing char and oils. These oils then pass over the hot char and are cracked to gases; as a result very little oil is produced. For this reason, downdraft gasifiers are particularly suitable for internal combustion engines.

Although not as well developed, **fluidized beds** (fig. 26-26 center) for biomass gasification have some theoretical advantages over updraft and downdraft gasifiers. Because of their high recirculation rates, fluidized beds have high heat transfer rates and high throughputs. Also, they are able to process wood in a wide range of sizes. Because contact time is short, however, they are not as efficient in consuming char or cracking oils and tars. In fluidized beds there is a tendency for light biomass fractions to separate from the bed prematurely. Less well developed is **suspended gasification** (fig. 26-26 bottom), even though it holds promise for high throughput with a feedstock of small wood particles (Reed 1980).

Readers needing a compendium of gasifier types that are in operation or undergoing research are refered to a survey by Solar Energy Research Institute (1979b). Research on gasifiers is active; Graham's (1980) bibliography of biomass pyrolysis/gasification contains 274 references. See also: Reed, T.B. (Ed.). 1981. Biomass gasification: Principles and technology, Energy technology review No. 67, Park Ridge, New Jersey: Noyes Data Corp.

Yields and efficiencies.—Thermal efficiencies of gasifiers are widely variable. Beck (1979) and Beck et al. (1980) found that the fluidized bed gasifier developed at Texas Tech University yielded 20-22 sdcf of gas per pound of dry ash-free wood; the gases contained significant amounts of hydrocarbons which led to high heating values. In tests using air and oak sawdust, the gas produced had a heating value of 250-350 Btu/sdcf, a very high value for gasification with air in a single vessel. These data suggest recovery of about 6,300 Btu in gas from each pound of dry oak wood, which typically has a higher heat of combustion of about 7,800 Btu/ovendry pound. Other researchers have reported thermal efficiencies as low as 60 percent. When wood gasifiers are used to drive motor vehicles with internal combustion engines, 12 to 20 percent of the energy contained in the wood is converted to mechanical power (Datta and Dutt 1981).

On-site combustion of producer gas.—Most of the gasifiers under development are air blown and produce a low Btu gas suitable to be burned on site so that

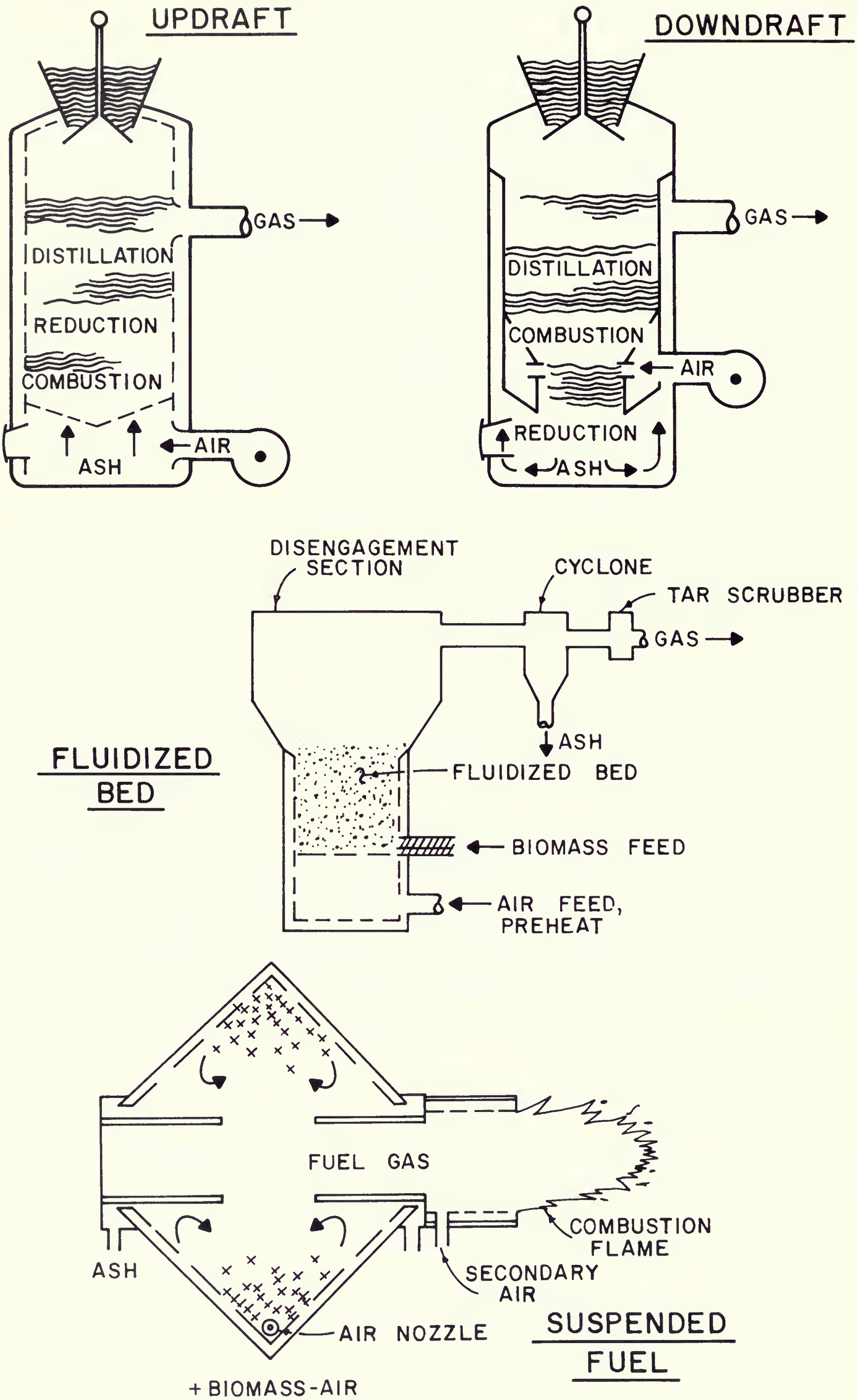

Figure 26-26.—Four types of wood gasifiers. (Top left) Updraft. (Top right) Downdraft. (Center) Fluidized bed. (Bottom) Suspended fuel. (Drawings after Reed 1980.)

the immediate (sensible) heat of the gas can be utilized (Love and Overend 1978). Such on-site utilization is best for low Btu gas since the gas cannot be stored effectively, and its low Btu content makes transport economically unattractive. After modification of burner nozzles, low Btu gas can be burned in standard natural gas and oil furnaces.

Such gasifier systems have advantages over solid-wood fueled furnaces. Ash and carbon residues remain in the gasifier; the furnace is subjected only to producer gas, a relatively clean fuel. While some tars, oils, and particulates may be carried over with the producer gas, in most cases no pollution controls are needed on the furnace.[12]

A portable gasifier developed by the University of California was successfully tested using wood as a fuel at the California State printing plant where the low Btu producer gas was burned in one of the plant's boilers (table 26-12). A feasibility analysis indicated that no major technical barrier exists to commercialization of gasifiers that produce low Btu gas for furnace boiler fuel.[11] Emissions were within acceptable standards. The costs of using the gasifier system over 20 years would be competitive with the cost of using natural gas (in California) assuming price increases at the rate of inflation.

TABLE 26-12.—*Input and output for one hour of prototype gasifier operation*[1]

Input	Output
.75 ton of wood[2]	10 million Btu of gas
1 gallon of gasoline	100 lb of char
5 Kw of electricity	1 quart of tar
	SO_x - negligible
	NO_x - 129 ppm
	particulates - 0.8 grams per standard cubic foot

[1]Data from California State Energy Commission, "Commercial Biomasss Gasifier at State Central Heating and Cooling Plant", Feasibility Study prepared by Fuels Office, Alternatives Division, April 1978, 63 p.

[2]Tests were based on kiln-dry wood, demolition wood, and pelletized sawdust; average moisture content was probably about 10 percent of ovendry weight.

In another demonstration, Applied Engineering Company, Orangeburg, S.C., designed, constructed, and in February 1981 began testing a wood gasifier (fig. 28-10) retrofitted to a 19,000 lb/hr watertube boiler originally equipped to burn oil or gas. The work was done under contract by the Georgia Forestry Commission and installation was made at the Northwest Regional Hospital at Rome, Georgia. See section 28-6 for an economic analysis of the retrofit.

The gasifier reactor vessel is cylindrical, insulated with firebrick, and enclosed in a carbon-steel shell. Air is injected at the bottom of the reactor and fuel added at the top. Gases produced exit at the top and ash is discharged from the bottom. The grate area, located above the ash hoppers, is water cooled. Gas

[12]G.D. Voss and V.A. Gauger. Gasification of wood residues. Paper presented at the For. Prod. Res. Soc. Annu. Meet. (Denver, Colo., July 1977). 13 p.

produced has a heat content of 150 to 165 Btu/standard cu ft and has composition, by volume, as follows: nitrogen and nitrogen compounds, 50 percent; carbon monoxide, 30 percent; carbon dioxide, 7 percent; oils and tars, 3 percent; hydrogen, 10 percent; water vapor, variable according to moisture content of wood.

Tests indicate that 75 tons per 24-hour day of hardwood or softwood chips with average size of 3 by 3 by ½-inch and maximum moisture content of 50 percent (wet basis) will produce 25 million Btu/hr. The system requires motors totalling 110 hp and consumes water at 10 gallons/minute. Plant steam in the amount of 500 lb/hr is required to cool the grates and enhance Btu content of the gas. Ash output is about 500 pounds per 24-hour day.

Economics of retrofitting boilers for on-site combustion.—Wood gasifiers, when commercially practical models are available, will be suitable for retrofit to existing furnaces and boilers now fired by oil or natural gas (see sect. 28-6). The Solar Energy Institute (1979a) estimated that the cost of retrofitting existing equipment with air gasifiers, having output in the range from 5 to 100 million Btu/hour, should be about two-thirds the cost of a new solid-fuel installation. Furthermore, gasifiers offer lower emissions and higher turndown ratios (better ability to adjust to fluctuating loads) than solid-fuel boilers. The Solar Energy Institute estimated that with a wood cost of $20/ton (green-weight basis), total cost including capital, operating, and wood costs should be in the range from $2.58 to $4.00/million Btu (1978 basis).

Numerous other economic analyses of gasifier applications are in the literature, e.g., Eckert and Kasper (1978), Desrosiers (1979), and Crane and Williams.[13]

Gas transportable in pipelines.—The medium Btu gas produced by oxygen-blown gasifiers is comprised mainly of carbon monoxide and hydrogen (table 26-11) and if suitably cleaned of corrosive oils and tars can economically be piped short distances to power turbines or synthesize chemicals (Reed 1980). A pipeline-quality gas for transport over long distances can be produced by the methanation reaction described in the next subsection (see equation 26-14), or by the water shift reaction to make hydrogen (see equation 26-13).

Fuel cells.—Generaton of electricity by **fuel cells** that use producer gas from wood is an unproven process but potentially a viable one (Hodam 1978; Eggen and Kraatz 1976). Fuel cells use hydrogen and oxygen (from air) to convert stored chemical energy directly to electrical energy (figure 26-28).

$$2H_2 + O_2 \xrightarrow{\text{Fuel Cell}} 2H_2O + \text{heat} + \text{electrical power} \qquad (26\text{-}12)$$

The concept is not new. Fuel cells have provided electrical power for moon landings and, on a demonstration basis, for apartments, commercial establishments, and small industrial buildings. It is expected that electrical generation from coupling wood gasifiers with fuel cells will be significantly more efficient than using turbines or diesel engines (Hodam 1978).

[13]Crane, T.H., and R.O. Williams. 1979. Gasification of mill residues with a downdraft gasifier. Paper presented at 33rd Ann. Meet., For. Prod. Res. Soc., San Francisco, July 8-13, 1979.

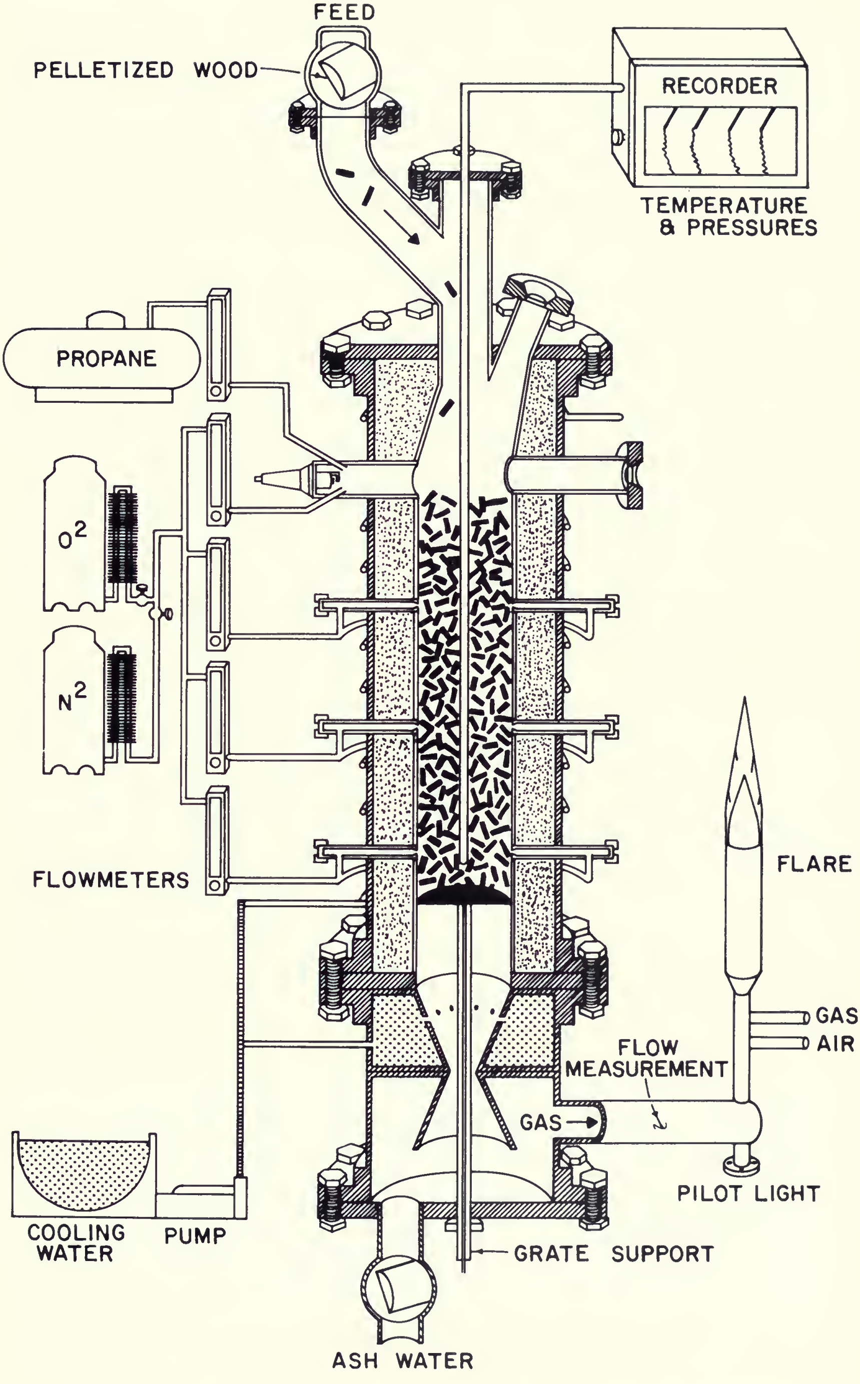

Figure 26-27.—Oxygen downdraft gasifier for production of clean synthesis gas comprised soley of hydrogen and carbon monoxide. Feed stock is pelletized wood. (Drawing after Reed 1980.)

Fuel cells can produce electricity at 38 to 40 percent efficiency, a rate about equal to the best combustion power plant. It is expected that by 1985 fuel cell efficiency may be 50 to 55 percent. Fuel cell emissions are well within environmental limits (Energy Research and Development Administration 1976.)

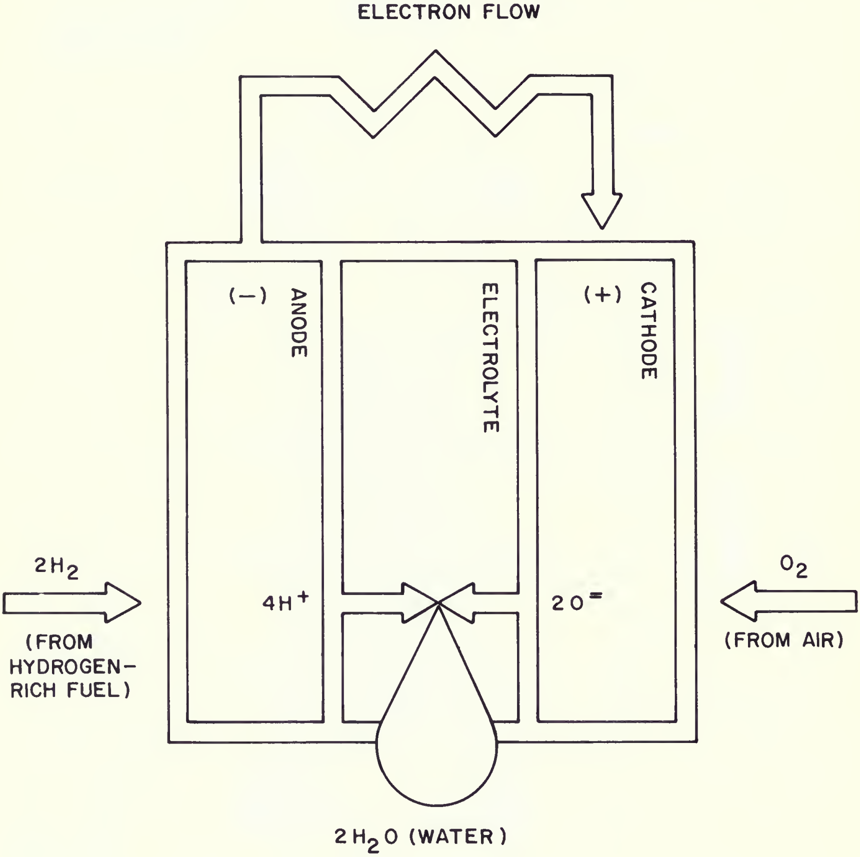

Figure 26-28.—The basic principles of fuel cell operation (Energy Research and Development Administration 1976). The fuel cell consists of an anode, cathode, and electrolyte, much as in a battery. Hydrogen rich fuel is fed down the anode side of the cell. Here the hydrogen leaves its electrons giving the anode a negative charge. Air enters the fuel cell on the cathode side. Here oxygen accepts electrons from the cell giving the cathode a positive charge. Electrical power is generated by the flow of electrons from the anode to the cathode. Hydrogen ions formed at the anode and oxygen ions formed at the cathode migrate through the electrolyte to combine and form water. Heat is also liberated in the process. The overall simplified process is shown in equation 26-12. (Drawing from Department of Energy.)

CHEMICALS AND FUELS PRODUCTION

Synthesis gas (hydrogen and carbon monoxide) can be used to produce several important chemicals and fuels (Wender 1980). Methane, hydrogen, ammonia, methanol, ethylene glycol, and gasoline can be made directly from synthesis gas. Additionally, a high octane gasoline can be produced from methanol in a one-step process.

Medium Btu gas from wood gasification should be well suited for use as synthesis gas because of its high hydrogen and carbon monoxide content. On the other hand, low Btu gas would not be so well suited since large amounts of nitrogen would have to be removed to convert it to synthesis gas. An exception might be in ammonia production.

Reed (1980), with a high-pressure downdraft design (fig. 26-27) using oxygen, propane, and nitrogen to gasify wood pellets, produced clean synthesis gas comprised solely of hydrogen and carbon monoxide.

Hydrogen, methane, ammonia, and methanol.—Hydrogen can be produced from synthesis gas by the **water shift reaction** (Wender 1980). Hydrogen already in the synthesis gas remains unchanged, but added water reacts at high temperature with carbon monoxide and a catalyst to yield hydrogen.

$$CO + H_2O \xrightarrow{\text{catalyst}} CO_2 + H_2$$
$$\Delta H = -9.84 \text{ kcal} \qquad (26\text{-}13)$$

Carbon dioxide formed can be removed from the gas stream to give pure hydrogen gas. The reaction is also used to obtain hydrogen to carbon monoxide ratios appropriate for certain syntheses. Methanol production requires $2H_2{:}1CO$, while methane requires $3H_2{:}1CO$.

Hydrogen holds much promise as an environmentally clean fuel; its combustion yields only water and heat energy. A promising new technology is the development of metal hydrides for the safe storage, shipping, and use of hydrogen as a fuel. Although its general use may be in the somewhat distant future, increased use of hydrogen as a transportation fuel may be expected, especially for mass transit in areas with air pollution problems.

Methane (CH_4) can be produced by the **methanation reaction** shown below:

$$3H_2 + CO \xrightarrow{\text{catalyst}} CH_4 + H_2O$$
$$\Delta H = -49.3 \text{ kcal} \qquad (26\text{-}14)$$

Since this reaction requires 3 moles of hydrogen to one mole of carbon monoxide, the water shift reaction can be used to adjust this ratio in the medium Btu gas and maximize the yield of methane. Methane is a suitable substitute for natural gas inasmuch as natural gas is composed primarily of methane (85 percent) with lesser amounts of other hydrocarbons and nitrogen. While the relatively low Btu values of low and medium Btu gas from wood gasification preclude storage or transport over any distance, conversion to methane provides a route for the production of a pipeline-quality substitute (950 Btu/sdcf) for natural gas (Bliss and Blake 1977).

Ammonia (NH_3) is manufactured from synthesis gas produced from natural gas by steam reforming, $CH_4 + H_2O \longrightarrow 3H_2 + CO$, the reverse of equation 26-14 (Wiseman 1972). The synthesis gas is enriched in hydrogen by the water shift reaction (equation 26-13). Carbon dioxide and small amounts of unconverted carbon monoxide have to be removed as they poison the ammonia synthesis catalyst. Most of the carbon dioxide is removed by scrubbing with a solution of potassium carbonate. After scrubbing, the gas still contains small amounts of carbon dioxide and carbon monoxide; final removal is accomplished by the methanation reaction (equation 26-14). Both carbon monoxide and carbon dioxide are converted into methane, which is left in the hydrogen gas as it dos not interfere with ammonia synthesis. In the final step (equation 26-15), ammonia synthesis is carried out by reacting the hydrogen gas with nitrogen gas at high temperature and pressure over an iron catalyst.

$$3H_2 + N_2 \xrightarrow{\text{catalyst}} 2NH_3 \qquad (26\text{-}15)$$
$$\Delta = \quad -26 \text{ kcal}$$

Ammonia is used to manufacture fertilizers, explosives, nitric acid, and synthetic fibers.

High yields of **methanol** (CH_3OH) are also obtainable from synthesis gas (Wender 1980). The water shift reaction alters the hydrogen to carbon monoxide ratio in the medium Btu gas to that required in equation 26-16.

$$2H_2 + CO \xrightarrow{\text{catalyst}} CH_3OH \qquad (26\text{-}16)$$
$$\Delta = \quad -26 \text{ kcal}$$

Methanol is a major industrial organic chemical, widely used as a solvent and in synthesis of other materials. Its largest use is for formaldehyde, important to the forest products industry as the basis for synthetic resins such as urea-formaldehyde and phenol-formaldehyde. The resins are used in the manufacture of plywood, particleboard, and plastics.

Coal to methanol conversion efficiency (59 percent) is higher than that for wood to methanol (38 percent),[14] and coal conversion facilities will be larger, making them even more efficient. Ammonia from wood appears more promising than methanol. Wood has a lower carbon to hydrogen ratio than coal which favors the wood feedstock. There is also a possibility that natural gas currently being flared in the Middle East will be converted to methanol or other synthesis gas derivatives and exported (Love and Overend 1978).

Liquid fuels for automobiles.—Methanol and ethanol (see section 26-7 for ethanol process) can both be used to fuel modified automobile engines. Such modification includes the use of fuel injection systems as well as some type of induction heating system to improve vaporization of the alcohols (Park et al. 1978ab). Methanol and ethanol can also be blended with gasoline to fuel unmodified automobile engines. Such mixtures are popularly termed gasahol.

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[14]Hokanson and Rowell (1977) projected a yield of 100 gallons of methanol per ovendry ton of wood, based on all process energy coming from the wood; the methanol would have a heat value amounting to 38 percent of projected total energy input.

Addition of methanol and ethanol increases the octane rating of gasoline, much in the way that tetraethyl lead and other additives do. Potential problems include loss of performance (especially in blends higher than 15 percent alcohol), possible phase separation of the alcohol from the gasoline caused by excessive moisture, and corrosion of fuel system parts. Although these problems will not be difficult to overcome, correction will cost the consumer.

Methanol can be used as a straight automotive fuel, not blended with gasoline. Although there is no mechanical problem in using straight methanol in the engines currently used in passenger cars, the engines and cars would require minor modifications. Because of the solvent properties of methanol, different gaskets would be required, and since the energy in a gallon of methanol is less than in a gallon of gasoline, larger fuel tanks would be required to obtain the same distance range (Flaim and Hill 1981). Walters (1980, 1981) concluded that automobiles fueled with methanol would have lower fuel cost per mile than if they burned gasoline and engine life would be significantly lengthened. Flaim and Hill (1981) concluded that biomass-derived methanol can be competitive with natural-gas-based methanol.

For economic analyses of ethanol production from southern hardwoods see section 28-5 (small scale) and 28-33 (large-scale). Readers needing additional information on alcohol fuels will find useful the bibliography produced by the Solar Energy Research Institute (1981).

A national gasahol plan for the United States has become a major controversy (Anderson 1978). Proponents contend that by blending 5 to 10 percent ethanol or methanol with gasoline, oil imports could be reduced as much as 20 percent. Opponents consider this uneconomic as long as gasoline reamins cheaper than the alcohols. In late 1981 the prices of fuel-grade methanol, ethanol, and gasoline at the refinery gate were about \$0.60, \$0.61, and \$1.00 per gallon, respectively.

In Brazil, a \$400 million program is now underway to produce ethanol from sugar cane and cassava to replace 20 percent of the country's gasoline requirements by the early 1980's (Hall 1978; Hammond 1977). But in Brazil, which imports over 80 percent of its oil, ethanol costs the consumer \$1 per gallon compared with \$1.50 per gallon for gasoline.

Park et al. (1978ab) indicate in a preliminary report to the Department of Energy that a national gasahol program appears premature. After 1990, the potential for such a program should be more promising. By then, however, methanol and ethanol might be economically converted to gasoline.

A new **process to convert methanol into gasoline** (fig. 26-29) has been developed by Mobil Research and Development Corporation (Meisel et al. 1976; Chang and Silvestri 1977). The **Mobil process** uses a newly discovered zeolite catalyst to quantitatively convert methanol to hydrocarbons and water.

$$XCH_3OH \xrightarrow{\text{catalyst}} \underset{99+\%}{(CH_2)_x} + XH_2O \qquad (26\text{-}17)$$

Most of the hydrocarbon molecules produced are in the gasoline boiling range (C_4 to C_{10}); total gasoline yield is about 80 percent of the hydrocarbon product. This synthetic gasoline has unleaded Research Octane Numbers (RON) of from

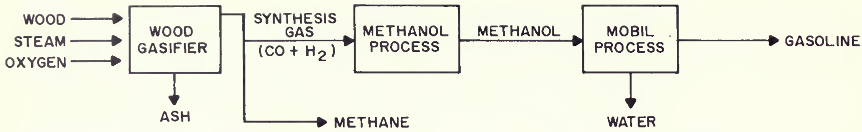

Figure 26-29.—Overall scheme for the production of gasoline from wood. Selling the methane produced in the gasification step instead of reconverting it into synthesis gas would lower the cost of methanol production. (Drawing after Meisel et al. 1976.)

90 to 100. Some of the remaining lower-boiling hydrocarbons can be converted into gasoline by an additional alkylation reaction. When this is done, total gasoline yield approaches 90 percent. The remaining 10 percent is valuable liquefied petroleum gas (LPG) (Meisel et al. 1976).

The primary source of methanol for the Mobil process is expected to be coal in the United States and perhaps natural gas in some other countries. However, in some areas it may be economically feasible to use wood as a source of methanol (fig. 26-29).

The **Fischer-Tropsch reaction** also makes hydrocarbons from synthesis gas (Wiseman 1972). The process was used by Germany during World War II to produce both liquid fuels and hydrocarbons for chemical syntheses. The reaction uses a cobalt catalyst at high temperatures to give a complex mixture of hydrocarbons. While gasoline can be made from the process, extensive facilities are needed to separate and upgrade the primary reaction products (Kuester 1980). Today the process is uneconomical in most countries, but is used in South Africa. Current active research and development, focused on mechanisms, catalysts, and reaction designs, may revive commercial use of the Fischer-Tropsch process to produce basic hydrocarbons (Haggin 1981).

Catalysis.—All of the reactions described above are carried out with **heterogeneous catalysis.** That is, reactants are gases and liquids which come in contact with a solid catalyst. The reactions occur on the surface and in crevices of the catalyst. Heterogeneous catalysis is advantageous because the catalyst can be separated readily from the product stream resulting from the reaction.

Heterogeneous catalysis has been the backbone of the petrochemical industry. Recently, **homogeneous catalysis** (both reactants and catalyst are in solution) by use of metal cluster compounds has been demonstrated for several reactions. Of interest to the utilization of synthesis gas is the reduction of carbon monoxide. **Ethylene glycol,** an important industrial chemical, can be produced in high yield from the reaction of synthesis gas with a rodium complex.

$$H_2 + CO \xrightarrow[\text{complex}]{\text{Rhodium}} HOCH_2CH_2OH\ (78\%) + \text{other alcohols}\ (22\%) \qquad (26\text{-}18)$$

Under certain conditions methanol can also be produced by this approach. While these homogeneously catalyzed reactions will undoubtedly be employed in the future, they are not yet commercially feasible (Anderson 1980; Wender 1980). Readers interested in further study should find useful Garten et al. (n.d.), an assessment and perspective of the application of catalytic technologies to the thermochemical conversion of biomass to gaseous and liquid fuels. For a more recent summary of the art of gasification, see: Overend, R.; 1982; Wood gasification—Review of recent Canadian experience; National Research Council of Canada, Ottowa, Paper no. 20094; p. 170-207.

26-5 PYROLYSIS

Pyrolysis is the thermal decomposition of organic matter in the absence of air, generally at lower temperatures than gasification. Primary products are solid or liquid fuels. The heat to initiate the process can be applied externally, or as is common in charcoal manufacture, by burning part of the wood in air (U.S. Department of Agriculture, Forest Service 1961).

The process can be visualized by recalling what happens when external heat is applied to a wood splint in a test tube. A clean combustible gas issues from the mouth of the tube, a brown corrosive liquid (pyrolysis oil) collects near the cool mouth, and charcoal remains in the lower portion.

Goldstein (1980a) found that oil yields can range from 1 to 40 percent and char yields from 10 to 40 percent. Overall thermal efficiency, about 45 percent, was less than that of gasification. Higher values are claimed for certain proprietary byproduct recovery systems (see sec. 28-10 and figs. 28-13 and 28-14). The yields of gaseous, liquid and solid products from wood pyrolysis are significantly affected by particle size and reactor pressure, heating rate, temperature, and residence time. Low temperatures favor liquids and char, low heating rates favor gas and char, and short gas residence time favors liquids (Goldstein 1980a). If heat is applied fast enough, little or no char results (Diebold 1980[15]).

In the past, one method of pyrolysis was referred to as destructive distillation. See Graham (1980) for a bibliography on biomas pyrolysis. Principal marketable products from a hardwood distillation industry 30 years ago were acetic acid, methanol, and charcoal (Beglinger 1948). Distillation was carried out in externally heated ovens and retorts. While methanol and acetic acid are now produced more cheaply by the petrochemical industry, wood charcoal remains an economically viable product.

Most charcoal produced in the United States today is processed into briquets for cooking. Some is used as an industrial fuel, some for metallurgical processing, and some to make activated carbon (Baker 1977; Walker 1980). In the near future, wood charcoal may be slurried with high-sulfur oil or mixed with high-sulfur coal before pulverization to make a fuel which would have lower sulfur dioxide emissions and thus possibly comply with air pollution regulations (Bliss and Blake 1977). Additionally, the charcoal-oil slurry could help reduce reliance on imported oil. Technically, both processes appear feasible, but adequacy of charcoal supplies for the proposed large, conventional oil- and gas-fired central stations has been questioned.

Wood is also suitable for making activated carbon. This can be done by steam activation of wood charcoal; yield is generally around 12-15 percent based on

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[15]Specialists' Workshop on Fast Pyrolysis of Biomass. Copper Mountain, CO; Oct. 20-22, 1980. Golden, CO: Solar Energy Research Institute.

the weight of the dry wood (Baker 1977). Currently, most activated carbon is made from coal or coconut hulls. About one-third of the market is for water and waste-water treatment (Walker 1980). Other uses are for air pollution control systems, catalyst supports, sugar decolorization, and auto evaporation control systems. Expanded demand is expected, however, if the Environmental Protection Agency (EPA) requires the use of activated carbon by all water treatment plants to remove suspected carcinogens such as chloroform and carbon tetrachloride.

In the United States, most wood charcoal is now produced either in a batch process using Missouri-type kilns or in a continuous process using a Herreshoff multiple-hearth furnace. Recently, other continuous processes have been developed which can be used to produce liquid and gaseous fuels as well as charcoal (Bliss and Blake 1977; Baker 1977).

CHARCOAL FORMATION IN KILNS

Ignition, coaling, and cooling, the three stages in the formation of charcoal from wood (Hallett 1971), are most readily described in relation to batch processes.

Ignition is endothermic (requires heat) and requires considerable air (U.S. Department of Agriculture, Forest Service 1961). The wood is first ignited with kindling and kerosene and allowed to burn. Temperatures in the kiln rise rapidly to about 1,000°F and then drop when most of the starter fuel has been consumed. Coaling begins around 540°F, and at that temperature the process becomes exothermic (gives off heat). When the coaling stage is reached, air intake is restricted to control kiln temperature and to ensure that the wood will form charcoal and not burn to ash. For the production of good quality charcoal, kiln temperatures of 850° to 950°F are maintained during coaling.

After coaling, the kiln is completely sealed to exclude all air and allowed to cool. When temperatures are 150°F or less, it is generally safe to open the kiln.

A complete cycle, from ignition through cooling, may require 6 to 7 days. Typical charcoal produced from wood will have a higher heating value of about 12,000 Btu/lb. Proximate analysis will be about 20 to 25 percent volatile matter and 75 to 80 pecent fixed carbon on a moisture free and ash free basis. Ash content is generally about four times that of wood (Peter 1957; Baker 1977; U.S. Department of Agriculture, Forest Service 1961).

The transformation of wood into charcoal has been studied by simulating commercial charring conditions in the laboratory (Slocum et al. 1978). Most work has been done on oak and hickory. Study of mass loss, shrinkage, and physical properties of charcoal produced under various coaling conditions will lead to a better understanding of this very complex and incompletely understood process (McGinnes et al. 1971; Anonymous 1975; Slocum et al. 1978). Analytical techniques that have been found especially useful for these studies include the use of scanning electron microscopy to follow shrinkage and small angle X-ray analysis to evaluate micropore formation in the charcoal (von Bastian et al. 1972; Blankenhorn et al. 1972; Beall et al. 1974; McGinnes et al. 1974; McGinnes et al. 1976).

Figure 26-30.—One-half-cord sheet metal beehive kiln. Fully portable, these kilns were developed in the 1930's and were still in wide use through the 1960's. The kiln shown here is in the coaling phase. (Photo from Page and Wyman 1969.)

In the past, small-scale charcoal production was accomplished with a variety of kilns. As any relatively air-tight structure with properly placed smoke and draft vents can be used to produce charcoal, small kilns with capacities of ½ cord to 10 cords or more were popular through the late 1950's (fig. 26-30). Such kilns varied considerably in construction and size; building materials commonly were cinder blocks, bricks, stone, metal, and reinforced concrete. Yields of charcoal varied greatly in the kilns, even under optimal operating conditions. In cinder block kilns typical yields for seasoned hardwoods averaged around 900 lb of charcoal per cord and slightly less for unseasoned hardwoods (Witherow 1956; Witherow and Smith 1957; Peter 1957; Page and Wyman 1969; U.S. Department of Agriculture, Forest Service 1961).

Today, over half of the Nation's wood charcoal is produced in Missouri-type kilns (Baker 1977), from roundwood or sawmill slabs (fig. 26-31). Typically the kilns are made of poured concrete and have an average capacity of 50 cords. Some, however, hold up to 100 cords. White oak and hickory are the two major species of wood used.

HERRESHOFF MULTIPLE-HEARTH FURNACE

The Herreshoff multiple-hearth furnace uses hogged wood or bark to produce charcoal in a continuous process (fig. 26-32). Production rates range from 1 to 4 tons per hour. As the units operate continuously, they must be fed a steady

Figure 26-31.—Missouri-type batch kiln. (Photo courtesy of Bob Massengale, Missouri Department of Conservation.)

supply of wood. The smallest of these furnaces requires about 100 tons of wood per day (dry basis); with wood that has moisture content of 40 percent (wet basis), production of charcoal is about 1 ton per hour.

The Herreshoff furnace consists of several hearths stacked one on top of the other and enclosed in a cylindrical, refractory-lined steel shell (Nichols Engineering and Research Corporation 1975; Bliss and Blake 1977). Passsing up through the center of the furnace is a shaft which carries arms with rabble teeth. As the shaft turns, the teeth constantly plow through and turn the fuel over while moving it in a spiral path across the hearth floors toward drop holes connecting with the next lower hearth. The drop holes alternate on each hearth floor between the inner periphery (around the shaft) and the outer periphery of the hearth. The rabble teeth are alternately angled so that the material moves in the direction of the next set of drop holes. In this way material fed at the top of the furnace is spread over and across each hearth floor in a radial flow that alternates inwardly and outwardly until the charcoal is finally discharged from the bottom of the furnace. Material is dried, heated, and carbonized as it passes downward through the furnace while hot combustible gas produced passes upward in a current counter to the flow of the material (fig. 26-33).

Heat for startup is provided by gas- or oil-fired burners mounted on the sides of the hearth. When the proper temperature has been attained, the auxiliary fuel is turned off. To sustain pyrolysis, sufficient combustion air is allowed into the furnace to burn some of the volatile gases produced. Air entry is regulated to maintain furnace temperatures at 900 to 1200°F. The evolving combustible gases are more than that needed for drying and carbonizing the wood and can also be burned in a boiler after they exit the furnace. With a heating value of about 200 Btu per sdcf plus the sensible heat of the exhaust temperature, the pyrolysis gases from the production of 2 tons of charcoal per hour can generate

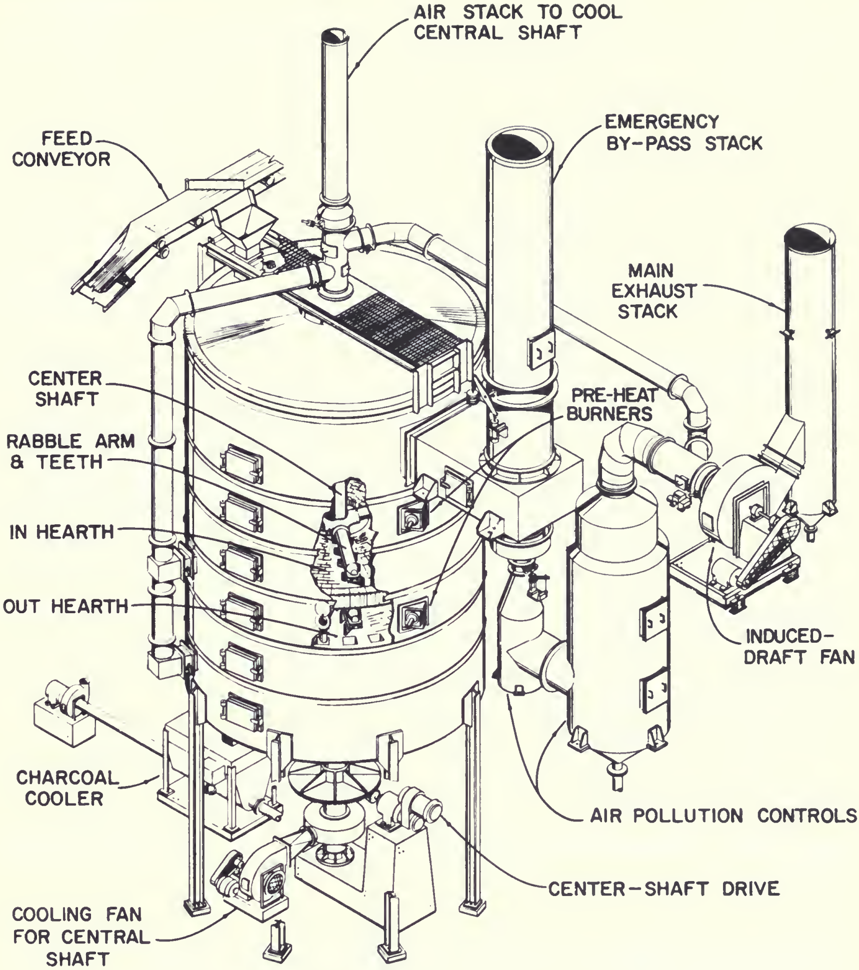

Figure 26-32.—Nichols-Herreshoff multiple hearth furnace for the production of wood charcoal. (Drawing from Nichols Engineering and Research Corporation.)

about 50,000 lb per hour of high pressure steam (Bliss and Blake 1977). Yield of charcoal will vary with moisture content of the feed; about 8 tons of wet wood (50 percent moisture content, wet basis) are required to produce 1 ton of charcoal.

For an economic analysis of charcoal production with a Herreshoff furnace see section 28-20.

TECH-AIR SYSTEM

Knight et al.[16] described a steady-flow pyrolysis system that produces a pyrolytic oil, charcoal, and off gases. The oil, which has a heating value of

[16]J. A. Knight and M. D. Bowen, Pyrolysis—a method for conversion of forestry wastes to useful fuels. 13 p. Paper presented at the Southeast. Tech. Div. of Am. Pulpwood Assoc. fall meeting. (Atlanta, Ga., Nov. 5-6, 1975).

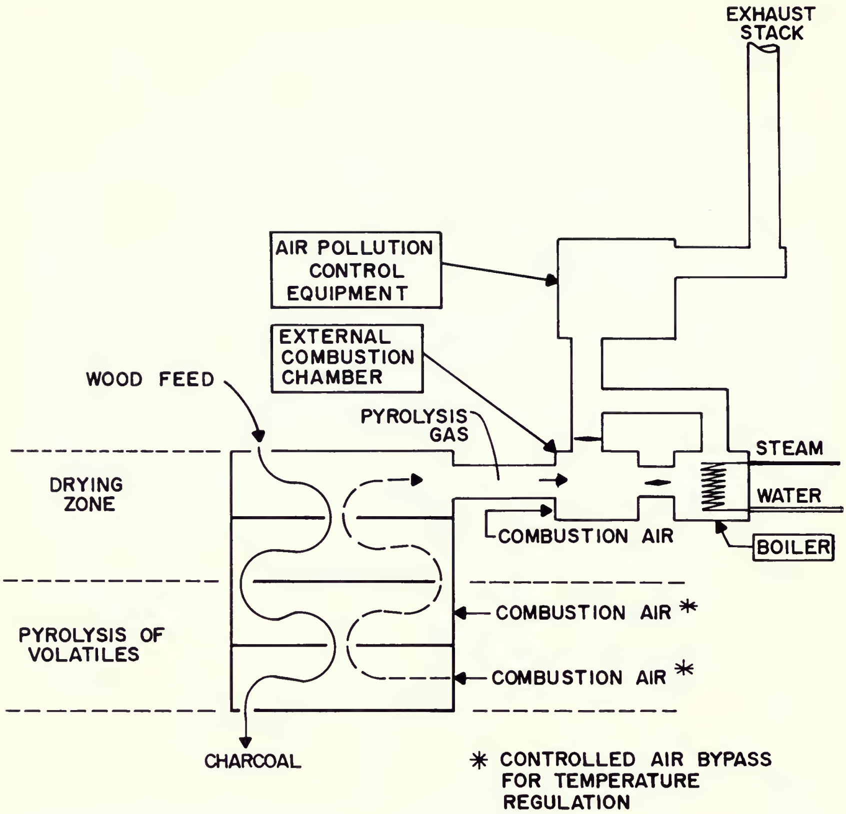

Figure 26-33.—Feed and gas flow diagram for the Nichols-Herreshoff multiple hearth furnace.

10,000 to 13,000 Btu/lb, is obtained by passing the pyrolysis vapors through a condenser. Remaining non-condensable gases which contain about 200 Btu/sdcf, are used to pre-dry incoming wood fuel (fig. 26-34) to about 4 percent moisture content. The non-condensable gases are sufficient to pre-dry fuel of up to 50 percent moisture content (wet basis). About 35 percent of the energy content of the wood fuel is in the charcoal and about 35 percent in the pyrolytic oil. On a weight basis, charcoal yield is 23 percent while pyrolytic oil yield is 25 percent. Charcoal heating values range from 11,000 to 13,500 Btu/lb. The process has been operated on a scale of 50 dry tons of fuel per day, and processing up to 200 tons per day appears feasible (Bliss and Blake 1977).

See section 28-10 for an economic analysis of a portable pyrolyzer.

OCCIDENTAL FLASH PYROLYSIS

Preston (1975) described a pyrolysis system that internally recycles the charcoal produced in order to supply heat energy for the pyrolysis process. The primary products are pyrolytic oil, off gases, and water. The process was developed primarily for pyrolyzing municipal refuse while recovering valuable

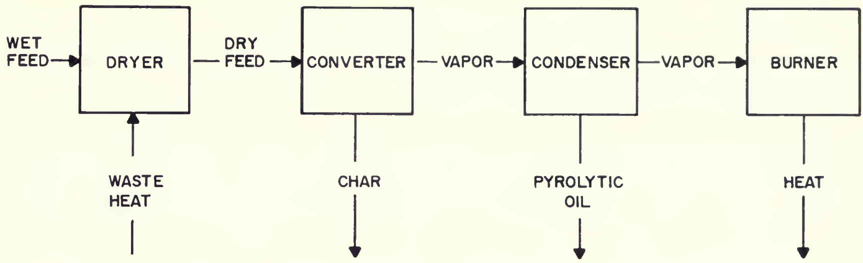

Figure 26-34.—Block flow diagram for the Tech-Air pyrolysis system. (Drawing after Knight and Bowen text footnote[16].)

metals and glass (fig. 26-35). It is presented here because the process will work as well, maybe better, with wood feed. Of course, the glass and metal recovery systems will not be needed.

This pyrolysis is aimed at producing a maximum yield of combustible liquid or oil. Pyrolysis is carried out on finely shredded organic material which is carried into the reactor by recycled off-gases. Pyrolysis takes place at 950°F at about 1 atmosphere pressure and with short residence time. The charcoal is separated from the product stream by cyclone separators and then combusted in the charcoal burner. The remaining pyrolytic vapors are rapidly quenched to prevent further cracking of the oils. At this point, the products are separated into pyrolytic oil, gas, and water. The pyrolytic oil (10,600 Btu/lb) produced is intended to be sold as a substitute for No. 6 residual (Bunker C) fuel oil. The pyrolysis gases have a heating value of about 380 Btu/sdcf, are recycled for use as a transport medium, and eventually are burned to provide heat to the rotary-kiln dryer.

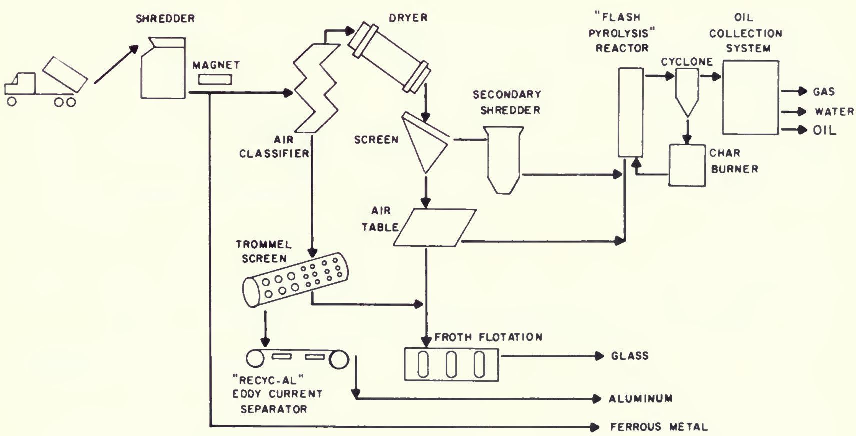

Figure 26-35.—Simplified flow diagram for the Occidental resource recovery system. (Drawing after Preston 1975.)

26-6 LIQUEFACTION

U.S. BUREAU OF MINES PROCESS

Wood can be converted to an oil by reaction with synthesis gas and an alkaline catalyst under high temperature and pressure (Lindemuth 1978) (fig. 26-36). The synthesis gas can also be produced from wood by gasification. Preparation for liquifaction includes drying and grinding the wood before blending with recycled oil to produce a wood oil slurry of about 30 percent solids. The slurry, synthesis gas, and the alkaline catalyst (sodium carbonate solution) are then reacted at 600° to 700°F and 2,000 to 4,000 psi for various lengths of time. The oil is separated from unreacted wood and ash and part is recycled to blend with incoming wood. The waste stream contains catalyst and unreacted wood.

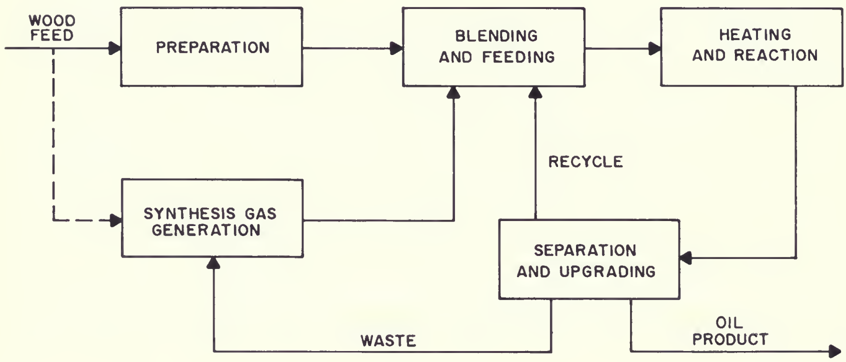

Figure 26-36.—Wood liquefaction scheme. (Drawing after Lindemuth 1978.)

In the original process, which was developed by the U.S. Bureau of Mines, carbon monoxide plus steam and/or hydrogen was used as a reducing mixture in the presence of alkaline catalysts (Na_2CO_3 or HCO_2Na) at temperatures up to 750°F and pressures as high as 5,000 psi (Appel et al. 1975). Under these conditions it was found that cellulosic materials such as urban refuse, sawdust, bovine manure, and sewage sludge could be converted to heavy oils. However, it was noted that materials containing larger quantities of lignin or other non-carbohydrates may require more severe reaction conditions. Bark, which has a high phenolic content that would consume considerable quantities of the alkaline catalyst, may not be suitable for this process as originally designed.

A unit in Albany, Oregon is testing the feasibility of using the U.S. Bureau of Mines process to liquefy wood and other biomass on a large scale. Incoming wood chips, which normally have a moisture content of about 50 percent (wet basis), are dried to about 1 to 5 percent moisture content in a gas-fired rotary dryer. The dried wood is then hammermilled to about 50 mesh before being slurried with recycled product oil. A catalyst solution of sodium carbonate is added and carbon monoxide gas is sparged through the mixture. Results to date have indicated reaction times of 25 to 30 minutes should be adequate for a commercial plant. Product yield ranges from 40 to 50 percent of wet wood weight. On a volume basis, the heating value of the wood-produced oil is about four times higher than that of wood. The viscosity of the oil is high and has presented some problems in mobility (table 26-13). Research at the Albany plant is aimed at solving problems of viscosity buildup and purification of the oil (Lindemuth 1978; Ergun 1979; Ergun et al. 1980).

TABLE 26-13.—*Average properties of oil produced from wood* (Lindemuth 1978)

Property	Reactor residence time	
	20 min	60 min
Viscosity @ 100. L.Cp	10,000-20,000	3,000-12,000
Heating value Btu/lb	15,700	16,000
Elemental analysis		
% C	86.0	88.3
% H	6.4	6.7
% O	6.4	4.0
% N	0.4	0.1

MILLER AND FELLOWS PROCESS

Miller and Fellows (1981) found that complete liquefaction of biomass was accomplished by heating it to 350°C for less than 1 hour in the presence of phenol, a lewis acid (e.g., zinc chloride), a mild acid (e.g., sodium dihydrogen phosphate), or a mild base (e.g., sodium carbonate), with or without hydrogen gas, and under sufficient pressure to maintain the liquid phase. When cellulose was used, yields of non-phenolic products ranged up to 50 percent of the dry cellulose weight. When wood was used, the reaction was also a net producer of phenols. Non-phenolic products were mainly furanoid or aromatic; xanthene was a major fraction. The phenolic fractions would be recycled, with some recovery of phenols. The non-phenolic fraction should be usable as a chemical feed stock, or, if produced on a relatively small scale, it could be blended with gasoline or diesel fuel after fractionation provided, in the case of diesel, it was a low percentage blend. If produced in large amounts, the non-phenolic fractions and surplus phenols should be able to be hydrogenated to make gasoline and diesel fuels.

26-7 HYDROLYSIS AND FERMENTATION

HYDROLYSIS PRODUCTS

Cellulose and hemicelluloses, the principal polymeric carbohydrates (polysaccharides) of wood, can be converted into simple hexose (six carbon) and pentose (five carbon) sugars by hydrolysis. Cellulose, which is a linear polymer of $\beta(1\rightarrow4)$ linked anhydroglucose units, yields the hexose sugar glucose.

Hemicelluloses are composed of several different polysaccharides (tables 6-3 and 6-4). In the pine-site hardwoods the major hemicellulose is an acetylglucuronoxylan. Hydrolysis of the pine-site hardwood hemicelluloses predominantly yields the pentose sugar xylose. Lesser amount of other constituents will also be released from the hemicelluloses, as follows: arabinose (a pentose sugar); glucose, galactose, and mannose (hexose sugars); and glucuronic acid.

Centrifugation or filtration can also recover an insoluble lignin residue from wood hydrolysis products (Hoyt and Goheen 1971). Called hydrolysis lignin, this material is condensed and contains some unhydrolyzed cellulose residues. Hydrolysis lignin should not be confused with kraft lignin or sulfite lignin, residues from pulping processes (Sarkanen and Ludwig 1971).

USES FOR HYDROLYSIS PRODUCTS

The three major products of pine-site hardwood hydrolysis, glucose, xylose, and lignin, potentially can be used in a number of ways. At present, using them to produce ethanol, furfural, and phenol is of much interest (fig. 26-37).

Ethanol is used as a solvent to manufacture pharmaceuticals and perfume and as an intermediate in organic syntheses. It could be used as a clean burning fuel and can be mixed with gasoline to make gasohol. In the United States, most ethanol is produced by the petrochemical industry from ethylene.

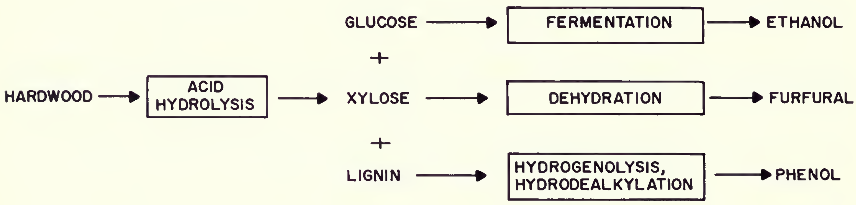

Figure 26-37.—Production of ethanol, furfural, and phenol from pine-site hardwoods by hydrolysis.

Fermentation to produce ethanol is an old, well established process. In one approach that might be taken with a pine-site hardwood hydrolysis mixture, glucose and the other hexose sugars can be selectively fermented to ethanol by *saccharomyces* yeast; xylose and arabinose are left unchanged, and the xylose can be recovered by crystallization (Herrick and Hergert 1977).

In the Madison process for obtaining ethanol from wood (fig. 26-38), yield of ethanol ranges from a low of 35 gallons per ton of dry hardwood to a high of 60 gallons per ton of softwood; hardwoods have fewer fermentable sugars than softwoods (Baker 1980).

For economic analyses of ethanol and furfural production from southern hardwoods, see section 28-5 (small-scale), and 28-33 (large-scale).

The dehydration of pentose sugars such as xylose to **furfural** is a well known acid-catalyzed reaction that is favored by high temperature and pressure. Current production of furfural in the United States is from pentose-rich residues such as

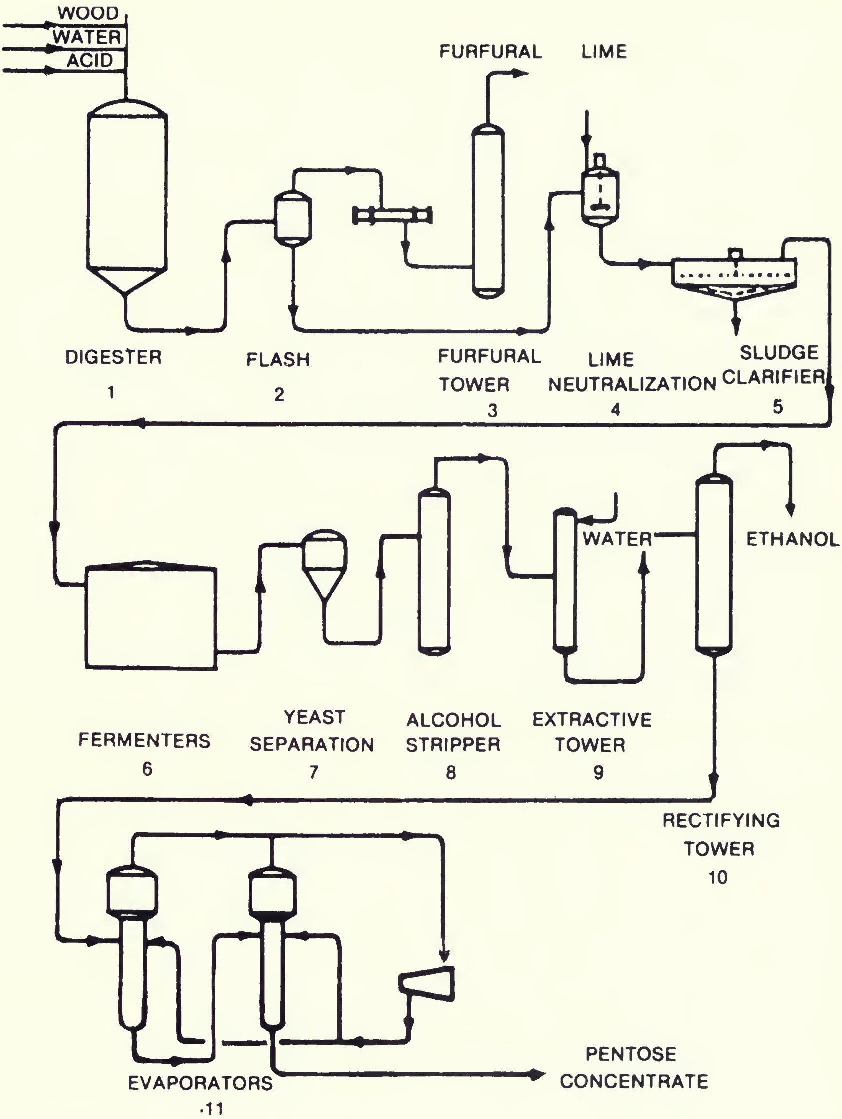

Figure 26-38.—Ethanol from wood by the Madison process. (1) Cellulose converted to sugar by acid hydrolysis under high pressure and temperature. (2) Sugar solution flashed. (3) Furfural in flash condensate recovered. (4) Sugar solution neutralized. (5) Calcium sulfate separated. (6) Sugars (6 carbon type) fermented to ethanol and carbon dioxide. (7) Yeast separated for re-use. (8) Ethanol stripped from dilute liquor. (9) Contaminants extracted from ethanol. (10) Ethanol concentrated to 190 proof. (11) Sugars (5 carbon type) concentrated. (Drawing after Baker 1980.)

corn cobs, grain hulls, sugar cane bagasse, and oak sawdust. Furfural is used as a solvent and as an intermediate for the production of furan derivatives.

The largest use of **phenol** is in producing plywood adhesives. Thus, the phenol market fluctuates with demand for new housing. Phenol is also used in molded products and adhesives that are used in automobile and appliance manufacture.

Today, nearly all phenol is made from cummene, a petrochemical, but various hydrogenolysis techniques also can produce phenols from lignin. Reportedly, yields in the neighborhood of 40 percent of monomeric phenol derivatives have been obtained in pilot-plant experiments (National Research Council 1976). However, hydrodealkylation of the mixture of phenol derivatives to a high yield of phenol is not a proven process.

Other potential uses for the hydrolysis products of pine site hardwoods include the production of *Torula* yeast, a protein supplement (Herrick and Hergert 1977). Unlike fermentation to ethanol, which utilizes only the hexose sugars, both hexose and pentose sugars, certain sugar acids, and carbohydrate fragments can be used to grow the yeast. A reagent such as Raney Nickel or a hydrogenation catalyst can reduce xylose and glucose to xylitol and sorbitol, their corresponding sugar alcohols. Hydrolysis lignin can be used as a soil conditioner, filler for resins and rubber, depressant in ore floatation, decay-retardant in fabrics, a binding agent for particle and hardboard, and a grinding aid for Portland cement (Hoyt and Goheen 1971). In the Soviet Union, much of the hydrolysis lignin is burned as fuel. However, the high moisture content must be removed first. In one process, the lignin is dried to 12-18 percent moisture content with hot flue gases and then pressed into briquettes. It has also been suggested that hydrolysis lignin be used as a source of activated carbon (National Research Council 1976).

WOOD HYDROLYSIS PROCESSES

Hemicelluloses are readily hydrolyzable under mild acidic conditions; cellulose, on the other hand, is much more difficult to hydrolyze because of its crystalline organization and stable structure. Efficient production of sugars from whole-wood hydrolysis must take into account this difference or a competing reaction in which sugars are destroyed can occur (Harris 1975).

There are a number of potential wood hydrolysis processes (Oshima 1965, Wenzl 1970, Titchener 1976; Bliss and Blake 1977, Karlivan 1980). The processes use hydrochloric acid, sulfuric acid, or enzymes (table 26-14). The acid-catalyzed processes can be further divided into those using dilute or concentrated acids. Hyrolysis with dilute acids is carried out in a single stage at elevated temperature and pressure. Concentrated-acid processes are generally conducted in two stages, a prehydrolysis and a main hydrolysis stage that is kept near ambient temperature.

Dilute acid processes are typified by the **Scholler-Tornesh process** which uses 0.5 percent sulfuric acid to complete hydrolysis in one stage at elevated temperature and pressure. Dilute acid is percolated through wood chips or sawdust followed by a charge of steam. The short hydrolysis time does not completely hydrolyze the cellulose, so the acid-steam percolation is repeated up to 12 times. The dilute sulfuric acid in the hydrolyzate is neutralized by calcium carbonate to form calcium sulfate ($CaSO_4$) which is removed by filtration. The

TABLE 26-14.—*Some processes for wood hydrolysis* (Bliss and Blake 1977)

Name	Main hydrolysis conditions			Yield of Fermentable Sugar (kg/t wood)	Sugar Concn (wt %)	Recovery method for medium	Status
	Medium	Temp. (°C)	Time (h)				
Scholler	½-1% H_2SO_4	180	12	352	4	As $CaSO_4$	Several plants operated in Europe before and during World War II
Madison	½% H_2SO_4	180	3	>352	5.5	As $CaSO_4$	Demonstration plant built 1946 and 1952
Hakkaido	80% $H_2S)_4$	40	>1	280-290	20	Ion exchange to recover 25-35% acid	100 T/D plant at Asahikawa in 1963
Rheinau-Udic	41% HCl	20	About 3	—	10	Vacuum distillation	Semi-commercial plant (2000 ODT/yr operated 1959)
Noguchi-Chisso	HCl gas	50	>1	—	30	Vaporization using hot air	1 t/d plant operated (1956)
U.S. Army Natick Development Center	Enzymes	50	48	90-220	1.6-4.6	—	Experimental bench-scale

yield of sugar on a weight basis is around 40-50 percent for softwoods (Titchener 1976; Bliss and Blake 1977).

The **Madison process** is a continuous-flow variation of the Scholler-Tornesh process. A continuous flow of reagent removes the hydrolyzate to a cool zone to reduce sugar degradation. Total saccharification time is about one-fourth of that required in the Scholler-Tornesh process, thus lowering the production cost. Hardwoods yield about 35 percent fermentable sugars and 20 percent pentoses on a weight basis (Titchener 1976; Herrick and Hergert 1977).

In the **NYU process** (fig. 26-39) sawdust is fed into the barrel of a twin-screw plastics extruder (fig. 18-280a). In the barrel the sawdust is heated to about 230°C and water is removed. As the water is removed, the material becomes very dense, forming a plug that allows pressures of about 500 psi to be generated in the forward sections of the barrel. As the screws convey the material toward the front of the barrel, their shearing action breaks up the sawdust particles making the cellulose more accessible to the chemical reaction that will convert it to glucose. Just before the material is expelled from the extruder barrel, a weak solution (1.0 to 1.5 percent) of sulfuric acid is injected into it. Contact times in this continuous hydrolysis method are short, e.g., 5 to 25 seconds. Output of the extruder is a mud-like material containing glucose, unconverted cellulose, decomposition products from the hemicellulose fraction, and degraded lignin. After separation, a liquor containing 8 to 10 percent glucose is available for fermentation to ethanol. Pilot-plant work has achieved 50 to 55 percent conversion of cellulose to glucose, but the process developers feel that 80 to 90 percent conversion will be possible ultimately (Chemical Engineering 1981).

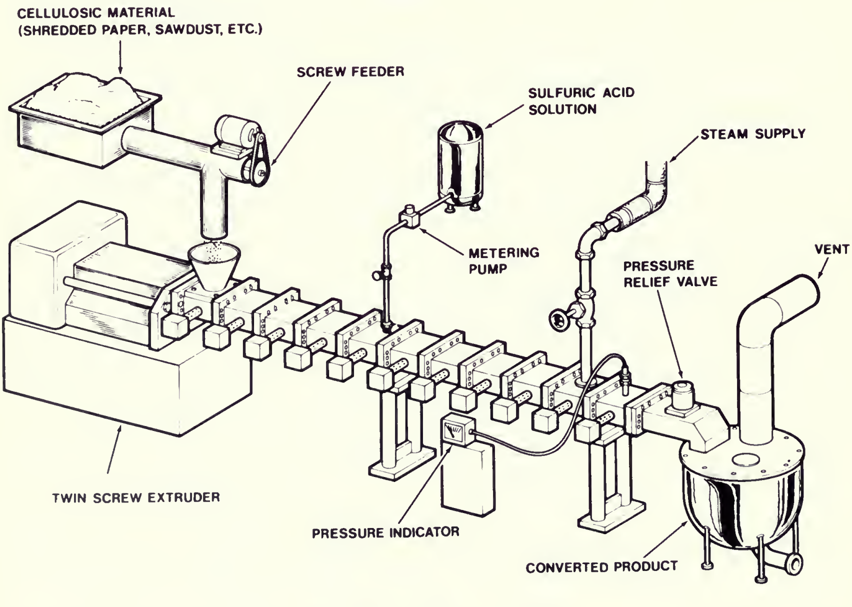

Figure 26-39.—NYU process for converting cellulose in lignocellulosic material to glucose. (Drawing after Chemical Engineering 1981.)

A typical example of a concentrated-acid process is the **Rheinau-Bergius process** which was used by Germany in World War II to produce yeast from hydrolyzed sugars. In stage one, fuming hydrochloric acid (up to 41 percent) is used to degrade cellulose mostly to lower oligomers at ambient temperatures. In the second stage, the acid is diluted with water and heated to yield monomeric sugars. In the **Rheinau-Udic process,** a modification of the earlier procedure, prehydrolysis is carried out with a 32 percent acid solution and the main hydrolysis uses 41 percent hydrochloric acid. The hydrochloric acid is recovered by vacuum distillation. The hydrolyzate is post-hydrolyzed, filtered, decolorized, and passed through an ion-exchange column, before cyrstallization of the glucose. Reportedly, 22 kg of crystalline glucose can be obtained per 100 kg of wood (Wenzl 1970). See section 28-33 and figures 28-45 and 28-46 for an economic analysis of a concentrated-acid process.

The use of hydrogen chloride gas, rather than concentrated hydrochloric acid, is the basis of several proposed processes (Titchener 1976). In the Japanese **Noguchi-Chisso process,** wood is first prehydrolyzed to remove hemicelluloses. The residue is heated with a 5 percent hydrochloric acid solution and cooled. Gaseous hydrogen chloride is then administered; the temperature is kept below 10°C. Next, the temperature is raised to 40°C for hydrolysis to lower oligomers. The hydrogen chloride is recovered by blowing hot air through the hydrolyzate. Post-hydrolysis at 100°C with 3 percent hydrochloric acid yields glucose. In this step, acid is removed by vacuum distillation. The advantages of this system are the simplicity of acid recovery, fewer corrosion problems, and more highly concentrated sugar solutions.

In the **Hokkaido process,** first prehydrolysis is carried out with steam or dilute sulfuric acid at temperatures up to 185°C. A furfural yield of 65 to 75 kg per ton of dry wood is obtained from dehydration of the pentose in the reactor. The prehydrolysis residue is then dried, powdered, and treated with 80 percent sulfuric acid for about 30 seconds. The reaction mixture is immediately washed with water and filtered. Acid is recovered by use of ion-exchange resins. The hydrolyzate, which still contains dilute sulfuric acid, is post-hydrolyzed by heating at 100°C. Yield of crystalline glucose is about 280-290 kg/metric ton of dry wood (Bliss and Blake 1977).

A recently developed technique that employs anhydrous hydrogen fluoride splits cellulose rapidly at 0°C with high yields (Chemical and Engineering News 1982).

ENZYMATIC HYDROLYSIS IN NATURE

The ligno-cellulosic matrix which comprises wood presents a formidable barrier to most enzyme systems. For example, anaerobic bacterial production of methane from slurried wood and bark (visualize marsh gas formation) is slow, and yields are low. Wood degradation by white and brown rotting fungi is also slow and selective.

Even termites are selective in their eating habits (table 11-6), do not eat all the wood and bark, and metabolize only part of what they do eat. The termite system of digestion is remarkable, however. Evidence suggests that the lower termites comminute wood, transport it to their hind gut where 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. Dwell time within the termite is about 24 hours. One could conceive of a wood utilization system in which termites were an intermediate in a protein production system.

Ruminants such as cattle and sheep require several hours to 2 days for complete passage of food through the digestive system. The rate of passage depends on the amount of fiber in the food and on particle size. Bulky feeds are retained in the rumen until rumination occurs—which often takes place at night. About 18 hours is thought to be an average for completion of microbial digestion in ruminants. Rumen digestion takes place at a pH of about 6.8.

The use of wood for ruminants is not yet fully practical, although foliage, wood, and bark of some species have some digestibility—hardwoods more than softwoods (table 26-14a).

Millett et al. (1970) found that vibratory ball milling for 20 to 120 minutes increased *in vitro* rumen digestibility of some woods. Aspen and sweetgum showed maximum dry-matter digestibilities of about 75 percent, red oak 57 percent, and hickory 40 percent. Softwoods were less responsive to vibratory ball milling than were the hardwoods. It is likely that *in vivo* digestibility would be considerably less than these *in vitro* data suggest because such finely ground material would pass quickly through the rumen.

To chemically obtain, by treatment with alkali, acid, ammonia, or sulfur dioxide, a product having the 60-percent *in vitro* digestibility of good-quality hay, the lignin content of hardwoods must be reduced by 25 to 35 percent (Hajny 1981).

TABLE 26-14a.—In vitro *digestibility of some woods and barks* (Millett et al. 1970)

Species	Digestibility	
	Wood	Bark
	Percent	
	HARDWOODS	
Trembling aspen	33	30
Soft maple	20	—
Black ash	17	45
Sugar maple	7	14
White birch	8	—
Yellow birch	6	16
American elm	8	27
Shagbark hickory	5	—
Eastern cottonwood	4	—
White oak	4	—
Red oak	3	—

TABLE 26-14a.—In vitro *digestibility of some woods and barks* (Millett et al. 1970) —Continued

Species	Digestibility	
	Wood	Bark
	Percent	
	SOFTWOODS	
Douglas-fir	5	—
Western hemlock	0	—
Western larch	3	7
Lodgepole pine	0	—
Ponderosa pine	4	—
Slash pine	0	—
Redwood	3	—
Sitka spruce	1	—
White spruce	0	—

W. Jelks developed a process in which small amounts of nitric acid are introduced, with a catalyst, to oak sawdust which is then steamed at 6 to 8 atmospheres pressure to produce a cattle food with about 50 percent digestibility. A sawmiller in Frohna, Missouri, who operates a feed lot with 600 to 700 cattle feeds a ration in which half the weight is this cooked oak sawdust. He believes that his total feed costs are lessened because his requirement for corn and soybean feed is significantly reduced.[17] At $3.00/bushel, corn costs about $125 per ovendry ton.

It is also possible to increase disgestibility of some woods by a process involving neither ball milling nor chemical addition. Bender and Heaney (1973) found that briefly treating chipped wood with steam at 300 psi, and then terminating the reaction by very rapidly discharging the chips to atmospheric pressure increased digestibility of some wood—particularly aspen. In 1981, Stake Technology Ltd. was operating at least two cattle feeding operations in the United States, one using steam treated aspen fiber, the other sugar bagasse, for a significant proportion of the cattle's ration. Southern hardwoods such as oaks are less well suited to the process than aspen. Readers needing a further review of wood and wood-based residues in animal feeds will find Baker et al. (1975) useful.

CONTROLLED ENZYMATIC HYDROLYSIS

Interest in controlled enzymatic hydrolysis of cellulose to glucose has been spurred by the United States Army Natick Development Center's development of strains of *Trichoderma viride* fungi and its mutants now designated as *Trichoderma reesei*. These fungi produce cellulase enzymes that have been tested on several cellulosic substrates (Mandels 1979; Mandels et al. 1978; Bliss and Blake 1977).

The **enzymatic hydrolysis process** requires two stages. In the first, the enzyme is produced by growing the fungus in a culture medium of cellulose

[17]Personal communication in November 1981 with B. Lorenz, Frohna, Missouri.

pulp. After a period of growth, the broth is filtered to give the enzyme-containing solution used in hydrolysis. Hydrolysis generally is carried out at pH 4.8 and 50°C on ball-milled cellulosic substrates. Pulverizaton by ball milling is necessary to break down cellulose crystallinity. Yields depend on the substrate and range from 16-77 percent. Pure cellulose pulp and shredded paper give respectable yields of up to 77 percent. Wood waste, on the other hand, yielded only 16 percent reducing sugars. On pulped wood chips the yield was 57 percent (Mandels et al. 1978; Bliss and Blake 1977).

While these enzymes may lead to a non-corrosive process (as opposed to acid hydrolysis), they require pretreatment of the wood cellulose because they are greatly inhibited by the cellulose crystallinity and the ligno-cellulosic complex. The best possibility for overcoming the low reactivity of wood is to develop a cost-effective pretreatment that makes lignocellulosics react to enzymatic hydrolysis (Millett et al. 1975). One promising avenue is steam explosion of chips to produce a fiberous material favorable to the enzymes.

The steam explosion process for wood chips yields fiber that is more reactive to enzymes than normal wood yet does not require the mechanical energy of ball milling or twin-screw extrusion, nor addition of chemical to dissolve lignin. Use of such fiber with selected or genetically engineered enzymes may lead to economic enzymatic hydrolysis. Goldstein (1980b) found that in the 1970's use of hypercellulolytic mutants of *Trichoderma* fungus have resulted in a 30-fold increase in enzyme concentration and a 24-fold increase in enzyme productivity.

Iotech Corp., Ottawa, Canada, is a pioneer in developing this process whereby hardwood chips (preferably *Populus* sp.) are treated with saturated steam and a catalyst at 240-300°C and 500-1,000 psi in a vessel (gun reactor) for 5 to 300 seconds and then exploded to atmospheric pressure to yield fibers and fine particles. These particles are subjected to enzymatic attack and resulting 5- and 6-carbon sugars are conventionally fermented into ethanol. Tests have recorded sugar concentrations of 10 to 12 percent and alcohol concentrations of 5 to 6 percent before distillation. Lignin can be recovered at the end of the process by filtration. The enzymes needed for the process reportedly can be grown directly on the exploded fiber, and need not be grown on purer cellulose substrates such as cotton-gin trash, as is the usual practice (Chemical Engineering 1981).

Readers needing additional information on enzymatic hydrolysis will find useful reviews by Goldstein (1980b) and Hajny (1981). Jones et al. (1979) provided an economic analysis of the Natick enzymatic hydrolysis process used to produce ethanol from wood.

26-8 PREHYDROLYSIS

An alternative to whole-wood hydrolysis is to remove the hemicelluloses for chemical or other use in a mild prehydrolysis step, and then to use the remaining fibrous cellulose residue for pulp, particleboard, fiber, or for fuel (fig. 26-40, Herrick and Hergert 1977).

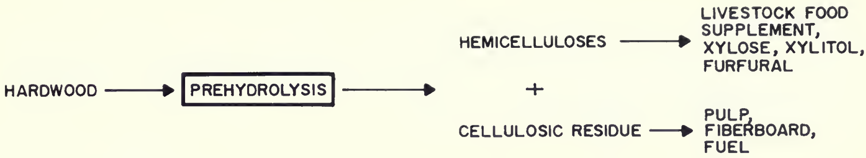

Figure 26-40.—Prehydrolysis of pine-site hardwoods for chemical, animal food supplement, and fiber or fuel use.

Prehydrolysis can be carried out by hot water extractions. Acids in the wood and those released by hydrolysis cause extensive depolymerization of hemicelluloses. The resulting water soluble carbohydrates are mostly low molecular weight polysaccharides with smaller amounts of monomeric sugars. Yield and composition depend on temperature and time of extraction. Typically, water temperatures of 100° to 170°C and extraction time of 30 minutes are sufficient. The polysaccharides containing xylose units (xylans) are more easily hydrolzyed than the corresponding glucans; thus, prehydrolysis recovers xylose from hardwoods at lower temperatures than needed to remove hemicellulose from softwoods. Typically the hot water prehydrolyzate of hardwood will contain polymers of xylose (30 percent) and glucose (25 percent) (Herrick and Hergert 1977).

Hemicellulose extracts have been marketed since 1965 as Masonex, an ingredient of livestock feed (Galloway 1975). The fibrous residue or pulp is used to manufacture hardboard. Only steam and pressure are used to pulp the wood chips and so the hemicellulose fractions removed are not contaminated by added chemicals. The hot water extract is separated from the pulp by vacuum filtration and concentrated by evaporation to 65-percent solids. The resulting product resembles molasses and can be added in cattle feed to 10 percent by weight. Reportedly, the product contains 890 kilocalories of metabolizable energy per gallon (10.4 lb).

Funk (1975) described a prehydrolysis process that enables recovery of up to 80 percent of the hermicelluloses, mainly as the monomeric sugar xylose. The process does not seriously affect the fiber residue. The degree of polymerization of the residual cellulose is on the order of 900 DP with viscosity between 30 and 40 centipoise.

In the process, organic acids (acetic and formic) are vaporized and injected with steam into the digester where the wood chips are. Reaction time ranges from 15 minutes to 1 hour and the temperature is kept below 135°C. Above 135°C, xylose degrades and fibers deteriorate. More acids are generated in this process than are injected, so acid recovery by vacuum distillation is feasible. Xylose can be separated from glucose and other sugars by selective crystallization or microbial conversion. An alternative is to reduce the product mixture and separate the sugar alcohols.

When furfural is desired as the product from a hardwood prehydrolysis process, it may be advantageous to add some dilute sulfuric acid. The dilute mineral acid helps to produce furfural by removing and hydrolzying the hemicelluloses and dehydrating xylose. Thus, it is possible to produce furfural in a one-stage process in which both hydrolysis and dehydration occur in the reaction vessel. Harris (1978) indicates that the residue from such a process can supply more fuel for heat energy than the process requires.

26-9 INDUSTRIAL USE OF WOOD ENERGY

The forest products industry is the fourth largest user of purchased energy in the Nation (U.S. Department of Agriculture, Forest Service 1976). (The petroleum, chemical, and primary metals industries are the three largest users.) In 1974 the forest products industry purchased about 1.8 quads, or slightly more than 2 percent of the Nation's total energy use (Salo et al. 1978). About 1.3 quads were fuel oil and natural gas, energy sources particularly vulnerable to curtailment and interruption.

The industry also generates such of its own energy from mill wastes and residues. Pulp and paper mills generate the most by burning spent pulping liquors, wood, and bark. Nationally, pulp and paper mills are about 40 percent energy self-sufficient, sawmills about 20 to 40 percent, and plywood and veneer mills, about 50 percent (U.S. Department of Agriculture, Forest Service 1976). At 50 percent, southern pulp and paper mills were more energy self-sufficient in 1976 than the national average (table 26-15). However, southern mills also use more energy than any other segment of the pulp and paper industry (table 26-16). The industry is vigorously moving toward a greater degree of energy self-sufficiency.

Most fuel, purchased and residue, is burned to generate steam for the process requirements of the industry. However, some electricity is also generated in the industry by co-generation. Pulp and paper mills in general produce only about one-half of their electrical needs, but many sawmills could sell excess electricity if the economics were favorable (Pingrey and Waggoner 1978).

TABLE 26-15.—*Energy use pattern for southern pulp and paper mills*[1]

Energy source	Total energy used
	Percent
Electricity	3
Natural gas	20
Oil	20
Coal	7
Pulping liquors	43
Wood and bark	7

[1]Data from U.S. Department of Agriculture, Forest Service (1976).

The forest products industry is in a good position to achieve greater energy self-sufficiency by burning more wood and bark residues to replace or supplement purchased fossil fuels (Grantham 1978; Salo et al. 1978; Pingrey and Waggoner 1978; Benemann 1978; Hodman 1978). Such action would also free

TABLE 26-16.—*Energy used by the pulp and paper sector by geographical area*[1]

Geographic area	Energy used	
	10^{12} Btu's	*Percent*
South	1,325	62
North	474	22
Rocky Mountain	43	2
Pacific Coast	302	14
Total	2,154	100

[1]Data from U.S. Department of Agriculture, Forest Service (1976).

oil and natural gas for use elsewhere as a fuel or petrochemical feedstock. Because of its proximity to vast amounts of virtually unused pine-site hardwoods, the forest products industry in the South has a better opportunity than anywhere else in the country to convert to wood fuel.

The industry already has experience in handling such bulky wood materials. However, certain problems will have to be addressed, mainly storing and handling the large volume of wood fuel that will be required to replace fossil fuels. Wood-fueled furnaces are less convenient and have more emissions than those operating on oil and natural gas. Finally, the use of pine-site hardwood chips as a fuel may have to compete with their use for higher-value products.

26-10 ECONOMICS

As a replacement for natural gas (at $3.00 per million Btu) to generate steam, pine-site hardwoods have a fuel value of about $23/green ton and when used to replace oil, the value is nearly $36 (table 26-17). In other words, 1 green ton of pine-site hardwoods can be used to generate the same amount of steam as $23 worth of natural gas. If the wood costs less than $23, there is then a savings in fuel cost. The replacement fuel value for the pine-site hardwoods will, of course, continue to rise with the cost of oil and natural gas. For example, decontrol of gas prices will tend to move the heat value of wood fuel toward $40/green ton.

TABLE 26-17.—*Fossil fuel cost for steam production and fuel replacement value for pine-site hardwoods*[1]

Statistic	Oil	Natural gas
Fuel cost, $/MM Btu[2]	5.00	3.00
Furnace efficiency, percent	80	76
Steam cost, $/MM Btu	6.25	3.95
Fuel replacement value for pine-site hardwoods, $/green ton[3]	35.75	22.58

[1]Does not include handling, storage, maintenance, amortization, or other costs.

[2]Representative values for natural gas and oil.

[3]Following assumed: 42 percent moisture content, higher heating value 7,827 Btu/lb, 63 percent furnace efficiency.

Fuel costs, however, are only one consideration in the total economic picture. Wood-fired boilers cost more and are more expensive to maintain than oil or gas-fired units. Koch and Mullen (1971) indicated that a steam boiler for burning bark and oil would cost about twice as much as a boiler using oil only. Similar cost comparisons have been noted by Corder (1973). Salo et al. (1978) estimated capital costs for installing new wood-fired steam boilers at about $13 million and $25 million for 155,000 and 387,000 lb/hr units. Annual operating and maintenance costs were projected at 1.4 and 2.8 million dollars. To retrofit an oil-fired boiler (1400 Bbl/day) to an 850 ovendry ton/day wood-fired unit would result in an additional capital investment of $21.5 million and an increase in annual operating and maintenance costs of $2.3 million, but would decrease fuel costs $4.2 million annually (1978 basis).

The economics of changing to wood fuel will be site-specific. Pingrey and Waggoner (1978) and Salo et al. (1978) indicate there is general lack of economic incentive to change based on fuel savings alone. Salo et al. suggest an early retirement tax credit or an investment tax credit to encourage the use of wood as a fuel.

The economics of converting the pine-site hardwoods to other energy-related products is subject to considerable uncertainty because most of the conversion processes are not yet widely used. Additionally, costs of harvesting such hardwoods with conventional equipment are sometimes excessive. Several studies have been made to estimate the cost of converting wood into various energy forms, and the projected costs vary considerably. For example, the projected price of methanol from wood ranges from 40¢/gallon to 98¢/gallon. Such differences occur because different variables are used in the models to make the projections. The most obvious variables include feedstock cost, production plant size, and the amount of return on investment.

In a Mitre Corp. study, Salo et al. (1978) estimate the plant gate selling prices for various wood-derived energy products in order to assess the near-term potential (table 26-18). These values should be considered optimistic as feedstock costs are very low and a 10 percent rate of return was used on all products for comparison purposes. For the methanol, ammonia, and ethanol, this rate would probably be too low to be attractive to a private enterprise. The conclusion was that direct combustion of wood fuel is probably the best option for the forest products industry. The study indicated that thorough gasification of wood to low Btu gas should be studied to determine the potential of such gasification for large-scale industrial applications such as pulp mills.

Stanford Research Institute is preparing an economic report on wood energy processes likely to achieve commercialization by 1985 (table 26-19) (Schooley et al. 1978). The base case assumes feedstock cost of $30/dry ton while the optimistic case assumes $20/dry ton. The model assumes no subsidies or tax incentives and 15 percent return on investment.

In 1981 the Solar Research Institute (Flaim and Hill 1981) found that methanol from forest biomass could be produced at a total cost, including maintenance

TABLE 26-18.—*Estimated "plant-gate" selling prices*[1] *for energy products derived from wood*[2]

	Plant size	
	850 dry tons/day	1700 dry tons/day
	Dollars/million Btu heating value	
Process steam	2.70	
Low-Btu fuel gas	2.70	
Medium-Btu fuel gas	3.10	2.60
Charcoal without credits	4.90	4.60
Charcoal with steam credit	2.10	1.90
Substitute natural gas	4.60	3.80
Ammonia	5.50 ($107/ton)	4.43 ($88/ton)
Methanol	7.60 ($0.50/gal)	6.20 ($0.40/gal)
Ethanol	20.40 (1.65/gal)	17.50 (1.40/gal)
Electricity	11.80 (40 mills/kWh)	8.80 (30 mills/kWh)

[1]Data from Salo et al. (1978). Assumptions include a 10-percent return on investment after taxes.
[2]Wood cost is $\$1.00/10^6$ Btu.

and capital charges of 22 percent of plant and working capital investment, of $0.56 to $1.05 per gallon. They predicted that the market price for methanol would increase from the 1979 price of $0.483/gallon to $0.980 in 1990 and $1.079/gallon in 1995 (all in constant 1979 dollars).

In 1975 Katzen Associates reported on the separate or combined production of chemicals from wood (U.S. Department of Agriculture, Forest Service 1976; Saeman;[18] Grantham 1978; Hokanson and Rowell 1977). Table 12-20 summarizes data on the selling prices for a hardwood plant. Assumptions included a delivered price of $34/dry ton and that its availability is limited to 1,500 dry tons per day. Conclusions drawn from the Katzen report are that chemicals production from wood is not economically attractive.

See table 12-21 for some energy equivalents useful in economic comparisons.

[18]J. F. Saeman. Energy and materials from the forest biomass 20 p. Paper presented at Institute of Gas Technology Symp. on Clean Fuels from Biomass and Wastes. (Orlando, Fla., Jan 25-28, 1977).

TABLE 26-19.—*Sales prices required on eight products to yield a satisfactory profit in large conversion facilities*[1]

Route	Conversion process[2]	Base case[3] (including feedstock at $30/ dry ton)	Base case (no feedstock cost)[3]	Optimistic case[3 4] (including feedstock at $20/ dry ton)
		Dollars per million Btu		
Wood to:				
Heavy fuel oil.......	CL	5.37	3.47	4.76
Methanol...........	GOB	7.77 (0.50/gal)	6.01 (0.39/gal)	6.72 (0.44/gal)
Ammonia ($/short ton)	GOB	164.00	126.00	
Substitute natural gas .	GOB	6.41	4.80	
Steam..............	DC	3.00	1.68	2.73
Electricity	DC	16.38	11.62	14.40
Steam and electricity .	DC	3.42	2.09	3.06
Oil and char	P	4.50	1.40	4.00

[1]Data from Schooley et al. (1978).
[2]Key: CL = catalytic liquefaction
GOB = gasification—oxygen blown
DC = direct combustion
P = pyrolysis
[3]1977 dollars in year 1985. Sales values tabulated will return yield calculated to yield a 15-percent discounted cash flow rate of return on equity and a 9-percent rate of return on debt.
[4]Capital cost = 80 percent of base case.

TABLE 26-20.—*Estimated selling prices for chemicals from single-product and multi-product hardwood plant*[1]

Type of plant	Product output	Plant size	Selling price[2]	1975 market price
		Dry tons/day		
Single-product plant				
Methanol.....	50 x 10^6 gal/yr	1,500	$0.98/gal	$0.38/gal
Ethanol	25 x 10^6 gal/yr	1,480	$1.90/gal	$1.04/gal
Furfural	40 x 10^6 lb/yr	760	$0.61/lb	$0.37/lb
Multiproduct plant[3]				
Ethanol	25 x 10^6 gal/yr	1,500	$1.28/gal	$1.04/gal

[1]Data from J.F. Saeman. Energy and materials from the forest biomass. 20 p. Paper presented at Institute of Gas Technology Symp. on Clean Fuels from Biomass and Wastes. (Orlando, Fla., Jan. 25-28, 1977).
[2]Selling price based on an annual depreciation of investment of 8 percent and profit of 15 percent (after Federal taxes).
[3]Selling price assumes a credit for furfural and phenol at 65 percent of market selling price.

TABLE 26-21.—*Some approximate heat contents of wood, oil, coal, gasoline, methanol, and ethanol*

Material	*Quantity*	*Heat content*
		Thousand Btu
Stemwood of pine-site hardwoods, ovendry	1 ton	15,650
Stemwood of pine-site hardwoods, green	1 ton	9,080
Oil, unrefined	1 barrel (42 gal or 7.03 pounds)	5,550
Coal, eastern	1 ton	26,000
Coal, western	1 ton	20,000
Gasoline (regular unleaded)	1 gallon (6.15 pounds)	120
Methanol	1 gallon (6.6 pounds)	64
Ethanol	1 gallon (6.6 pounds)	84

26-11 THE FUTURE

Wood fuel will play a major role in supplying increasing amounts of energy for the forest products industry through the turn of the century. The industry will probably depend on oil and natural gas, however, for as long as these resources are available. Natural gas use is likely to continue for numerous decades. Coal is a less attractive fuel alternative due to environmental considerations and the cost of shipping and handling, but its use will grow to perhaps 25 percent of the industry needs by 1985 (Junge 1975b). Wood residues will remain the best energy bargain, but economic use of wood sources such as the pine-site hardwoods will depend on the development of adequate harvesting technology.

Oil and natural gas will continue to be the primary feedstocks for organic chemicals through the turn of the century and for as long thereafter as they remain the least expensive alternative (Krieger and Worthy 1978; Grantham 1978; Maisel 1978; Herrick and Hergert 1977). A popular view is to reduce the use of oil and natural gas for fuel and to reserve this source for petrochemical production. Before the 1940's, coal was the major source of organic chemicals and is considered the first alternative for both fuel and petrochemicals. Some experts believe that methanol will be the first liquid fuel from coal to compete on its own merits. At current energy consumption rates, there is enough coal to last several hundred years.

Wood will become more important as an industrial raw material because it is renewable. Demand for fibers for paper and textile products will more than double by the turn of the century (Jahn 1980). Although perhaps not competitive with petroleum and coal for petrochemicals, wood should be studied for other specialized chemical products that take advantage of the unique molecular structure of wood and bark.

Wood research thus should focus on making the ligno-cellulosic complex accessible to chemical and biological action, on increased use of cellulose and lignin as polymers, on production of specialized chemicals, and on catalyst research and development.

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27
Measures and yields of products and residues

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Chapter 27

Measures and yields of products and residues

CONTENTS

CHAPTER 27

Measures and yields of products and residues[1,2,3]

27-1 UNIT OF MEASURE

Wood-using industries employ a variety of units to measure southern hardwood trees and logs. Pulpwood dealers have historically used stacked measure—the cord or related unit; lumber manufacturers have preferred the board foot. As the industry has moved toward whole-tree utilization, however, measures of total or bark-free volume (cubic feet) and of weight (pounds) have become increasingly popular; this trend is likely to continue.

Since wood is a variable material, and much of it is produced in irregular shapes, all units provide more or less imperfect approximations of intrinsic value. Applicability of measuring systems to specific situations must often be determined by experience. Even more variable are estimates of wood yield, which are additionally affected by factors specific to individual sites, stands, and processes. The data on product and byproduct yields are presented as best available approximations—yields in specific situations can be determined accurately only by local studies.

THE CORD

A **standard rough** cord occupies 128 gross cubic feet and is defined as comprised of 4-foot-long **rough** (bark in place) roundwood stacked into a pile or rick 4 feet high, 4 feet wide, and 8 feet long; a rick of any dimension that contains 128 cu ft of wood, bark, and airspace, however, is considered a standard cord. The word cord, if it appears unmodified in this text, refers to the standard rough cord of 128 cu ft.

Because pulpwood is commonly cut about 5 feet in length, numerous wood procurement programs in the South are based on non-standard units. The most prevalent of these are defined as follows:

1. The 160-cu-ft **long cord** comprised of 5-foot rough bolts stacked in a rick 4 feet high and 8 feet long.

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[1]Acknowledgement is due M. E. Lora who prepared the first draft of this chapter.

[2]For convenient reference, all tables are grouped at the end of the chapter; for metric conversion data, see the last table in the chapter, i.e., table 27-154.

[3]Some abbreviations are used throughout the chapter as follows:
Mbf—Thousand board feet.
dbh—Tree diameter at breast height, i.e., 4.5 feet above ground outside bark.
dob—Diameter outside bark.
dib—Diameter inside bark.
Scaling diameter—Log diameter inside bark at small end.

2. The **168-cu-ft unit** of 5-foot 3-inch rough bolts stacked in a rick 4 feet high and 8 feet long. According to Forest Farmers Association (1966), one of these units is equivalent in volume to 1.315 standard cords.
3. The **200-cu-ft unit** of straw-piled rough bolts 5 feet 3 inches long.

Volume of solid material in a cord.—The solid content (wood and bark) in a standard rough cord is most if the wood is compactly piled, short, well trimmed, straight, and of large diameter (table 27-1). Airspace in a cord of hardwood typically varies from 23 to 53 percent for stemwood and up to 61 percent for topwood. Solid content ranges from 50 cu ft for stacks of small-diameter, 8-foot topwood sticks to 98 cu ft for large-diameter, straight, 4-foot sticks (table 27-1). As an average, 90 cu ft per cord is often used for cords composed of straight sticks (Worley 1958). A study in New York oak stands resulted in an average of 85 cu ft per cord (Schnur 1937). However, scrub oak sold for fuel in Texas averaged only 70 cu ft per cord; the sticks were 4 feet long and had a minimum diameter of 1½ inches (Baudendistel 1941).

Often it is preferable to know the volume of bark-free wood in a rough cord. For many years a South-wide average of 79 cu ft per cord was used for hardwoods (Taras 1956). A recent survey of the North Carolina Piedmont (Welch 1975) showed an average of 74 cu ft of wood per standard cord of hardwood (table 27-2).

Wood volume can be easily estimated once the percentage volume of bark is known. Chamberlain and Meyer (1950) list bark volumes (in percent of unpeeled wood) corresponding to the average ratio of diameter inside bark to diameter outside bark (table 27-3). These ratios have been tabulated for the following species:

Maple, red	0.92-0.94
Oak, black	.86- .88
Oak, chestnut	.84- .88
Oak, northern red and scarlet	.88- .92
Oak, white	.87- .93

For bark volume as a percent of volume of wood and bark in pulpwood piles of four of these species, see table 13-22.

For ratios of bark volume to stemwood volume in 6-inch trees of 22 species of pine-site hardwoods, see table 13-21, which also relates cubic feet of bark per standard rough cord to the volume of wood, free of bark and voids, contained in the cord.

In long cords of mixed oaks, bark occupied 12 percent of the stacked volume of unpeeled, straight bolewood and 13 percent of the stacked volume of unpeeled topwood and crooked, knotty bolewood (Barrett et al. 1941).

The number of standard cords of unpeeled wood needed to make one standard cord or one long cord of peeled wood varies according to the bark thickness of the species cut, as shown in table 27-4.

Wood volume in long cords of peeled oak was studied in the southern Appalachians (Barrett et al. 1941). The average wood volume per long cord for straight, split bolewood was found to be 109 cu ft; the range in the 66 stacks measured was 91 to 125 cu ft. The volume of solid wood averaged 93 cu ft and ranged from

81 to 107 cu ft per long cord for peeled topwood and crooked, knotty bolewood. Based on examination of 41 stacks of topwood and cull bolewood, the following equation was developed to predict solid wood volume:

$$Vw = 0.2342\ N + 0.4403\ R + 72.0569 \qquad (27\text{-}1)$$

where:

Vw = wood volume (cu ft) per 160-cu-ft long cord of peeled sticks
N = number of sticks per unit
R = percent of sticks round

A cord of large bolts contains more solid material than a cord of small bolts (tables 27-1, 27-2; fig. 27-1). Large bolts tend to come from the lower bole positions and are straighter and more nearly free of trimmed branches and protruding knots than small bolts.

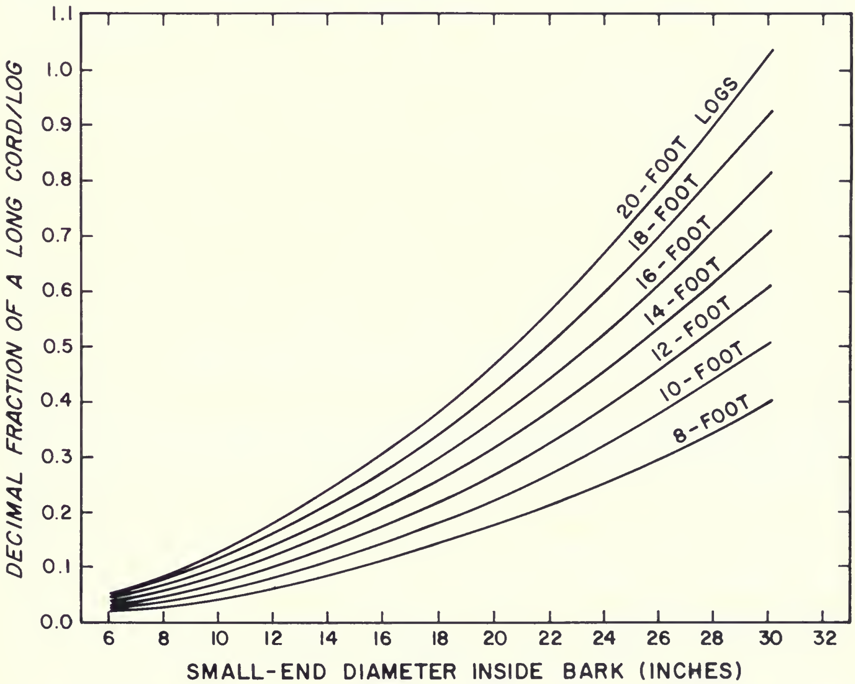


Figure 27-1.—Relationship of log length and diameter to the decimal fraction of a cord provided by each log; e.g., two 10-foot-long logs measuring 30 inches in dib at the small end are required for a 160-cubic-foot cord comprised of 5-foot lengths of peeled and split mixed oak sticks. (Drawing after Barrett et al. 1941.)

However, Barrett et al. (1941) found that in cords composed of oak topwood and crooked, knotty bolewood, small sticks resulted in higher wood volume than did large sticks (fig. 27-2). The explanation is that for ease of handling, relatively straight-grained, smooth sections were split into small pieces, but large pieces that were especially knotty or crooked could not be split and were left whole. The knots and crook associated with large pieces, therefore, resulted in more airspace in the stack. Cords in which a greater percentage of the sticks were round also had greater wood volumes than cords with a high percentage of split sticks (fig. 27-2).

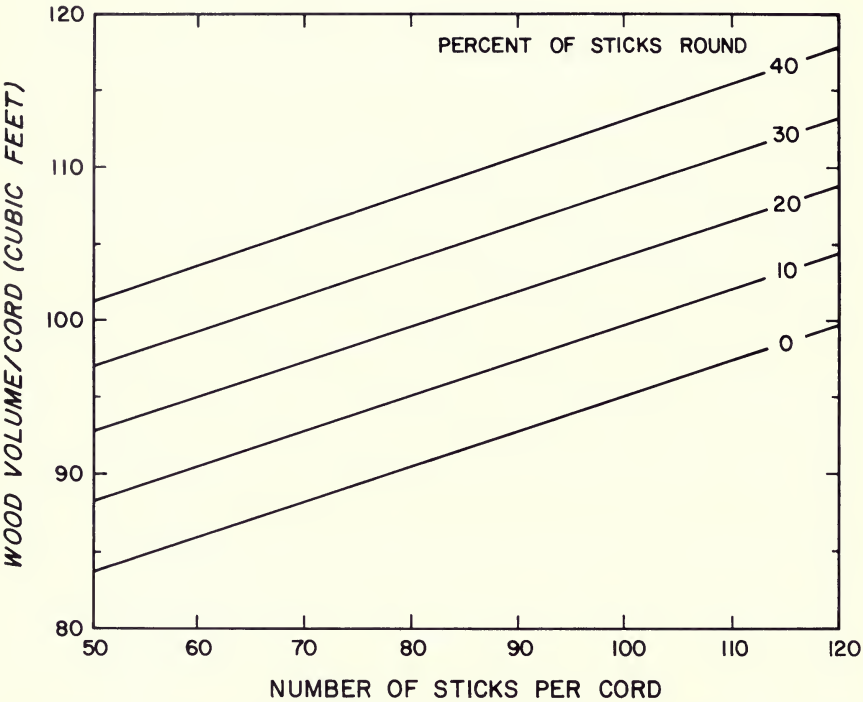


Figure 27-2.—Number of sticks per cord and percentage of the sticks that are round (the balance being split) related to the volume of wood, free of bark and voids, in a 160-cu-ft stacked cord of peeled, 5-foot-long sticks of mixed oak (Drawing after Barrett et al. 1941.)

In general, cords of short bolts contain more solid material than cords of long bolts (table 27-1), probably because the longer the bolt the greater the effect of crook or taper can be.

Number of pieces per cord.—The number of pieces in a standard rough cord is obviously a function of bolt diameter and length, irregularities in the bolts, and compactness of the pile.

For pulpwood of better than average straightness and surface smoothness, table 27-5 shows the number of rough bolts required to make a standard cord, as a function of both bolt length and midlength dib; e.g., 152 4-foot-long, 5-inch bolts are required, whereas only twenty 6-foot-long, 12-inch bolts are needed.

Veneer cores approach the ultimate in straightness and surface smoothness; the number of 4-foot veneer cores required to make a cord is of interest because this number should represent the upper limit for extremely straight and smooth, bark-free pulpwood (table 27-6).

Number of trees required per cord.—The number of hardwoods required to yield a standard rough cord depends on tree diameter, height, and form. Table

27-7 lists the number required for trees of various sizes and two form classes. Form class is an indication of stem taper and is calculated as follows:

$$\text{Form class} = 100 \frac{\text{Dib at top of 16-foot butt log}}{\text{Dbh}} \qquad (27\text{-}2)$$

Small hardwood timber usually has a taper within the range of form class 75 to 80 (Worley 1958).

Cords of topwood per tree after removal of saw logs.—Substantial volumes can be cut from the tops residual after hardwood saw logs are removed. For example, in a North Carolina study of mixed oaks (Barrett and Buell 1941) topwood yield per tree ranged from 0.01 long cord (peeled) for a 9-inch, 2-saw-log tree to 1.3 long cords (peeled) for a 32-inch, 1½-saw-log tree (table 27-8).

Cords per acre.—When entire stands are converted to pulpwood, the yield is proportional to basal area and total tree heights in species with undivided stems such as sweetgum, black tupelo, hickory sp., and yellow-poplar, as follows (Minor 1953):

Average tree height	Volume per square foot of basal area
Feet	*Cords*
30	0.14
40	.18
50	.24
60	.30
70	.34
80	.37

Yields per acre have been tabulated for upland oak stands based on site index and stand age (table 27-9) and on site index, stand age, and basal area (tables 27-10 and 27-11).

A study of mixed hardwood stands throughout the South (Porterfield 1972) showed that upland slopes and ridges in Piedmont and mountain regions generally had lower cord volumes than branch bottoms, wet flats, bottomlands, and swamps (table 27-12).

THE BOARD FOOT-LUMBER SCALE

Traditionally, lumber was sawn to correspond to nominal thickness in inches and designated by thickness in quarter-inches, e.g., 4/4, 6/4, and 8/4 corresponded to 1-, 1.5-, and 2-inch-thick boards. Boards were also sawn to even widths of 4, 6, 8, 10, and 12 inches. A board foot (lumber scale) is the volume of wood in a 1-foot length of a 12-inch, 4/4 board; alternatively, it could be defined as a 1-foot length of a 6-inch, 8/4-board or any other combination that would yield a similar volume.

Although softwood lumber is frequently sawn thinner than nominal thickness (e.g., a 4/4 board is sawn only 15/16-inch thick), hardwood lumber must be dried to the thickness called for. Thus, 4/4 hardwood lumber must be a full inch thick when it is dry or it is scaled at the lesser thickness (Smith 1967). Furthermore, a hardwood board from 1 to 1¾ inches thick (4/4 to 7/4) must not vary more than ¼-inch between its thickest and thinnest points or it is classified as a miscut. Sawmills must cut hardwood lumber thicker to permit shrinkage during drying. Circle sawmills must cut 1-inch lumber 1⅛ inches thick to allow for shrinkage and sawing inefficiencies. Band sawmills are generally more accurate, and a good band mill can saw lumber 1-1/16 inches thick and still have a full inch of lumber when dry.

An industry survey (Hanks 1977) determined the following averages for the actual thickness of green hardwood lumber:

Nominal thickness	Average thickness
Inches	*Inches*
3/8	0.45
2/4	.60
5/8	.70
3/4	.90
4/4	1.15
5/4	1.40
6/4	1.65
7/4	1.95
8/4	2.20
9/4	2.50
10/4	2.70
3 to 10	nominal

In addition, Hanks reported that the industry practice for trimming hardwood lumber is to leave 2 inches of trim beyond the nominal length. The actual width of rough hardwood boards is random; this means that the industry average width of boards in the 7-inch class is 7.0 inches. In commercial practice, boards are scaled by area, rather than width.

THE BOARD FOOT-LOG SCALE

Numerous scaling procedures, i.e., **log scales,** have been developed to estimate the board foot (lumber scale) yield of logs. Application of log scales can only approximate lumber yield from logs because sawmills vary widely in efficiency of lumber recovery. Schumacher and Jones (1940) discussed general development of empirical log rules applicable to particular mills. Freese (1974) summarized the major log rules (over 95 are in use in the United States and Canada) and compared board-foot volumes attained by various rules. Fahey et al. (1981) compared the precision of log scaling systems using the relationship between lumber recovery and scaled volume, and compared the abilities of scaling systems to adjust volume for defect.

In the paragraphs that follow, specific formulae are presented for the log scales most widely used in the South: Doyle, Scribner Decimal C, and International ¼-inch. Log diameter, usually measured inside bark at the small end, and log length are the primary determinants of log content.

Doyle log scale.—The Doyle log scale is defined as follows:

$$V = \frac{L(D - 4)^2}{16} \tag{27-3}$$

To faciliate linear programming studies, Grosenbaugh (1952, p. 12) expressed the Doyle log scale as a regression equation:

$$V = 0.0625D^2L - 0.500DL + 1.000L \tag{27-4}$$

where:

V = volume, board feet
D = scaling diameter, inches
L = scaling length, feet

Gross board foot volumes in logs as computed by the Doyle scale (equation 27-3) are shown in tables 27-13 and 27-14. For a given scaling diameter, volumes of 8-foot logs are half those shown in table 27-14.

Gross log scale may be reduced because of defects in logs. The reductions (table 27-17) calculated for the Scribner rule, are adjusted to Doyle scale by multiplying by the diameter-related factor tabulated below (Forbes 1961, p. 1.62).

Scaling diameter	Factor
Inches	
8 to 11	0.6
12 to 13	.8
14 to 20	.9
21 to 31	1.0
32 to 40	1.1

Actual scaling practices differ widely from textbook scales. Some deviations occurring in the application of log rules are: giving logs 8 inches or less in diameter their length in feet as the board foot value; rounding scaling diameters to the nearest inch; and including various bark thicknesses in the diameter measurement. A modification of the Doyle rule, to include one bark thickness in the diameter, gives upward bias of:

Scaling diameter	Upward bias
Inches	*Percent*
6	20.0
9	10.7
12	9.2
15	8.4
18	1.8

Errors may be introduced by scaling even inches. If measurements are always rounded downward—i.e., logs 12.0 to 12.9 inches tallied as exactly 12 inches—the average downward bias for the Doyle rule is (Row and Guttenberg 1966):

Scaling diameter	Downward bias
Inches	*Percent*
6	35.9
9	17.3
12	11.5
15	8.6
18	6.8

Scribner Decimal C log scale.—Scribner did not base his log scale on a formula; instead he drew circles of different diameters and plotted the ends or cross sections of boards which might be sawn within each circle, computed the board cross sectional area in square inches, divided this value by 12 to get board feet per foot of log length, and finally, multiplied by the log length. As a result of this method of computation, values for successive inch classes increase in an irregular manner. In the Scribner Decimal C rule, the last figure in the scale of a log is rounded to the nearest 10 (e.g., a log scale of 114 bd ft is rounded to 110). Log contents according to the Scribner decimal C log scale are shown in table 27-15.

Grosenbaugh (1952, p. 12) expressed the Scribner scale in a regression equation as follows:

$$V = 0.0494D^2L - 0.124DL - 0.269L \qquad (27\text{-}5)$$

For precise computations, volume of 16-foot logs based on nearest tenth-inch scaling diameter are useful (table 27-16). These values were computed by the following equation:

$$V = 0.79D^2 - 2D - 4 \qquad (27\text{-}6)$$

In these equations,

V = volume, board feet
D = scaling diameter, inches
L = scaling length, feet

Gross log scale may be reduced because of defects. Appropriate deductions (board feet) can be read from table 27-17 if the length and cross sectional area of the defects are known.

International ¼-inch log scale.—This formula-based scale accounts for taper in logs by evaluating them in 4-foot lengths. Content of a log is computed by summing the contents of the 4-foot lengths comprising it and assuming that taper increases diameter ½-inch in each 4 feet of log length. Saw kerf is assumed to be ¼-inch. The formula for each 4-foot length of log is as follows:

$$V = 0.905\,(0.22D^2 - 0.71D) \qquad (27\text{-}7)$$

Log contents computed from this formula are usually rounded to the nearest 5 board feet as shown in table 27-18.

Row and Guttenberg (1966) expressed the International ¼-inch log scale as a regression expression containing both scaling diameter and length, as follows:

$$V = 0.0498D^2L - 0.185DL + 0.0422L + 0.00622DL^2 + 0.000259L^3 - 0.0116L^2 \qquad (27\text{-}8)$$

To compute the contents of 16-foot logs by scaling diameter in tenths of an inch (table 27-19), the following equation for the International ¼-inch log scale is useful:

$$V = 0.796D^2 - 1.375D - 1.230 \qquad (27\text{-}9)$$

For 8-foot logs (table 27-19):

$$V = 0.905\,(.44D^2 - 1.20D - 0.3) \qquad (27\text{-}10)$$

In these equations:

V = volume, board feet
D = scaling diameter, inches
L = scaling length, feet

Gross log scale may be reduced by deductions (board feet) computed by selecting the diameter-related factor tabulated below (Forbes 1961, p. 1.62), and multiplying it by the appropriate value from table 27-17.

Scaling diameter	Factor
Inches	
8 to 14	1.2
15 to 19	1.1
20 to 36	1.05

Gross volume in trees.—At least one-third—and in less than 2½-log trees more than half—the board-foot volume in hardwood trees is in the butt log. For hardwoods of average form class, the percentage of total tree volume in each 16-foot log is as follows (U.S. Department of Agriculture, Forest Service 1965a):

Merchantable height, Number of logs	Position of log in tree						
	1	1½	2	2½	3	3½	4
	Percentage of total tree volume						
1	100	—	—	—	—	—	—
1½	70	30	—	—	—	—	—
2	55	—	45	—	—	—	—
2½	45	—	40	15	—	—	—
3	40	—	35	—	25	—	—
3½	40	—	30	—	20	10	—
4	35	—	30	—	20	—	15

Volume per log in board feet (International ¼-inch rule) is given in table 27-20 for hardwoods in form class 78.

The amount of taper typical of 16-foot logs taken above the butt log is described in table 27-21.

Table 27-22 gives board-foot volumes of **hardwood trees** as measured by the International ¼-inch rule; form classes 65, 75, 85, and 90 were selected as those most likely to be encountered among hardwoods growing on southern pine sites. Merchantable height, applicable to these three tables, includes that portion of a tree from stump height to a point on the stem at which merchantability for sawtimber is limited by branches, deformity, or minimum diameter. For smooth stems this minimum diameter is usually not less than 60 percent of tree diameter breast high in the case of the smallest (10-inch) saw log trees, or 40 percent for large trees 30 to 40 inches in diameter. If height measurements include small tops of southern hardwoods, the tables will overscale. Tree volumes for other form classes can be found in Mesavage and Girard (1956).

Volume tables and predicting equations have also been developed for individual species growing in various parts of the country. The most pertinent ones are listed below by species.

Species and equations	Volume tables		
	International ¼-inch	Scribner	Other
	Table number		
Ash sp. (Table 27-23)	27-24	—	—
Hickory sp. (Table 27-23)	—	—	—
Maple, red (Table 27-23)	27-25	—	—
Oak, black	27-26	27-27	—
Oak, chestnut (Table 27-23)	27-28	27-29	—
Oak, red sp. (Table 27-23)	27-30	27-31	—
Oak, scarlet (Table 27-23)	27-32	27-33	—
Oak, white (Table 27-23)	27-34	27-35	—
Sweetgum (Table 27-23)	—	27-36	27-37
Tupelo, black (Table 27-23)	—	—	—
Yellow-poplar (Table 27-23)	27-38, 27-39	27-40, 27-41	27-42, 27-43

In addition, Beck and Della-Bianca (1970) give the following equation for predicting board-foot volume (International ¼-inch scale) in **yellow-poplar:**

$$V = 0.0148\,(D^2H) + 0.0203\,(D^3) - 0.5982(D)^2 - 44.8597(D/H) + 1321.0515(1/H) - 32.6851 \qquad (27\text{-}11)$$

where:

V = volume in board feet (International ¼-inch scale)
D = diameter at breast height (inches)
L = height (feet)

A taper-based system for estimating stem volumes in upland oaks was developed from measurements of felled trees in the Central States (Hilt 1980). The system uses diameter at breast height *inside* bark and total tree height to predict board-foot or cubic-foot volumes to any desired top diameter; a computer program is available.

Other estimates of board-foot volumes include predicting equations for hardwood species and species groups in the Northeast (Scott 1979) and tables for red maple, white ash, yellow-poplar, and various oaks based on field measurements in Pennsylvania (Bartoo and Hutnik 1962).

Board feet per acre.—Yields of naturally occurring, mixed hardwood stands are given in table 27-44. This table and the regression equations on which it is based were developed with data from 641 plots in nine forest site types extending from Virginia to Florida and west to Louisiana and Arkansas (Smith et al. 1975). The authors note that the average yields from these sample plots are representative only of fully stocked, relatively uniform, even-aged southern hardwood stands and are higher than can be expected from stands of inferior structure. Only values for those forest site types where pines could likely predominate are reproduced here. Smith et al. found that on upland slopes and ridge sites, total green above-ground biomass, excluding only smaller pieces (less than 4 inches dob) from tops and branches of larger trees, was 44 tons per acre in 20-year-old stands and 162 tons per acre in 60-year-old stands (see col. 13 plus col. 17 of table 27-44). Other sites had significantly more biomass per acre.

Based on rangewide studies, Schnur (1937) prepared yield tables for fully stocked, even-aged, second-growth **upland oak** forests (table 27-45).

Yields for natural, unthinned stands of **yellow-poplar** (table 27-46) were based on 141 plots in the Appalachian Mountains of North Carolina, Virginia, and Georgia (Beck and Della-Bianca 1970). These even-aged stands each had 75 percent or more of the overstory in yellow-poplar. For each age on a given site index, board-foot yield reaches a maximum volume, beyond which increases in numbers of trees do not increase yield. Figure 27-3 illustrates this culmination at four ages on site index 100, where a 60-year-old stand with 200 trees/acre contains 600 bd ft/acre less than one with 150 trees/acre. Values in table 27-46 are in board feet International ¼-inch scale. Table 27-47 gives Scribner values for yellow-poplar derived from 89 plots scattered well over the species range and representing the best stocked areas that could be found (McCarthy 1933).

Ash yields (table 27-48) are for pure, even-aged, well stocked stands on different quality sites.

Yield tables for a variety of hardwoods and from many different publications are collected in Evans et al. (1975).

THE CUBIC FOOT

While the cord and board foot (log scale) are convenient units of volume, they are indirect and only approximate measures of actual cubic volume. Cubic measurement has a definite advantage: it accounts for the total wood content in a tree without being tied to any particular end product.

A **cunit,** the unit of measure used by the U.S. Forest Service for pulpwood or sawtimber sales, is 100 cubic feet of wood fiber, always in the form of roundwood—pulpsticks, sawlogs, or standing trees (Anonymous 1976).

Cubic feet in logs.—The increasing value of logs and of products from whole logs or residues has caused a trend in log scaling away from board-foot log rules and towards cubic log rules. In fact, cubic log rules are now virtually standard outside the United States (Hartman et al. 1978).

Many cubic foot scales are based on formulae that mathematically transform logs and bolts into equivalent true cylinders. Volumes, therefore, are computed

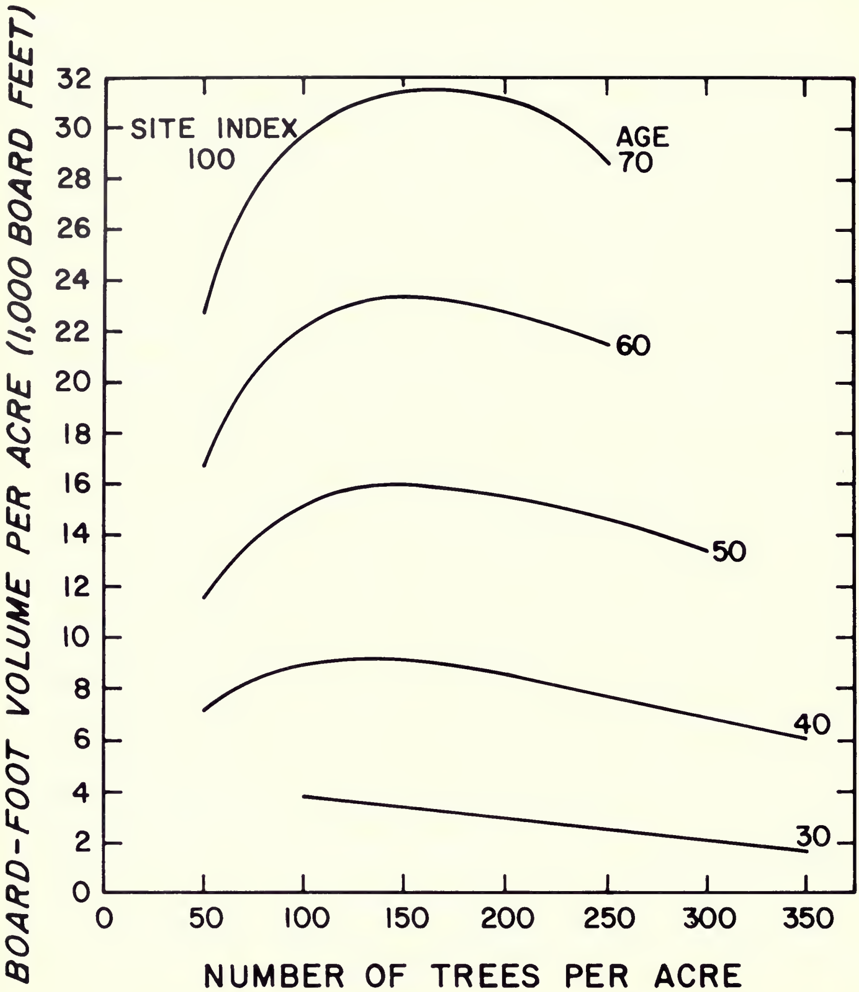


Figure 27-3.—For certain combinations of age and site index, board-foot yields (International ¼-inch rule) of yellow-poplar culminate with increasing stand density. These even-aged, unthinned stands were in the Appalachian Mountains of North Carolina, Virginia, and Georgia. Site index, height at age 50, is 100 feet. (Drawing after Beck and Della-Bianca 1970, p. 4.)

by multiplying log length by cross-sectional area. The principal variation among cubic foot scales is in the method of computing cross-sectional areas of logs and trees.

The most common cubic log rule is Smalian's formula:

$$V = 0.005454 \left[\frac{D^2 + d^2}{2} \right] L \qquad (27\text{-}12)$$

where:

V = cubic volume inside bark, cu ft
D = average large-end diameter inside bark, inches
d = average small-end diameter inside bark, inches
L = log scaling length, feet

This formula may be used for metric log scaling in cubic meters by noting diameters in centimeters and length in meters and then changing the constant 0.005454 to 0.00007854 (Hartman et al. 1978). Gross scale may be reduced if defects are visible.

For **yellow-poplar** sawlogs, the cubic volume without bark can be estimated using the following equation:

$$V = 0.23526 + 0.00618\ D^2L \qquad R^2 = 0.99 \quad Sy.x = 0.03 \tag{27-13}$$

where

V = volume without bark, cu ft
D = log-scaling diameter, inches
L = log length, feet

This equation was developed by Clark (1976) from measurement of 230 sawlogs in western North Carolina.

Cubic feet in individual trees.—Gross cubic foot volumes (inside bark) based on length and form class (equation 27-2) of merchantable stems have been published by Mesavage (1947); tables 27-49 and 27-50, applicable to form classes 70, 80, and 90, give values typical of hardwoods growing on southern pine sites.

Tables and equations for estimating cubic volumes have also been developed for individual species.

For **white oak, red oaks** (black and northern red), or **red maple** growing in the Appalachian region of Virginia, main stem volume can be predicted using the following equation (Oderwald and Yaussy 1980):

$$V = kD^2\ \frac{(H\text{-}.5)^{2b+1} - [(H\text{-}4.5)(d/D)^{1/b}]^{2b+1}}{(2b+1)\ (H\text{-}4.5)^{2b}} \tag{27-14}$$

where

V = cubic foot volume
k = $\pi/(2.12)^2$
D = diameter at breast height, inches
H = total height, feet
d = desired top diameter, inches
b = the appropriate species coefficient

To determine volume *outside* bark, d is calculated as the desired top diameter outside bark, and the appropriate species coefficient is inserted in equation 27-14:

white oak	0.72858
red oak	.72735
red maple	.73045

To determine volume *inside* bark, those same coefficients are used, but

d = desired top diameter inside bark
D = dbh x the species dib/dob ratio, as listed below:

white oak	0.92017
red oaks	.90356
red maple	.94306

Based on measurements of 62 **northern red oaks** felled in North Carolina, Phillips and Cost (1978) developed equations for predicting the volume (inside bark) of the total tree (excluding 0.5 foot stump) and of the merchantable stem (to a 4-inch top outside bark):

$$\text{Log}_{10}\text{total-tree volume (cubic feet)} = -2.62944 + 1.00979\ \text{Log}_{10}(D^2Th)$$
$$R^2 = 0.99;\ Sy.x = 6.08 \text{ cubic feet} \qquad (27\text{-}15)$$
$$\text{Log}_{10}\text{stem volume (cubic feet)} = -2.67736 + 0.99529\ \text{Log}_{10}(D^2Th)$$
$$R^2 = 0.99;\ Sy.x = 2.94 \text{ cubic feet} \qquad (27\text{-}16)$$

where

D = diameter at breast height, inches
Th = total height, feet

Volumes calculated for trees 6 to 24 inches in dbh using these equations are listed in table 16-19.

Beers and Gingrich (1958) provided a cubic volume equation and tables for northern red oak based on measurement of 236 trees in Pennsylvania. Hilt (1980) developed a taper-based system for estimating stem volumes in upland oaks to any desired top diameter. Naturally, the larger the merchantable top diameter selected, the smaller the cubic volume (Fig. 27-4); the difference is most pronounced in trees with a small diameter at breast height. Hilt's work is based on measurements of felled trees in the Central States.

Clark et al. (1980 abc) provided tree volume equations (tables 27-65 ABC) and volume data computed from the equations (tables 27-66 ABC) for **scarlet oak** from the Tennessee Cumberland Plateau, **southern red oak** on the Highland Rim in Tennessee, and **northern red oak** in western North Carolina.

Yellow-poplar has been the subject of many studies, and several equations for predicting cubic-foot volumes are available. Beck's (1963) equations and volume tables (tables 27-51 through 27-53) were prepared from measurements of 336 trees in the southern Appalachian regions of Georgia, North Carolina, and Tennessee, and Virginia. Sample trees ranged from 1 to 30 inches in dbh and from 10 to 138 feet in total height. The equations, which account for 98 percent or more of the total variation in volume, are as follows:

$$\text{Total cubic-foot volume outside bark} = 0.0025\ D^2H - 0.0028 \qquad (27\text{-}17)$$
$$\text{Cubic-foot volume outside bark to 4.0-inch top (ob)} = 0.0024\ D^2H - 0.6417 \qquad (27\text{-}18)$$
$$\text{Cubic-foot volume outside bark to 8.0-inch top (ob)} = 0.0024\ D^2H - 5.3000 \qquad (27\text{-}19)$$

Cubic-foot volume inside bark to 4.0-inch top (ob) =

$$0.0020\ D^2H - 0.6837 \qquad (27\text{-}20)$$

Cubic-foot volume inside bark to 8.0-inch top (ob) =

$$0.0020\ D^2H - 5.1000 \qquad (27\text{-}21)$$

where

D = diameter at breast height, inches
H = total tree height, feet

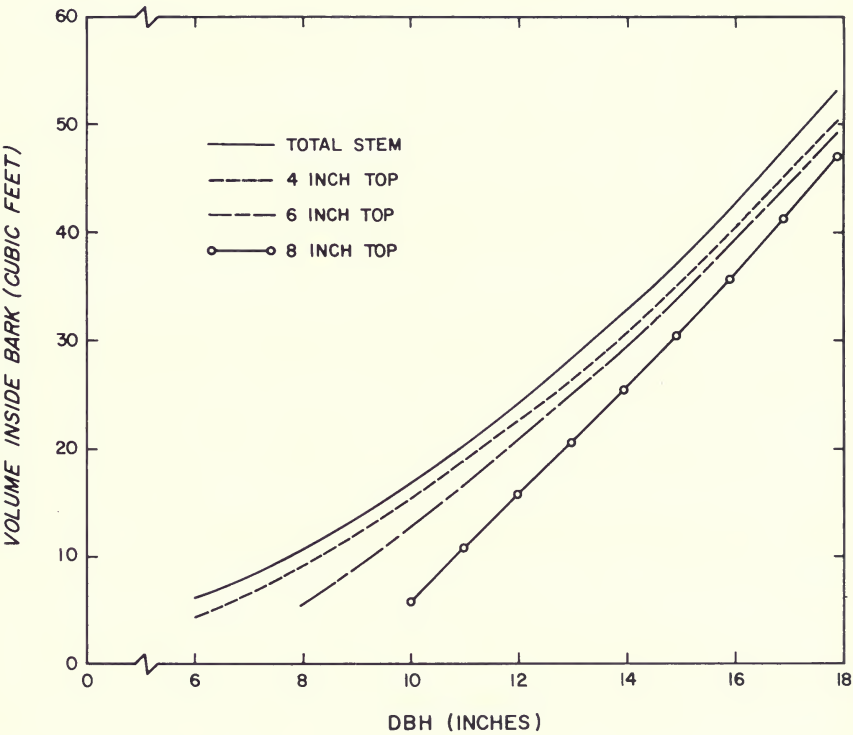


Figure 27-4.—The effect of merchantable top diameter, measured inside bark, on stemwood cubic volume per 80-foot-high oak tree. The data are based on upland oaks sampled in Ohio, Kentucky, Missouri, Indiana, and Illinois. (Drawing from Hilt 1980, p. 4.)

Table 16-30 lists another set of equations for predicting cubic volumes in yellow poplar trees. These are based on a sample of 39 trees 6 to 28 inches in dbh growing in natural, unevenaged mountain cove stands in western North Carolina. Table 27-66D displays data computed from these equations.

Volume tables for yellow-poplar are also published in Schnur (1937) based on 264 trees measured in Ohio and West Virginia, in McCarthy (1933) based on 512 trees measured in Pike County, Ohio, and Fairfax County, Virginia, and in Clark and Schroeder (1977) based on 39 trees measured in western North Carolina.

Sweetgum growing in 50 natural stands in Alabama were the basis for volume tables 27-54 and 27-55, which are derived from the following equations (Lyle 1973):

$$Vob = 0.00227205\ D^2H \qquad R^2 = 0.997 \qquad Sy.x = 0.8239 \qquad (27\text{-}22)$$

$$Vib = 0.00228576\ D^2H - 0.03039457 \qquad R^2 = 0.996 \qquad Sy.x = 0.776 \qquad (27\text{-}23)$$

where

Vob = volume outside bark, cu ft
Vib = volume inside bark, cu ft
D = diameter at breast height, inches
H = total tree height, excluding 0.5 ft stump, feet

The cubic volume equations or tables most pertinent to hardwoods growing on pine sites are listed below by species.

Species and equations	Volume tables: Whole tree	Volume tables: Merchantable stem
	Table number	
Ash		
Equation 16-4 and table 16-13	—	—
Table 27-23		
Elm		
Equation 16-4 and table 16-13	—	—
Hickory		
Equation 16-6 (and species discussion	16-7	
in section 16-1)	27-56	27-56
Table 27-23		
Maple, red		
Equation 16-6 (and species discussion	16-7	
in section 16-1)	27-57	27-57
Equation 27-14		
Table 27-23		
Oak, black	27-58	27-58
Oak, chestnut		
Equation 16-6 (and species discussion	16-7	
in section 16-1)	27-59	27-59
Table 27-23		
Oak, red		
Equation 16-6 (and species discussion	16-7	
in section 16-1)	27-60	27-60
Equation 27-14		
Equation 27-15		
Equation 27-16		
Table 27-23		
Oak, northern red		
Table 27-23	16-19	16-19
Table 27-65A	27-66A	27-66A
Oak, scarlet		
Table 27-23	27-61	27-61
Table 27-65B	27-66B	27-66B
Oak, southern red		
Table 27-65C	16-7	
	27-66C	27-66C

Species and equations	Volume tables: Whole tree	Volume tables: Merchantable stem
	..........*Table number*..........	
Oak, white		
Equation 16-6 (and species discussion in section 16-1)	16-7	
Equation 27-14	27-62	27-62
Table 27-23		
Sweetgum		
Equation 16-4 and table 16-13	27-54	27-63
Equation 27-22	27-55	
Equation 27-23	27-63	
Table 27-23		
Yellow-poplar		
Equation 16-6 (and species discussion in section 16-1)	16-7	
Table 16-30	27-51	27-52
		27-53
Equations 27-17 through 27-21	27-64	27-64
Table 27-23	27-66D	27-66D

In addition, equation 16-2 relates dbh and height of the merchantable stem to the volume of bark-free stemwood in second-growth northern hardwoods in New York.

Since most pine-site hardwoods are small, studies of the cubic volume in small trees are of particular interest. Phillips and McClure (1976) found that understory hardwoods 1.0 to 4.9 inches in dbh averaged 1.03 to 1.40 cubic feet in total above-ground volume and 67 to 88 percent of that was in the stem (table 16-7). The seven species sampled were in the North Carolina mountains and the Georgia Piedmont.

In a study of hardwoods planted in an Arkansas small stream bottom, average stem volume outside bark at age 5 ranged from 0.2 cubic feet for the oaks to 0.7 cubic feet for sycamore (*Platanus occidentalis* L.). Intermediate values were 0.3 cubic feet for green ash and 0.4 cubic feet for sweetgum and yellow-poplar. Average dbh ranged from 1.7 to 3.1 inches (Krinard et al. 1979).

Cubic feet per acre.—For **mixed hardwoods** growing on a variety of sites, table 27-44 estimates cubic-foot volumes per acre for total above-ground biomass, for merchantable stems, for small trees, and for residues. Table 16-1 gives yields per acre for hardwood trees 1.0 inch dbh and larger on 4,014,566 acres of commercial forest land in the mountain region of North Carolina.

In **upland oak** forests, stand volume per acre and merchantable volume per acre are a function of both site index and stand age, as illustrated in figures 27-5 and 27-6. Yields for the entire stems and for the merchantable stems are listed in table 27-45.

In natural stands of **yellow-poplar,** total and merchantable cubic-foot yields increase with increasing age, site idex, and density level (fig. 27-7). The greater the number of trees, the larger the yield at all ages and all levels of site index (Beck and Della-Bianca 1970). Yields are presented in table 27-67 (total wood and bark from trees 4.5 inches in dbh and larger) and in tables 27-68 and 27-47 (wood only in merchantable stems).

Yields for **ash** and **hickory** stands are in tables 27-48 and 27-69.

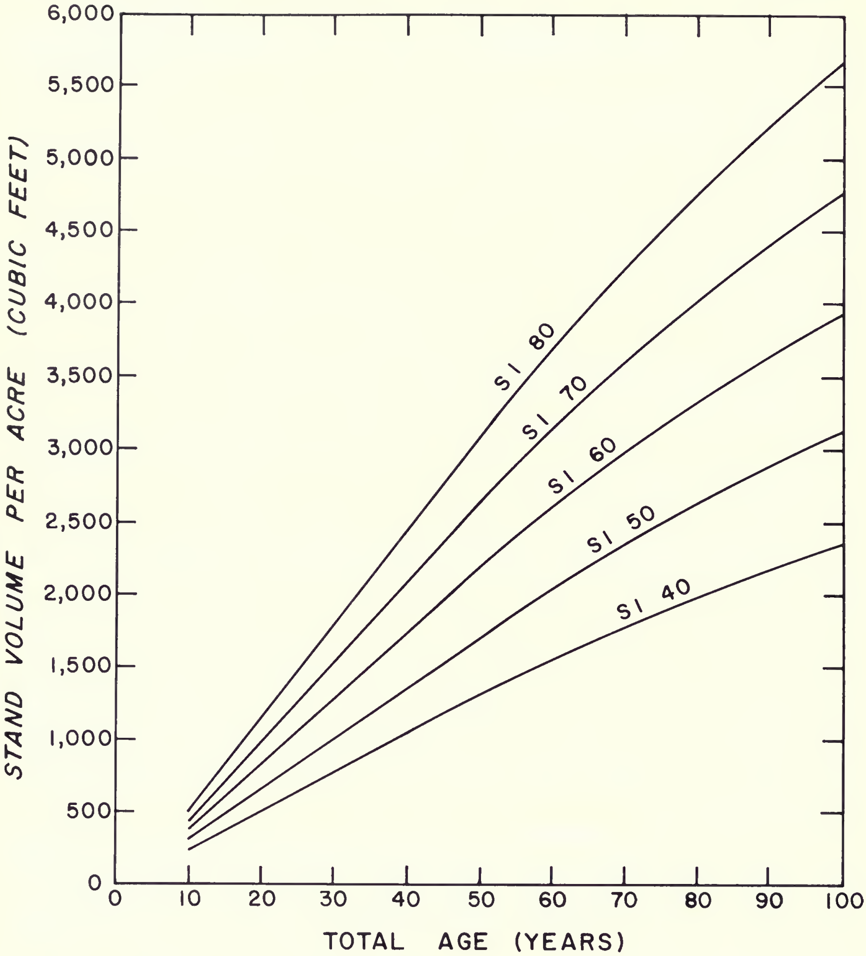


Figure 27-5.—Yield of wood in entire stems per fully stocked acre of upland oaks, in cubic feet excluding bark, showing trends with age and 50-year site index (SI). (Drawing after Schnur 1937.)

THE POUND

While the weight of a cubic foot of wood varies with its moisture content (sect. 8-1), ovendry extractive-free specific gravity (ch. 7), and extractive content (sec. 6-6), gross weight is for loggers and many wood users a convenient and equitable measure of value. Conversion of weights to a conventional volume measurement is difficult both because of this variation and because the irregularity of tree sections makes volume calculation difficult.

Weight of a standard rough cord.—Table 7-1 shows the weight of a cubic foot of wood as a function of specific gravity and moisture content. Table 8-2 gives an estimate of tree moisture contents by species, and tables 7-6 and 7-7 unextracted tree specific gravity by species. Table 7-2A gives the weight per cubic foot of green tree portions of five important southern oaks, sweetgum, and yellow-poplar in the Southeast; table 8-1A gives green moisture contents of these tree portions. With this knowledge, plus an estimate of the cubic foot content of solid wood (tables 27-1, 27-2; figs. 27-1, 27-2) and bark (table 27-3) in a cord, it should be possible to compute an approximate weight for cordwood of any species. The specific gravity of bark is given in chapter 13; some weights for standard rough cords of oak are computed in table 13-24.

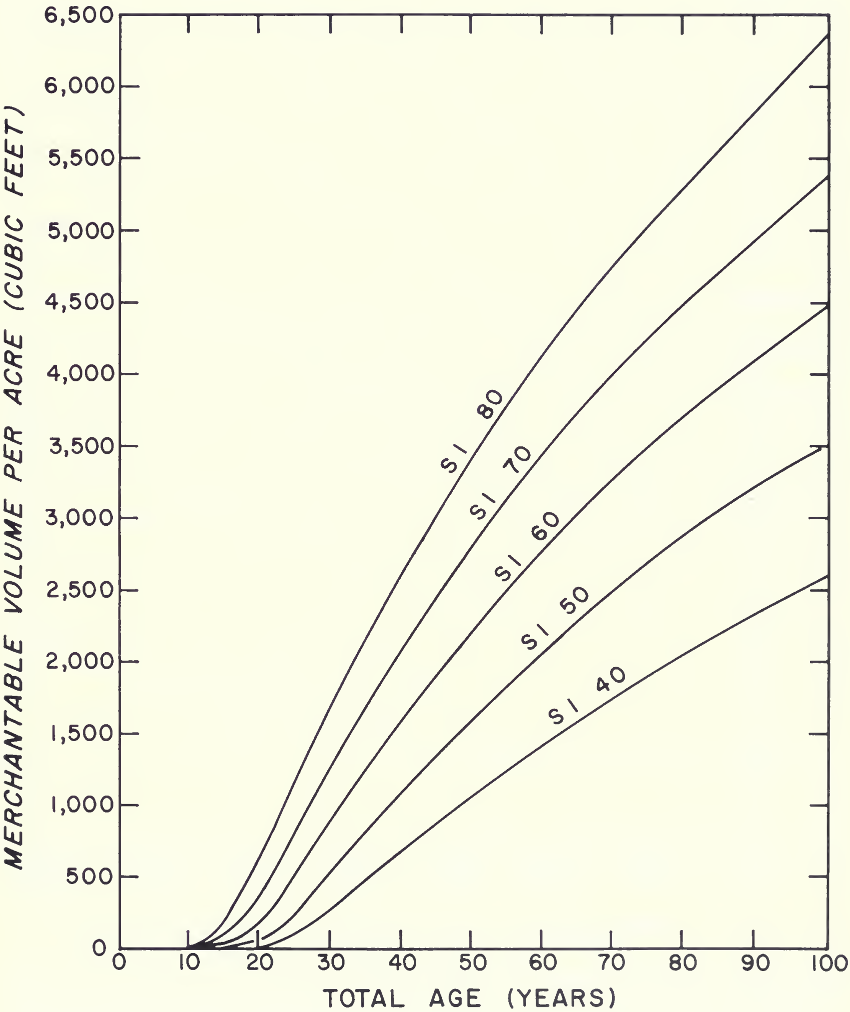


Figure 27-6.—Yield per acre fully stocked with upland oaks, in cubic feet of merchantable stem including bark (to a 4-inch top outside bark) showing trends with age by 50-year site index, SI. (Drawing after Schnur 1937.)

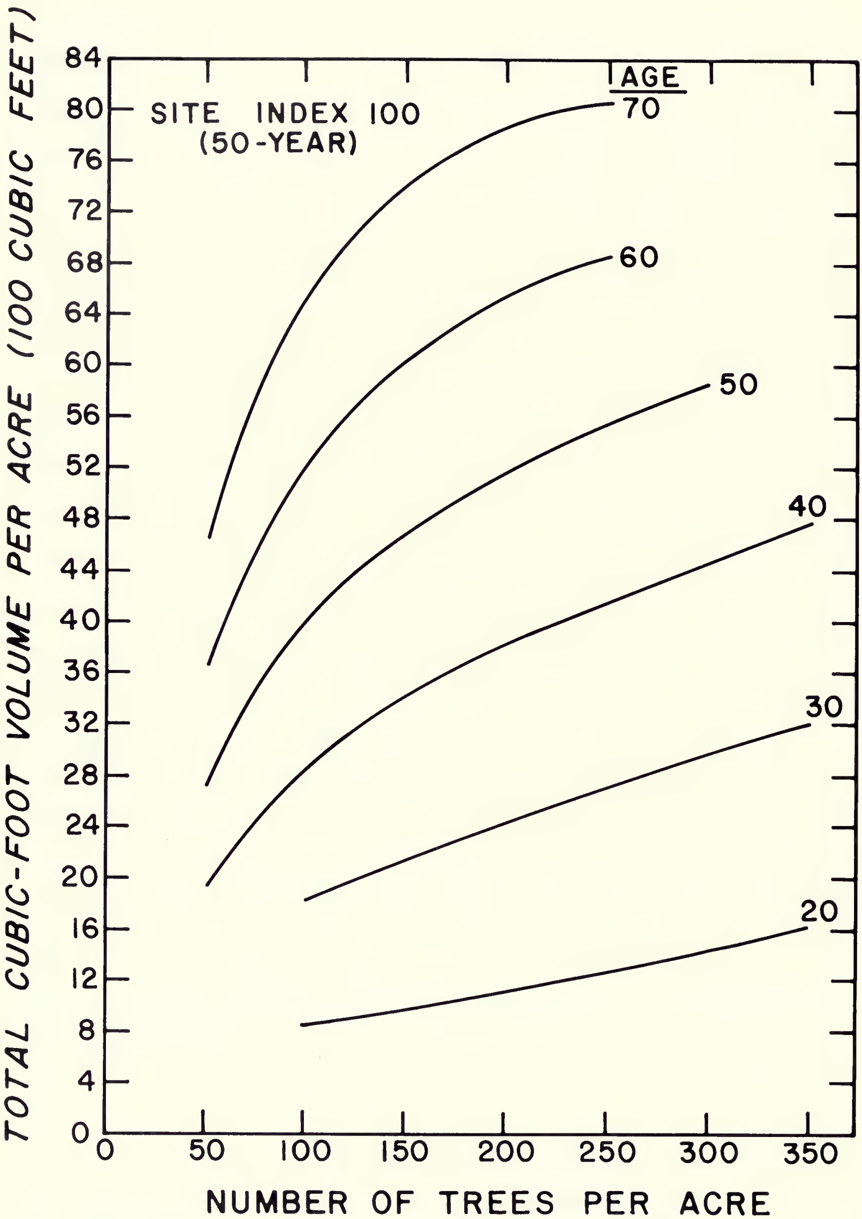


Figure 27-7.—In yellow-poplar stands, total cubic-foot volume of wood and bark per acre (in stems from 1-foot stump to apical tip) increases with number of trees. In older stands the rate of increase declines sharply after the first 100 trees per acre. (Drawing after Beck and Della-Bianca 1970.)

Wiant and Wingerd (1981) suggest an average weight of 5,809 pounds for a green cord of Appalachian hardwoods comprised of a typical species mix. Taras' (1956) average was very similar—5,758 pounds per cord—and was based on weights in use by various pulp companies throughout the Southeast.

Taras listed green cordwood weights for some individual species, three of which are commonly found on pine sites:

Species	Bark and wood	Wood free of bark	Bark
	Pounds/cord		
Sweetgum	5,670	4,880	790
Blackjack oak	5,760	4,700	1,060
Green ash	4,930	4,320	610

Based on the assumptions that a cord contains 80 cu ft of solid wood and that airdry wood contains 20 percent moisture content in terms of ovendry weight, Page and Wyman (1969) listed the following weights for airdry hardwoods:

Species	Pounds/bark-free cord
Ash	3,440
Elm, American	2,960
Hickory, shagbark	4,240
Maple, red	3,200
Oak, red	3,680
Oak, white	3,920

Weight of saw logs.—The weight of saw logs can be computed from general knowledge of unextracted specific gravity and moisture content together with bark volume and specific gravity as previously noted for cordwood. The variable form of logs makes such computations difficult, however. Schumacher (1946) was among the first to explore volume-weight ratios. Row and Guttenberg (1966) reviewed the effects of log taper, log shape, trim allowance, bark volume and specific gravity, and wood moisture content and specific gravity; they concluded that total log weight was best expressed by an equation of the following form:

$$W = a_1D^2L + a_2DL^2 + a_3L^3 \qquad (27\text{-}24)$$

where:

W = log weight, pounds
D = scaling diameter, inches
L = scaling length, feet
a_1, a_2, and a_3 = constants determined by regression analysis of weights of sample logs

Hardwood log weights determined by direct measurements (table 27-70 through 27-80) have been published by Massengale (1971), Timson (1972), Phillips (1975), and Clark (1976).

Weight of individual trees and parts.—Numerous studies have been made of whole-tree or merchantable stem weights. The most relevant ones are summarized below. Predicting equations and weight tables contained in this book are listed by species at the end of this subsection. In addition, section 16-1, DISTRIBUTION OF TREE BIOMASS, page 1428, contains information on whole-tree and stem weights, both in pounds and as a percentage of total tree biomass. For weights of **bark** see chapter 13, for **roots** chapter 14, and for **foliage** chapter 15.

The 22 hardwood species commonly found on southern pine sites show considerable variation in weight. When **trees 6 inches in dbh** were sampled (see tables 3-1 and 16-3 for dimensions), green weight of the above-ground tree parts (excluding foliage) ranged from 307 pounds for Shumard oak to 201 pounds for sugarberry; the average was 244 pounds (table 16-10). Dry weights ranged from 97 pounds for sweetgum to 185 pounds for Shumard oak and averaged 143 pounds. Complete-tree weights of 6-inch hardwoods (including stump and roots) are given in table 16-2

For **small understory hardwoods** (table 16-8) in the North Carolina mountains and the Georgia Piedmont, average whole-tree weight (ovendry) ranged from 28 pounds for sweetgum to 50 pounds for southern red oak (Phillips 1977). The average diameter of all trees examined was between 2.9 and 3.0 inches.

In a hardwood plantation established in an Arkansas small stream bottom, average whole-tree weight (ovendry) **at age 5** ranged from 15 pounds for water oak to 51 pounds for sycamore (Krinard et al. 1979). The average tree size by species ranged from 1.6 inches in dbh (cherrybark oak) to 3.1 inches in dbh (sycamore) and from 13.4 feet in height (Nuttall oak) to 20.5 feet (sycamore).

Equation 16-1 and the coefficients in table 16-6 can be used to estimate green or dry whole-tree weights of **small trees** in the following species and species groups: red oaks, white oaks, chestnut oak, black tupelo, red maple, yellow-poplar, hickories, hard hardwoods, and soft hardwoods. The equations were derived from measurement of trees 0.3 to 5.0 cm in dbh growing in natural, even-aged (2 and 6 years) stands in Tennessee (Hitchcock 1978).

The equation and coefficients in table 16-5 predict green and ovendry weights of complete trees, whole trees, and tree components of mockernut hickory, sweetgum, white oak, and southern red oak **3 to 12 inches in dbh** from natural lower Piedmont stands near Auburn, Ala.

A whole-tree weight table (table 16-9) and prediction equations for small **Appalachian hardwoods (1 to 10 inches in dbh)** were developed based on a sample of 200 trees of 17 species from a site in central West Virginia (Wartluft 1977). Average green weight of the trees (all material above a 6-inch stump) was 434 pounds, 80 percent of which was in material greater than 3 inches dob. The weighted average moisture content of the 200 trees was 69 percent, ovendry basis. The prediction equations are as follows:

$$\mathrm{Ln(GWT)} = 1.54934 + 2.39376\ \mathrm{Ln(dbh)} \qquad R^2 = .97 \qquad (27\text{-}25)$$

$$\mathrm{Ln(OGWT)} = 0.95595 + 2.42640\ \mathrm{Ln(dbh)} \qquad R^2 = .97 \qquad (27\text{-}26)$$

$$\mathrm{PG} = 0.83059 - 14.57918 \times e^{-\mathrm{dbh}} \qquad (27\text{-}27)$$

where:

GWT = whole-tree green weight (pounds)
OGWT = whole-tree ovendry weight (pounds)
dbh = diameter breast height (1 inch $\leqslant$ dbh $\leqslant$ 10 inches)
Ln = natural logarithm function
PG = proportion of weight in material $>$ 3 inches dob.

Equation 27-27 is used for both green and ovendry weights.

Hughes (1978) sampled 248 trees in an **uneven-aged, pine-hardwood stand** in Caldwell Parish, La., and published equations for estimating the weight of the total tree (above ground portions), the merchantable stem (for sawtimber or for pulp timber), and of the top. The equations for hardwoods are as follows:

Mixed hardwood sawtimber biomass

$$(1.0242)L_nW_{t_{1\text{-}4}} = 1.9273L_n dbh + 0.3491L_nH_{m_{1\text{-}3}} + 1.4991L_nFQ + 1.8125 \quad R = 0.962 \tag{27-28}$$

$$(1.0106)L_nW_{t_{1\text{-}3}} = 2.0622L_n dbh + 0.8165L_nH_{m_{1\text{-}3}} + 1.3588L_nFQ - 0.5217 \quad R = 0.991 \tag{27-29}$$

$$(1.0000)L_nW_{t_5} = 4.0765L_n dbh - 0.7276L_nH_{m_{1\text{-}3}} + 1.7277L_nFQ - 1.4411 \quad R = 0.835 \tag{27-30}$$

Mixed hardwood pulp timber biomass

$$(1.0730)L_nW_{t_{1\text{-}4}} = 1.9580L_n dbh + 0.6584L_nH_{m_{1\text{-}4}} + 0.2801L_nFQ - 0.0439 \quad R = 0.986 \tag{27-31}$$

$$(1.0000)L_nW_{t_5} = 2.9422L_n dbh - 0.8213L_nH_{m_{1\text{-}4}} + 1.3122L_nFQ + 2.4291 \quad R = 0.907 \tag{27-32}$$

Premerchantable mixed hardwood biomass

$$W_{t_{1\text{-}5}} = 0.6506\ (dbh^2H_{t_{1\text{-}5}})\ 0.8415 \quad R = 0.980 \tag{27-33}$$

where:

$W_{t_{1\text{-}4}}$ = Weight in pounds of wood and bark to a 4.0-inch or merchantable pulpwood top outside bark (includes the topwood portion of the tree).

$W_{t_{1\text{-}3}}$ = Weight in pounds of wood and bark to an 8.0-inch or merchantable sawlog top outside bark for pine sawtimber, and 10.0-inch or merchantable top outside bark for hardwood sawtimber (does not include the topwood portion of the tree).

W_{t_4} = Weight in pounds of wood and bark of topwood portion of tree from upper sawlog merchantability to upper pulpwood merchantability (does not include limbs, tip, and foliage of tree)

W_{t_5} = Weight in pounds of unmerchantable top, limbs, and foliage (includes wood and bark on these components)

$W_{t_{1\text{-}5}}$ = Weight in pounds of entire above-ground biomass of tree.

dbh = Diameter breast height outside bark in inches.

H_m = total merchantable length for the respective product code, feet

$H_{m_{1\text{-}4}}$ = merchantable length to a 4.0-inch pulpwood top.

$H_{m_{1\text{-}3}}$ = merchantable length to an 8.0-inch or merchantable sawlog top for pine and 10.0-inch or merchantable sawlog top for hardwood.

H_t = Total height from 0.5-foot stump to terminal bud

$H_{t_{1\text{-}5}}$ = Total height of stem from 0.5-foot stump to terminal bud, for trees less than 3.6 inches in dbh

FQ = Form quotient (outside bark form class) or the ratio of diameter outside bark at 17 feet to dbh outside bark expressed as a decimal fraction

L_n = Natural logarithm

The term given in parentheses on the left side of each equation is the percentage correction factor for logarithmic transposal discrepancy.

Wiant et al. (1977) determined the weight of stemwood and branchwood of **West Virginia hardwoods to 16 inches in dbh,** including hickory, red maple, yellow-poplar, and five oak species (table 16-12, and 27-86 through 27-89).

Whole-tree weights of four **Mississippi hardwoods** are given by equation 16-4 with factors from table 16-13; species described are sugarberry, sweetgum, American elm, and green ash.

Ribe (1973) developed the following equation for predicting the dry weights of **red maple** stems, leaves, and branches:

$$\text{Log } 10 \text{ Y} = B_0 + B_1 (\text{Log } 10 \text{ x}) \qquad (27\text{-}34)$$

Coefficients for the respective components are as follows:

	B_0	B_1	R_2
Stem	2.8479	2.6522	9.9930
Leaves	2.1237	1.8015	0.8520
Branches	2.3088	1.9148	0.8960

The equation is based on 30 sample trees in the Northeast; weight tables were also generated. See species list in table 27-97 for additional information on red maple.

The Tennessee Valley Authority (1972) provided equations for **black oak** (table 27-81) and a weight table (table 16-14) for estimating the green or dry weights of the complete tree and various tree components. For 12-inch to 36-inch trees, dry weight ranged from 1,873 to 18,965 pounds for the complete tree (includes stump, roots, leaves) and from 811 to 8,158 pounds for the merchantable bole. See species list in table 27-97 for additional information on black oak.

Clark et al. 1980abc and Clark and Schroeder (1977) provided green and ovendry weights of whole trees and stem portions of **northern red oak** in western North Carolina, **scarlet oak** from the Tennessee Cumberland Plateau, **southern red oak** on the Highland Rim in Tennessee, and **yellow-poplar** from natural unevenaged mountain cove stands in western North Carolina (tables 27-82 through 27-85; tables 16-20 through 16-23 and 16-27).

For weight data on **mockernut hickory** and **white ash** see: Clark, Alexander, III, and W.H. McNab. 1982. Total tree weight tables for mockernut hickory and white ash in north Georgia. Ga. For. Res. Pap. 33. Macon, Ga.: Georgia Forestry Commission, Research Division.

For a **list by species** of chapter 16 and chapter 27 weight tables and prediction equations see table 27-97. Data on bark are in chapter 13, roots in chapter 14, and foliage in chapter 15.

Readers interested in eastern hardwoods should find useful the work of Young (1976) who summarized 62 biomass studies containing regression equations (and in many cases weight tables) relating physical dimensions of trees to the weight of various components, groups of components, or the complete tree. Young's summary includes weight data on root systems, as well as above-ground tree portions.

Pounds per acre.—Total above-ground biomass on **all commercial forest land** in the South varies considerably by state. McClure et al. (1981) found that the Southeastern average (Florida, Georgia, North Carolina, and Virginia) above-ground green weight of wood and bark in all live trees 1.0-inch dbh and larger (foliage-free) was 70.7 tons per acre, representing a very wide range. The average for Florida was 55.2 tons and that for Virginia 81.8 tons (table 27-98A). Three factors obviously influence the biomass on a forest acre—age, stocking, and productivity of the site. A newly established stand may contain no woody material in stems over 1 inch in diameter at breast height, while a mature hardwood sawtimber stand on a good site may contain over 250 green tons of biomass per acre. In Forida, where average biomass per acre is relatively low, more than half of the material is softwood. A large proportion of this softwood biomass is in pine plantations that are managed on short rotations. At the end of each rotation, biomass returns to near zero. In Virginia, on the other hand, more than three-fourths of the biomass is hardwood, and many of the hardwood stands are not managed for high timber production. Biomass has been allowed to accumulate in these stands for long periods, and it will continue to do so as long as hardwoods are underutilized (McClure et al. 1981).

For **mixed hardwood** stands on a variety of sites, table 27-44 provides estimates of the green and dry weight of (1) all live trees, (2) all trees between 3.5 and 5.5 inches in dbh, and (3) residues left after subtracting the board-foot component of the stand.

For evenaged, **upland oak** forests, the yield per acre of all trees and of all trees 5 inches or more in dbh has been tabulated for stand ages 10 to 100 years and for five site indexes (table 27-98). Wiant and Castaneda (1978) developed these preliminary tables by applying the species weight equations (Wiant et al. 1977) to Schnur's (1937) stand tables for fully stocked, evenaged second-growth upland oak forests. Wiant and Castaneda (1978) give tables for both green and dry weights, with and without bark; only the dry weight with bark is reproduced here. For bark weights, see chapter 13.

In a study of stands on various sites and containing species mixtures typical of **Appalachian mountain hardwoods,** Frederick et al. (1979) developed regression equations for predicting the weight yields of the total stand and of the merchantable boles. Merchantable basal area (BA) expressed as square feet per acre was found to be the most reliable variable for estimating total stand weight yields in tons per acre:

$$\text{Total green weight} = 9.34 + 1.22\,(\text{BA}) \qquad R^2 = 0.84 \qquad (27\text{-}35)$$

$$\text{Total dry weight} = 1.81 + 0.76\,(\text{BA}) \qquad R^2 = 0.81 \qquad (27\text{-}36)$$

Weight of merchantable boles in tons per acre to a 4-inch dob top was best related to the ratio between merchantable basal area (BA) in square feet per acre and number of merchantable trees (NM) per acre:

Green weight of merchantable boles =

$$-26.50 + 271.22\frac{\text{BA}}{\text{NM}} \qquad R^2 = 0.73 \qquad (27\text{-}37)$$

Dry weight of merchantable boles =

$$-20.83 + 167.59\frac{\text{BA}}{\text{NM}} \qquad R^2 = 0.71 \qquad (27\text{-}38)$$

In equations 27-37 and 27-38, variables obtained from a standard prism tally account for 73 and 71 percent of the variation in merchantable green and dry weights, respectively.

Another study in West Virginia (Wiant and Fountain 1980) showed that oak site index by itself is a poor predictor of the aboveground biomass. The study was established on the 8,000-acre West Virginia University Forest near Morgantown. This 46-year-old forest is evenaged, and approximately 62 percent of the forest area is in the upland oak type, dominated by white, chestnut, scarlet, northern red, or black oaks. The remainder is cove hardwood type, dominated by yellow-poplar, black cherry, and northern red oak. The estimated total dry-weight biomass averaged 78 tons per acre for the cove hardwood and 66 tons for the upland oak type; the difference was statistically significant. However, the average 50-year site index was also higher for the cove hardwood type (81) than for the upland oak type (66). When data for the two forest types were pooled and common regressions were computed for the components of biomass (table 27-99), the correlation coefficients were highly significant in most cases, but they were too low (0.30 to 0.50) for the regressions to have much predictive value. Oak site index by itself accounted for only about 25 percent of the variation in total tree biomass.

Density and bulk density.—The density of wood (lb/cu ft) is discussed in section 7-1. For the 22 hardwood species commonly found on pine sites, table 7-1 gives stemwood density values for a range of moisture contents and specific gravities. Density of freshly felled 6-inch trees with bark ranged from 50.7 pounds per cubic foot in green ash to 65.9 pounds per cubic foot in blackjack oak, as shown in table 7-2. Stem and branch densities (with and without bark) are also given in table 7-2.

Small understory hardwoods (average diameter 3.0 inches) in the Georgia Piedmont were more dense than comparable trees from the mountains of North Carolina (tables 7-3 and 16-7).

Trees 6 to 22 inches in dbh have green wood and bark bulk densities that vary with species and location in tree (table 7-2A). Freshly felled wood of chestnut, northern red, scarlet, southern red, and white oak is more dense than water; sweetgum wood, when green, has density about equal to that of water, and yellow-poplar wood has lower density than water. Green bark of these species in trees sizes 6 to 22 inches is less dense than water, as follows (table 7-2A):

Species	Whole-tree density	
	Wood	Bark
	----*Pounds/cu ft* ---	
Chestnut oak (North Carolina	65	53
Northern red oak (North Carolina)	65	62
Scarlet oak (Tennessee)	67	61
Southern red oak (Tennessee)	66	59
White oak (North Carolina)	65	54
Sweetgum (Georgia)	63	48
Yellow-poplar (North Carolina)	52	49

Bulk density of green wood varies with wood specific gravity and moisture content, and these vary within and among trees as detailed in chapters 7 and 8.

Clark et al. (1974) found that in mountain cove stands of North Carolina the density of **yellow-poplar** averaged 48.5 pounds/cu ft (table 27-100).

In an early study of **sweetgum,** Chittenden and Hatt (1905) reported that ovendry wood weighs about 30.2 pounds per cubic foot. Wood thoroughly airdried (i.e., containing 15 percent moisture) weighed about 32.4 pounds per cubic foot. And green wood from Hollywood, Alabama, weighed, on the average 49.2 pounds per cubic foot, with a range of 38.8 to 66 pounds per cubic foot.

As part of a biomass study in a **Louisiana pine-hardwood stand** (Hughes 1978), bulk density was determined for four classes of hardwood timber (table 27-101); in general, the tops of sawtimber trees were more dense than the sawlog portion.

Similar data for **sweetgum** and for chestnut, northern red, scarlet, southern red, and white **oaks from the Southeast** are given in the species descriptions of section 16-1, and for three of the oaks in table 13-23.

The density of **hardwood sawlogs** was investigated by Timson (1975). He reported that sawlogs harvested in western Virginia, West Virginia, and western Maryland had green weights per cubic foot ranging from 46 pounds for white ash to 59 pounds for true hickory, chestnut oak, northern red oak, and yellow-poplar (see section 7-1).

For data on bulk density of semi-manufactured products, see sections 13-6 and 16-3 as follows:

Product	Table
Bark residues	13-42 (and related discussion)
Whole-tree chips	16-44
Bark-free chips	16-44
Pulp chips and fibers	16-44A
Sawdust	16-44, 16-46
Planer shavings	16-44
Flakes	16-44
Branches	16-45
Logging residue chunks	16-45
Steel-strapped firewood	16-45

Weight of lumber.—Estimated lumber weights for all standard items are included in grade books for hardwoods, e.g., National Hardwood Lumber Association (1978). The tabulated values are not actual weights, however, but are used in computing delivered prices per Mbf of lumber in freight movements. Railroads base their transportation charges to the shipper on actual lumber weights, which are generally less than the estimated weights tabulated in grade books.

Accurate weights of Mbf lumber scale can be computed by multiplying the appropriate weight per cubic foot (from table 7-1) by the actual cubic foot content of 1,000 bd/ft of lumber.

In a North Carolina study of yellow-poplar sawtimber (Clark et al. 1974), lumber weight per green rough board foot averaged 4.6 pounds (table 27-100).

PRIMARY UNITS—A NEW MEASUREMENT CONCEPT

Access to electronic computers and dendrometers has enabled foresters to avoid many of the difficulties associated with traditional units of measure. Grosenbaugh (1954) found that the products derivable from trees or logs can be closely approximated in terms of aggregate weight and length. He proposed and developed computer programs (Grosenbaugh 1967ab, 1968), for systems in which felled or standing tree inventory data are sampled with varying probability and measured in terms of these primary units. Essentially, such timber estimates require physical or optical segmenting of tree stems into sections of irregular length but each reasonably homogeneous as to quality and defect, and the measurement, by calipers, diameter tape, or precision dendrometer, of sectional diameters and lengths. Volumes and surface areas, along with lengths, are computer-accumulated by species, quality, and defect classes.

Local product-yield studies can relate these aggregates of primary units to actual outturn and value for a specific operation, and can provide estimates of costs and residues at any desired stage of the manufacturing process. At the same time, estimates can be cheaply made in terms of traditional units for accounting or other purposes.

Although not yet widely employed, this concept could greatly improve the accuracy of product estimation wherever a wide range of size, defect, or value classes is involved.

BIOMASS INVENTORIES

As recently as 1975, whole-tree and complete-tree harvesting accounted for less than 0.1 percent of the total forest harvest worldwide (Keays 1975). However, the concept is rapidly becoming an economic necessity. As more complete utilization becomes widespread, forest inventories should be developed in terms of whole aboveground biomass and complete above- and below-ground biomass as well as in terms of conventional merchantable timber.

Traditionally Forest Survey inventories have not included total tree height, and this measurement is essential for calculating the volume or biomass of the complete tree. Thomas (1981) provided equations for estimating total tree height from data readily available in Forest Survey inventories. The equations, which are based on studies in Arkansas and are now being tested in other parts of the South, give more accurate estimates than those based on dbh alone ($R^2 = 0.85$ for these hardwood equations vs 0.74 for estimates by dbh alone). Since the equations are long and complex they are not reproduced here.

Studies on nearly 2.4 million acres of Maine forests indicated that if a biomass inventory is made in conjunction with a volume inventory, the combined inventory costs at most 5 percent more than a volume inventory alone but yields more than twice as much useful information (Young 1978a, p. 40). The additional field work simply involves measuring all trees in the 1-inch class and larger on a point sample and all woody shrubs and trees larger than 1 foot in height and less than 1 inch in diameter on a small sized plot of 1/1000 acre (Young 1978b, p. 25). A complete set of fresh and dry weight tables or regression equations for individual components, groups of components, and the complete tree or shrub is essential, but Young (1978b) points out that all the field and lab work for a single species' tables can be done by two men in 6 weeks or less.

CONVERSION TABLES

The foregoing paragraphs describe the content of logs and trees in terms of cords, board feet, cubic feet, and pounds. Since all of these units of measure are in widespread use, conversion data are useful; some tables for this purpose follow.

Cords to cubic feet.—Tables 13-21, 13-24, 27-1, and 27-22 provide data to convert cords to cubic feet.

Cords to board feet log scale.—Cordwood volume should not be expressed in terms of board foot log scale unless the cordwood is comprised of bolts large enough for lumber manufacture, i.e., more than 6 inches in diameter. According to the Service Foresters Handbook (U.S. Department of Agriculture, Forest Service 1970, p. 6), the following conversion factors permit cords to be approximately expressed in terms of board foot log scale.

	Cords per Mbf/log scale		
Tree dbh	Int'l ¼	Scribner	Doyle
Inches			
8	4.0	4.4	6.8
9	3.7	4.1	6.8
10	3.4	3.8	6.8
11	3.2	3.6	6.3
12	2.9	3.4	6.2
13	2.7	3.2	5.2
14	2.5	3.0	4.5

Worley (1958) computed cord-to-board-foot ratios by tree diameter, form class, and merchantable length, as scaled by three log rules (table 27-102). He chose form class 75 and 80 as typical of small hardwoods and gave separate values for short and tall trees because the upper portions of tall trees will yield fewer board feet per cubic foot than the lower or butt section of the tree. Thus, for 8-inch trees of form class 75, it takes 2.8 cords from tall trees to equal 1 Mbf International ¼-inch scale but only 2.6 cords from short trees.

Cord to board foot ratios can also be based on bolt diameter. For short bolts (26 to 72 inches long) of yellow-poplar, sweetgum, and oak, Redman (1957) found that the conversion factors ranged from 5.30 cords per 1 Mbf Doyle scale for 8-inch bolts to 2.14 cords per 1 Mbf for 18-inch bolts (fig. 27-8).

Barrett et al. (1941) tallied the board-foot content of long cords (160 ft^3) of peeled mixed oak (table 27-103). He noted that the ratio of cords to board feet varies with bolt diameter, length, and taper. For his table, average log taper was assumed, and bolts were 5 feet long; factors for obtaining the board-foot content for standard cords of 4-foot wood (rough or peeled) are given in table 27-103.

Cords to board feet lumber scale.—To make this conversion, it is first necessary to convert cord volume to cubic foot volume as previously explained.

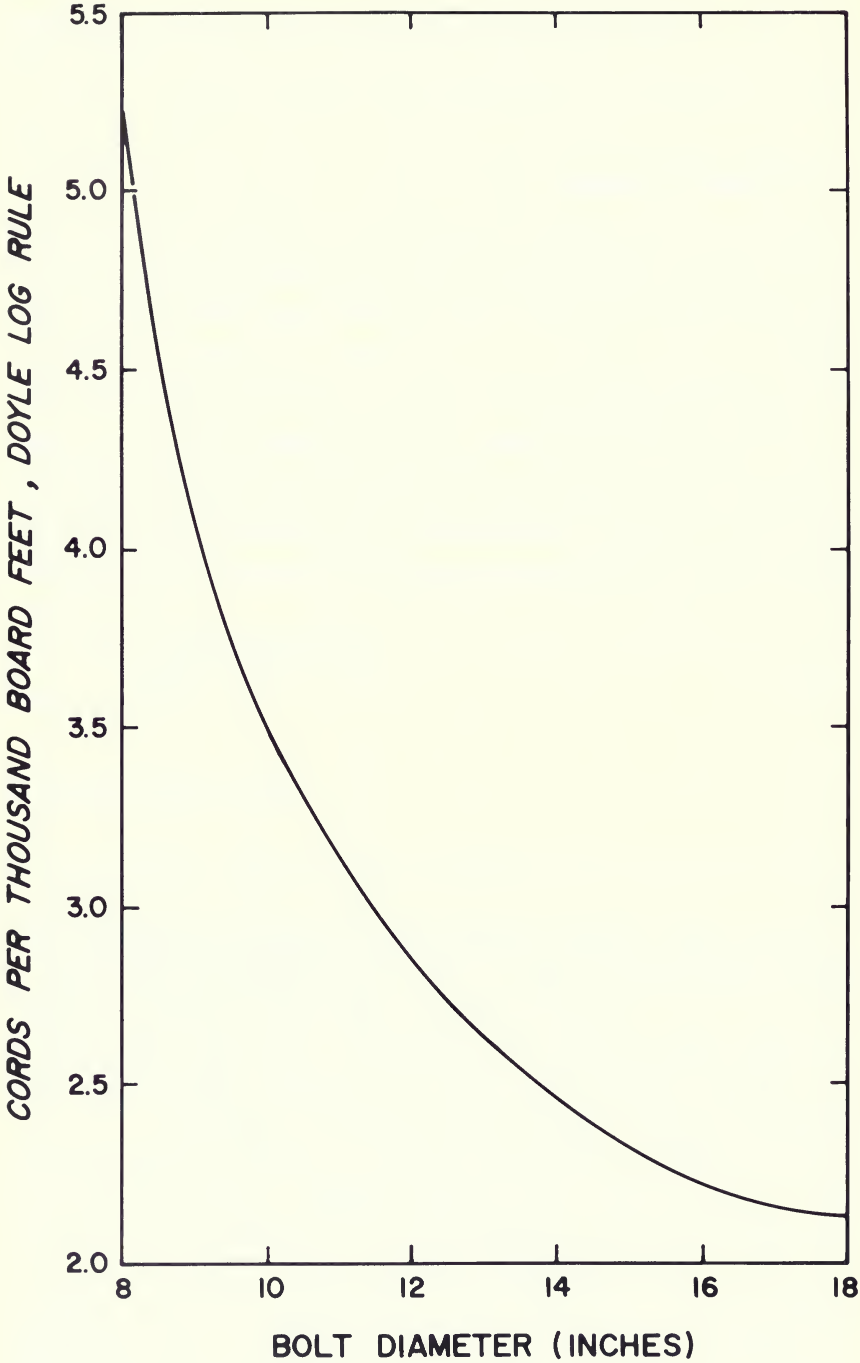


Figure 27-8.—Relationship of bolt diameter (inside bark at small end) to the number of standard rough cords required to scale one Mbf by the Doyle log rule. Bolts were oak sp., sweetgum, and yellow-poplar 26 to 72 inches in length. (Drawing after Redman 1957.)

Then, according to Bruce and Schumacher (1935, p. 160), 5 to 7 board feet can be cut from each cubic foot of cordwood; the ratio depends on the cordwood diameter as follows:

Diameter at small end	Board feet (International ¼ log scale) per cubic foot
Inches	
6	4.9
7	5.5
8	6.0
9	6.4
10	6.7

In many mills, lumber yield closely approaches International ¼-inch log scale.

Cords to weight.—The weight of a cord of hardwood pulpwood is discussed in a previous subsection, THE POUND.

Log volume in board feet by various log scales.—Log volumes in terms of one scale can be converted to another by use of previously tabulated board foot scales, values in table 27-104, and the following procedures by Lane and Schnur (1948).

To convert International volume to Doyle or Scribner, multiply the International volume by the percentage (from table 27-104) for the desired scale, log diameter, and length. Example: Given 1,000 bd ft, International volume, in 14-inch logs 12 feet long, what is the Doyle volume?

$$1{,}000\ (0.77) = 770 \text{ bd ft, Doyle volume}$$

To convert Doyle or Scribner volume to International, divide the Doyle or Scribner volume by the percentages for the given scale, log diameter, and length. Example: Given 1,000 bd ft, Doyle volume, in 16-inch logs 10-feet long, what is the International volume?

$$1{,}000 \div 0.83 = 1{,}205 \text{ bd ft International}$$

Doyle volume can be converted to Scribner, or vice versa, by first changing to International and then to the desired scale, using the above procedures.

Dollar values per unit volume in terms of one scale can be converted to another scale by substituting dollar values for log volumes in the above procedures and by dividing where multiplying is indicated and vice versa. Example: Given a number of logs 16 inches in diameter and 12 feet long, worth $100.00 per Mbf International scale, what is an equal value by the Doyle scale per Mbf?

$$\$100.00 \div 0.82 = \$121.95$$

Tree volume in board feet by various log scales.—Tree volumes in terms of one log scale can be converted to another log scale by application of the conversion factors given in table 27-105; since values shown are for southern pines, they must be used with caution on hardwood logs differing in taper from southern pine.

Board feet log scale to board feet lumber scale.—The amount of lumber actually sawn from a log in excess of the log scale is expressed as overrun.

$$\text{Percent overrun} = (100)\ \frac{\text{Bd ft lumber yield} - \text{Bd ft log scale}}{\text{Bd ft log scale}} \qquad (27\text{-}39)$$

Overrun is greatly influenced by width and thickness of the product, accuracy of manufacture, thickness of saw kerfs, and ability of the sawyers and edgermen. Log diameter, log length, and the log scale used can also affect overrun. For example, when 432 yellow-poplar logs were sawn at 34 circular mills scattered throughout the Tennessee River watershed, overrun averaged 19 feet per log by the Doyle rule and 2 feet per log by the Interntional ¼-inch rule (table 27-106). With the Doyle rule, board-foot overrun increased with increasing log diameter, especially between 5 and 15 inches dib, and with increasing log length from 8 to 16 feet. With the International rule, log diameter but not log length was significantly related to board-foot overrun. The International rule gave a close estimate of lumber tally for logs 5 to 14 inches in diameter.

In another study of yellow-poplar, two bandmills sawings factory grade logs produced an overrun of 6.8 percent by the International rule and 16.8 percent by the Scribner Decimal C rule (table 27-107). There was no clear correlation between overrun and log grade, but usually smaller logs showed a higher percent overrun than larger logs. The relationship of log diameter to percent overrun is shown in figure 27-9.

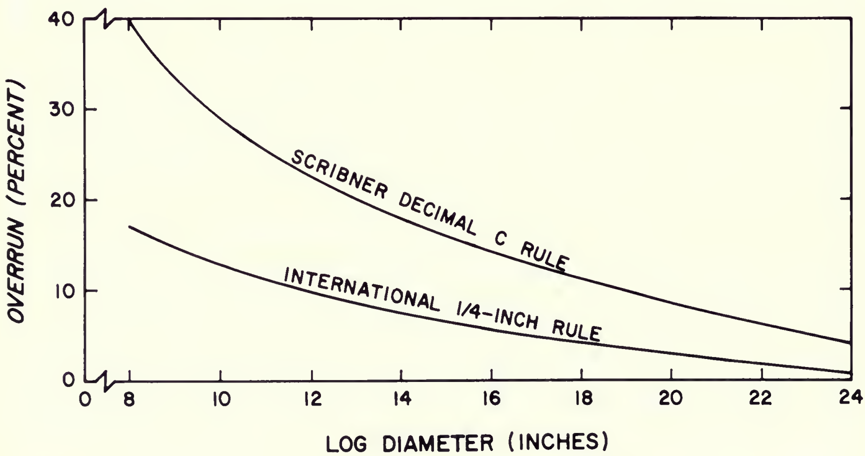


Figure 27-9.—Relationship of log diameter (inside bark at small end) to percent overrun in second-growth factory-grade yellow-poplar logs sawed in bandmills. (Drawing after Campbell 1959.)

Data on hickory (table 27-108) and hard maple (table 27-109) show similar trends: percent overrun is greatest with the Doyle rule, lowest with the International rule, and intermediate with the Scribner rule.

Another factor influencing overrun is type of sawing. Huyler (1974) found that live-sawing factory grade 3 northern red oak resulted in a 7.3 percent overrun based on the Scribner Decimal C log rule, compared to only 2.0 percent when grade-sawing (table 27-110). The greater overrun from live-sawing was attributed to two factors: (1) fewer saw cuts and therefore less volume lost to saw kerf, and (2) the log is turned only once so less volume is lost to slabbing. As diameter increased, live-sawing was progressively better than grade-sawing in terms of overrun (fig. 27-10).

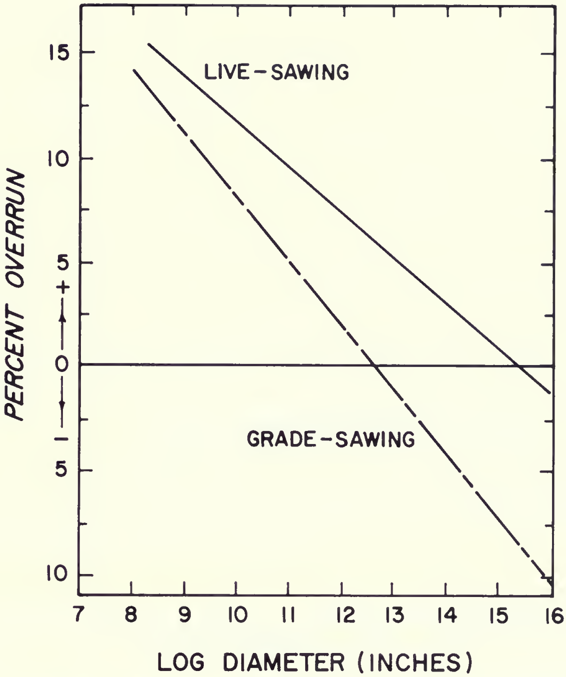


Figure 27-10.—Percent overrun for grade 3 northern red oak saw logs related to diameter at small end inside bark. (Drawing after Huyler 1974.)

A study of white oak sawn at seven mills in Arkansas, Tennessee, and Louisiana (Garver and Miller 1936) showed that quarter-sawing yielded about 12 percent less lumber per thousand board feet of logs than plain-sawing (table 27-111). One explanation was that quarter-sawn lumber is generally cut 1¼-inches thick to yield a finished 1-inch board but plain-sawn lumber is cut 1⅛-inches thick for the same 1-inch board.

Taper also has a marked effect on overrun. Board-foot log rules generally ignore differences in taper since only log length and small-end diameter are considered. Using a computer to simulate sawing for maximum yield from any specific log, Hallock et al. (1979) investigated the effect of taper on yield. Although he simulated softwood log breakdown, the trends he noted are pertinent to hardwoods too. In general, the greater the taper, the higher the overrun—the more lumber the sawmill operator will get for his log investment (fig. 27-11). The percentage increased yield due to taper is less pronounced in large-diameter logs than in small-diameter logs.

Board feet log scale to cubic feet.—Table 27-112 presents cubic foot volume per Mbf by log scale for 8- and 16-foot southern pine logs. The Doyle scale disregards taper, and requires more wood volume per Mbf for the longer logs.

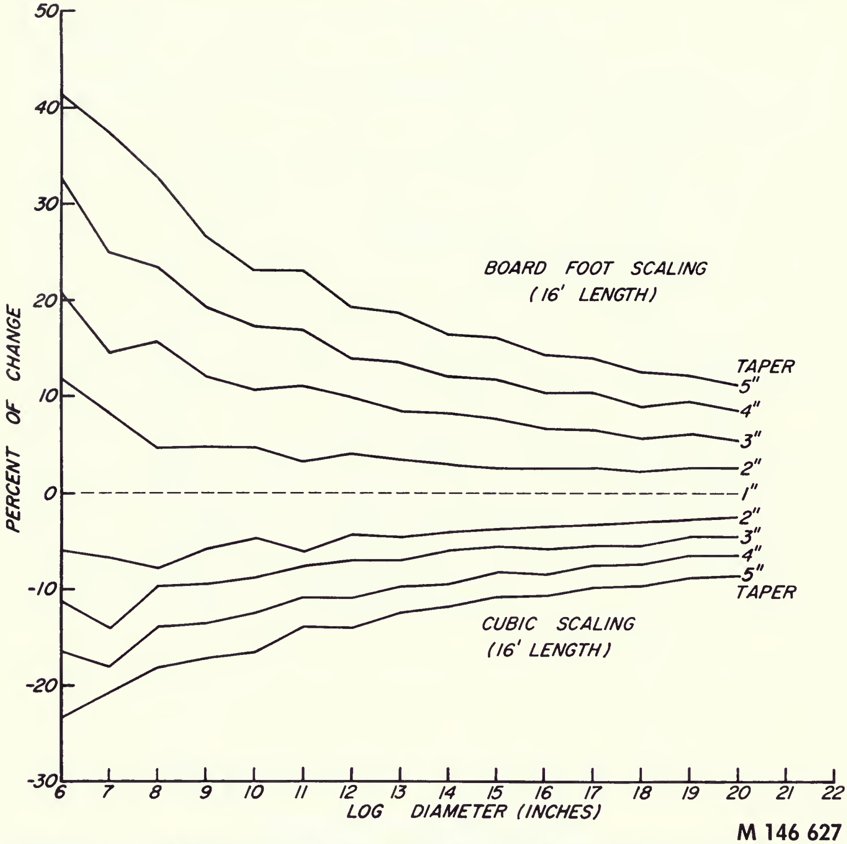


Figure 27-11.—The effect of log diameter on the absolute yield when logs are scaled by conventional board-foot log rules (above the "0" y axis) and on the lumber recovery factor (LRF) when the logs are cubically scaled for taper of 1 to 5 inches per 16 feet. All logs are 16 feet in length (Hallock et al. 1979).

Most pine-site hardwoods have more taper than the southern pines on which these tables were based; they therefore have more cubic foot content per Mbf log scale than indicated by table 27-112.

The first four columns of table 27-105 relate tree diameter to cubic foot content and board foot contents as measured by the three principal log scales.

For upland oaks, the ratio of board foot volume by log scales to entire stem cubic foot volume above stump (excluding bark) have been graphed by three investigators, as follows:

Reference and sample description	Basis	Log rule
Schnur (1937) Rangewide (404 plots)	Ratios for **stands** of upland oaks for given mean stand diameters	Scribner
Jokela and Lorenz (1957) Illinois; 738 trees 10 to 26 inches in dbh	"Local ratio table" for upland oak **trees** in the Sinnissippi National Forest; trees were relatively short	International ¼-inch
Hilt (1980) Kentucky, Missouri, Ohio, Indiana, and Illinois; 334 trees 2.4 to 25.5 inches in dbh	Based on taper equations for individual **trees** of various heights	International ¼-inch

Schnur's graph (fig. 27-12A) shows that entire bark-free stems in oak stands averaging 14 inches in dbh contained about 4.6 board feet, Scribner scale, per cubic foot.

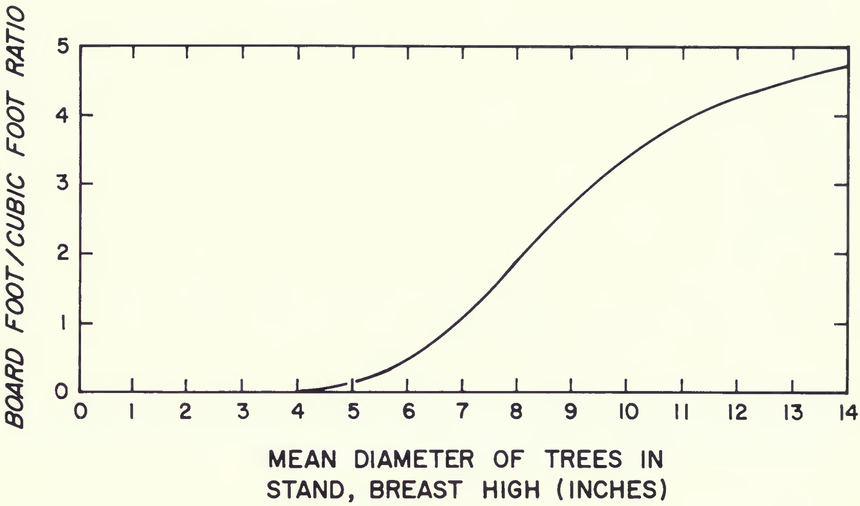


Figure 27-12A.—Ratio of board-foot volume by the Scribner log scale to cubic feet in entire bark-free stems above stump height in stands of upland oaks sampled rangewide. (Drawing after Schnur 1937.)

Jokela and Lorenz found (fig. 27-12B) that by International ¼-inch scale entire bark-free stems of 14-inch trees in the Sinnissippi National Forest contained about 3.4 board feet per cubic foot. The authors noted that the accuracy of the graphed averaged ratios is related to site conditions and their use results in overall board foot estimates 3 percent low for good sites, and 0.3 percent low for medium sites, and 4 percent high for poor sites.

Hilt's data (fig. 27-12C) on black, chestnut, northern red, scarlet, and white oaks indicate that entire bark-free stems of 14-inch trees sampled in five states contained about 4.6 board feet, International ¼-inch scale, per cubic foot.

Beck (1964) found that for yellow-poplar, the board-foot/cubic-foot ratio can be computed with the following equation (based on International ¼-inch log scale and cubic volume including bark):

$$\text{Bd ft/cu ft ratio} = 6.1670 + 8.4641\ D/H - 249.2550\ 1/H \qquad (27\text{-}40)$$

where:

D = diameter at breast height (inches)

H = total tree height (feet)

The equation and table 27-113 show that the ratio increases with an increase in both diameter and total height and that diameter has more effect on the ratio than

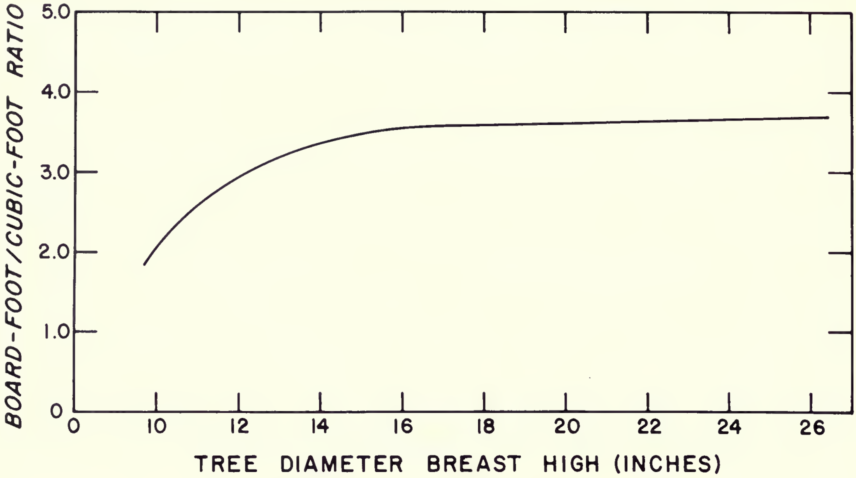


Figure 27-12B.—Ratio of board-foot volume by the International ¼-inch scale to cubic feet in entire bark-free stems of upland oak trees from the Sinnissippi National Forest in Illinois. (Drawing after Jokela and Lorenz 1957.)

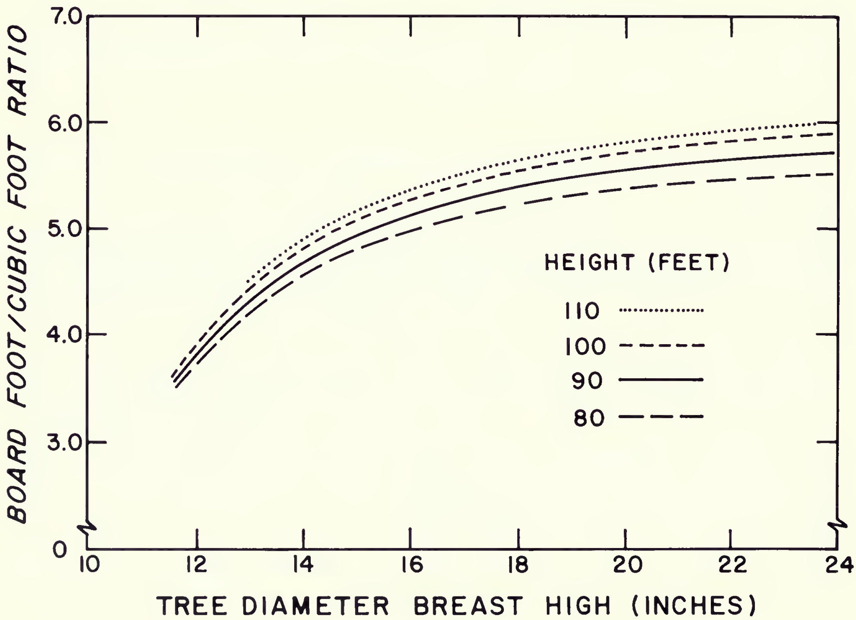


Figure 27-12C.—Ratio of board-foot volume by the International ¼-inch log scale to cubic feet in entire bark-free stems of upland oak trees sampled in Kentucky, Missouri, Ohio, Indiana, and Illinois. (Drawing after Hilt 1980.)

does height. Also, the larger the dbh, the less effect total height has on the ratio. Equation 27-40 and table 27-113 are based on 204 sample trees measured in the southern Appalachians; saw log utilization (and cubic volume computation) was from a stump height of 1 foot to a fixed top diameter limit of 8.0 inches outside bark (Beck 1964). In 14-inch trees, the ratio varied from 4.16 to 5.16 bd ft International ¼-inch scale, per cubic foot including bark.

Cubic feet to board feet lumber scale.—The number of cubic feet required to yield 1,000 bd ft of lumber varies widely; if pieces are sawn in large sizes from large logs and if saw kerf is small, fewer than 125 cu ft will yield 1,000 bd ft of timbers; if, however, 4/4 boards are innaccurately sawn from small logs with saws taking a large kerf, more than 250 cu ft of logs are required to yield 1,000 bd ft of lumber. Table 27-112 shows the cubic footage of southern pine wood required to yield 1,000 bd ft International ¼-inch log scale according to log diameter and length; these values could also be used for lumber, as the International ¼-inch log scale yields close to zero overrun on a mill equipped with bandsaws cutting boards to exact nominal thickness.

Lumber recovery factor (LRF) is the ratio of actual lumber volume produced to the cubic volume of the piece processed; it is expressed as board feet/cubic foot. In general, LRF is lower for hardwoods than for softwoods because hardwoods are sawn thicker than nominal thickness but softwoods are sawn thinner than nominal thickness. In addition, LRF varies with log size, product sizes, type and condition of mill, and method of processing. Larger logs and product sizes result in a larger LRF. Bandsaws, with smaller kerfs than circular saws, have a higher LRF. Sawing live usually produces a higher LRF than sawing around, and careful and accurate edging and trimming can increase lumber yield and LRF.

In a study of 10 New York mills sawing hard maple logs (Burry 1976), LRF averaged 6.7 for band mills and 6.4 for circle mills (table 27-109). The 1,030 sample logs averaged 13.4 inches in diameter and 11.5 inches in length.

Similarly, an average lumber recovery of 6.7 bd ft/cu ft was reported for yellow-poplar sawtimber trees bucked into 8- to 16-foot logs, debarked, and sawn into 4/4 lumber on a bandsaw in North Carolina (Clark et al. 1974). However, the LRF was shown to vary with tree size, ranging from 5.2 for 12-inch trees to 7.0 for 28-inch trees (table 27-100). LRF increased with tree size up to 20 inches in dbh and then remained relatively constant.

To determine the LRF for a specific small-log mill, Dobie and Warren (1974) suggest a sample size of 60 to 100 logs per 2-inch diameter class. The average LRF for a specific area can be obtained by weighting average LRF's of mills of a product type according to their contribution to the area's total output. Three or four mills of a product type should be an adequate sample.

Cubic feet to log weight.—Data are available on the cubic foot content of cordwood (tables 27-1 and 27-2), logs (tables 27-49 and 27-50), trees (tables 27-51 through 27-66D), and tops (table 16-31). Weight per cubic foot of green wood is extremely variable, however, because of variations in specific gravity (see ch. 7) and moisture content (see sect. 8-1). Table 7-1 relates green wood density to both specific gravity and moisture content. Tables 7-2, 7-2A, and 7-3 give weights per cubic foot of green wood of important classes of southern hardwoods.

A delay in bucking after the tree is felled with reduce tree moisture content, as will a delay in getting wood to the weight scaling station (page 2356 and figs. 20-15ABCD and 20-16). Also typically, wood moisture content is inversely core-lated with wood specific gravity (fig. 8-1).

To make a reasonable estimate of rough log weight based on cubic foot content of wood, one must first pick the appropriate volume inside bark from the tables, then multiply by an appropriate green density in pounds per cubic foot based on knowledge of the log source; to this product add an appropriate percentage (see sect. 13-3) to account for weight in the bark.

Log weight to board feet log scale.—Weights of single logs or whole truckloads can be accurately and quickly determined; less readily determined is the weight per Mbf log scale. This is so because of species and regional variability in wood moisture content and specific gravity, and also because cubic foot content per Mbf, the primary determinant of weight, varies with diameter and length of log, and with the various log scales.

Data specific to southern hardwoods are scarce but some information is available on northeastern hardwoods.

Nyland et al. (1972) give the following rule-of-thumb for estimating International ¼-inch log scale volume based on the weight of winter-cut tree-length logs: volume in board feet is about 8 percent of weight in pounds for pieces 1,000-1,500 pounds, about 9 percent of weight for pieces 1,500-2,500 pounds, and about 10 percent of weight for heavier logs. Their finding was based on a sample of 278 tree-length pieces of mixed northern hardwood species cut in New York.

Trimble (1965) objected to weight scaling hardwood saw logs because it would give equal value to all log grades. A realistic appraisal of value, he contended, must take into account species, log diameter, log grade, and volume.

Weight scaling.—Along with the shift to tree-length logging and hauling came the need for a means of estimating volume without first bucking the pieces into short logs for conventional scaling. Weight scaling proved fast and inexpensive. The easiest method is to apply a constant conversion factor (board feet/pound, for example) to the net truckload weight. However, constant factors fail to account for variation, among species, in average timber size among tracts, seasonal variation caused by shifting harvesting operations between dry and wet sites, or local utilization standards. Constant factors are even more inadequate if two or more products are contained on the same load.

Weight scaling is more reliable when the size of the pieces is taken into account. Nyland (1973) measured 190 sample truckloads in which sugar maple, red maple, beech, and yellow birch predominated. The difference between estimated and actual volume averaged about 1 percent in groups of loads from 15 different woodlots. The regression equations he developed are as follows:

$$\text{Doyle volume, board feet} = 0.08207(W) - 43.25815(N) + 465.711 \quad (27\text{-}41)$$

$$\text{International } \tfrac{1}{4}\text{-inch volume, board feet} = 0.09230(W) - 9.19587(N) + 420.158 \quad (27\text{-}42)$$

where:

W = weight of the load, pounds

N = number of pieces on the load, with logs less than 20 feet long counted as a half log

Adams (1976) proposed a method of weight scaling that would systematically adjust for changes in timber size and species composition in the truckloads of mixed hardwood saw logs delivered to a mill. The steps in his adjusting factor method are as follows:

1. Weigh and stick-scale (check-scale) the first 10 loads. Add the weights of the 10 loads; add the volumes of the 10 loads.
2. Divide total weight of the 10 loads by total volume of the 10 loads to get a weight/volume conversion factor.
3. As the next 20 loads come in, check-scale one load at random, and weigh-scale the other 19 using the conversion factor from step 2.
4. Add the newest check-scaled load to and delete the oldest check-scaled load from the 10-load tallies for weight and volume.
5. Return to step 2 to compute a new, adjusted conversion factor, and continue the process.

Any log rule can be used with the adjusting factor system, and a test of the method indicated that over a period of time the weight-scaled volume should average within 3.5 percent of the actual volume. The adjusting factor method, however, does not include a way of determining log quality; so mills that purchase logs by grade cannot use it.

Several studies have addressed the problem of scaling multiple products by weight. Guttenberg and Fasick (1973) developed a computer program for simultaneously estimating the saw log and pulpwood volumes on each truckload. Fasick et al. (1974) developed equations for predicting volume and weight of veneer logs, saw logs, and pulpwood based on net truckload weight and number of trees per load; their equations were based on 10 random samples of 200 loads each of tree-length southern pine. A manual that explains the computer programs available to produce multiproduct weight conversion tables from sample loads of tree-length material is available from the Southeastern Forest Experiment Station, Asheville, N.C. (Tyre et al. 1973)

Log weight to board feet lumber scale.—This conversion can be accomplished indirectly by first converting log weight to log scale as described in the foregoing paragraphs and then computing the overrun.

English units to metric units.—The American forestry industry has been gradually moving toward the adoption of standardized international units of measure. Table 27-154 gives metric equivalents for the most common units used in forestry. For ease in locating and using this table, it has been placed last among all the tables in chapter 27.

27-2 PRODUCT YIELDS AND MEASURES

Most wood products are sold by measures distinctive to the product. The paragraphs and tables in this section contain conversion information that has been found useful.

LUMBER

The subsection THE BOARD FOOT—LUMBER SCALE defines the unit of measure for lumber. Data on lumber yields, by volume, are given in this chapter in paragraphs headed *Cords to board feet lumber scale,* page 3279; *Board feet log scale to board feet lumber scale,* page 3281 (see also tables 27-106 through 27-111); figs. 27-9, 27-10); *Cubic feet to board feet lumber scale,* page 3287 (see tables 27-100, 27-109, 27-212); and *Log weight to board feet lumber scale,* page 3289.

Lumber and residue yields, in cubic feet, are listed in tables 18-57 through 18-62 for six species by tree diameter and merchantable height. Chapter 18 also discusses the effects of various sawing and machining practices on the amount of lumber recovered.

Lumber yields, by grade, from hardwood logs and trees are discussed in sections 12-7 and 12-8 (see tables 12-12 through 12-23, tables 12-26 through 12-31, and tables 12-34 through 12-40ABC). See also Forest Prod. J. 35(1): 26-32.

Volumes and value losses during lumber drying are covered in section 20-3 and tables 20-1 and 20-32.

The weight of 1,000 bd ft of lumber is discussed in this chapter under the paragraph heading *Weight of lumber,* page 3277.

Woodfin (1964) provided tables of lumber yield by grade from mill-run hardwood sawlogs when veneer grade logs are removed as opposed to when veneer grade logs are not taken out but are sawn for lumber.

VENEER AND PLYWOOD

Although plywood is manufactured in a variety of thicknesses from a range of thicknesses of veneer, the mensurational common denominator of the industry is 1,000 sq ft of 3/8-inch-thick plywood. Surface measure (square feet) of other thicknesses can be converted to 3/8-inch basis if multiplied by the following factors:

Panel thickness		
Not sanded	Sanded	Factor
----------*Inch*	---------	
5/16	1/4	0.8333
3/8		1.0000
7/16	3/8	1.1667
1/2		1.3333
9/16	1/2	1.0000
5/8		1.6667
11/16	5/8	1.8333
3/4		2.0000
13/16	3/4	2.1667

Because log scales have been devised primarily for logs in lengths different from the 53-inch and 103-inch lengths (termed bolts or blocks) common to the plywood industry, and because rotary-peeled veneer is cut without kerf and thin (compared to boards), the usual yield and overrun tables are not directly applicable for veneer yield computation.

Veneer yield by grade and width.—Current and proposed systems for grading hardwood veneer and veneer logs are discussed in sections 12-6 and 12-7 (see tables 12-3, 12-4) and in table 22-16. Yields of 1/6-inch, rotary-peeled veneer by grade and tree diameter (or block diameter) are given in tables 12-5 through 12-10. Figures 12-46 and 12-47 show the yield of 1/28-inch-thick veneer from three grades of yellow birch and sugar maple logs.

Rotary-peeled veneer is normally clipped to standard widths of 54 or 27 inches when possible; narrower veneer is clipped to random widths. **Fishtails** are pieces of veneer that are not constant width full length; they are either salvaged as 4-foot-long veneers for center plys or chipped for pulp.

Yield of veneer for ⅜-inch plywood per board foot log scale.—A mill-run sample of factory grade 3 Appalachian oak logs yielded 2.18 sq ft of ⅜-inch panel per board foot of log input, Doyle scale, or 1.50 sq ft of ⅜-inch panel per board foot of log input, International ¼-inch scale (Craft 1970, 1971). The 8-1/2foot bolts with an average small-end diameter of 11.7 inches totaled 3,567 bd ft Doyle scale, or 4,933 bd ft International scale. They were processed through a southern pine sheathing plywood plant.

According to a nomograph (fig. 18-256) for predicting veneer yield from 8-1/2-foot bolts of various diameters, 14-inch bolts produce 3.4 sq ft of ⅜-inch panel per board foot Doyle scale while 9-inch bolts produce 4.7 sq ft. Figure 18-256 also gives yield per cubic foot of log input and per cord of log input.

Theoretical veneer yield per bolt.—If bolts were perfect cylinders, the lineal footage of veneer produced from each would be a function only of bolt and core diameters and veneer thicknesses (table 27-114).

Veneer recovery.—In general, veneer recovery is highest by rotary cutting, less by flat slicing, and least by quarter-slicing (see sect. 18-23 subsection VENEER YIELD). For crooked logs typical of pine-site hardwoods, yield can be increased by peeling 4-foot bolts rather than 8-foot bolts (fig. 18-255). When veneer-quality logs of northern red oak were sliced, 56.7 percent of the total log volume ended as dry veneer (fig. 18-257).

Volume in stacks of veneer.—Stacked veneer sometimes accumulates in mills and must be inventoried in terms of equivalent ⅜-inch plywood. According to one southern pine mill, a 103-inch-long stack of 54-inch-wide, 1/8- or 1/10-inch-thick dry veneer contains enough veneer per inch of stack height to make 55.9 sq ft of 3/8-inch plywood; a comparable figure for random-width dry veneers is 44.1.

At the same mill, stacked green veneers were equivalent to the following square footage of 3/8-inch plywood per inch of stack (Williams and Hopkins 1969, p. 60):

Veneer width	Veneer thickness in inches	
	1/10	1/8
Inches	---------*Square feet*---------	
54	56.9	58.5
27	56.9	58.5
Random	54.9	56.4
Fishtails	27.4	28.2

The foregoing conversion factors allow for normal losses during manufacture of southern pine plywood; losses during hardwood plywood manufacture would likely be greater.

Weight of hardwood plywood.—One of the drawbacks of hardwood plywood is that it weighs more than pine plywood. A thousand square feet of three-ply 3/8-inch-thick panel with oak faces and sweetgum or yellow-poplar core would weigh about 1,215 pounds at 8 percent moisture content. The same amount of loblolly pine plywood would weigh about 115 pounds less. However, a five-ply, ⅝-inch panel of this hardwood composition would weigh about the same as a comparable all-pine panel. For a tabulation of weights for various hardwood plywoods, see page 2695.

Additional information on veneers is contained in section 22-8 under subsection VENEER CONTAINERS, in section 22-9 DECORATIVE VENEER AND PLYWOOD, and in section 22-10 under subsection STRUCTURAL PLYWOOD; pages 2647, 2649, and 2692.

DIMENSION STOCK AND FURNITURE

Clear lengths of hardwood lumber ranging from 13 to 100 inches in length are the basic raw material for furniture manufacture. However, most furniture parts are quite short. In a study of an entire year's production by a major manufacturer of a full line of furniture, the average cutting length required was only 31 inches (Bingham and Schroeder 1976). Thus, even small, low-quality hardwoods growing on pine sites may be a source of high-value furniture and dimension stock. See section 18-11, subsection LOG AND LUMBER LENGTHS, page 1954.

Use of hardwood dimension stock by the southern furniture industry is discussed in section 22-3, subsection DIMENSION STOCK. Grade specifications for this material are briefly discussed in subsection SAWBOLT GRADES of section 12-7, and in footnote 2 of table 27-115.

Hardwood blank standard sizes.—Recommended sizes for hardwood blanks for furniture manufacture are listed in table 27-115. These recommendations are the result of research conducted at Princeton, West Virginia, by the Northeastern Forest Experiment Station, USDA Forest Service.

Sawing pattern related to yield.—Sawing patterns and edging practices can substantially affect yields of furniture components. This topic is discussed at length in section 18-11, SAWMILL LAYOUTS FOR SHORT, SMALL, HARDWOOD LOGS, page 1954. One subsection in particular, BOLT SAWING PATTERNS, is recommended. Also section 18-12, RIPPING AND CROSSCUTTING LUMBER TO YIELD FURNITURE PARTS, page 1975, contains information on yield of cuttings. One additional study is summarized in the following paragraphs.

In a study with high-quality hard maple logs (*Acer saccharum* Marsh)., Neilson et al. (1970) found that both dollar value and surface area yield of furniture components were 15 percent greater with live sawing than with grade or taper sawing. Live sawing also resulted in a greater proportion of long, wide cuttings (fig. 27-13). Furthermore, unedged boards produced 4 percent greater

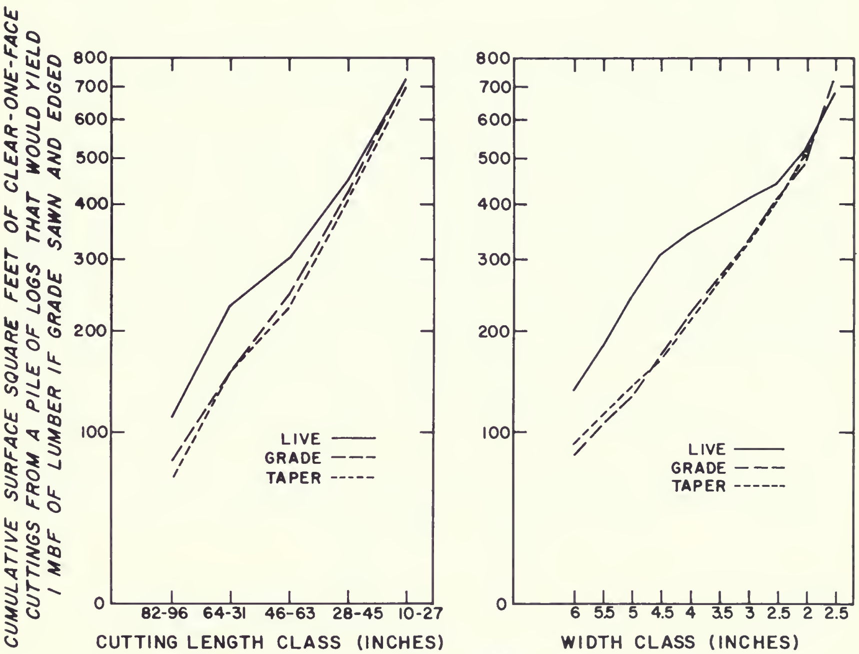


Figure 27-13.—Effect of sawing pattern on cutting length distribution (left) and cutting width distribution (right) from unedged hard maple boards of all grades. (Drawing after Neilson et al. 1970.)

value and surface area yield than conventional or NHLA optimum edging practices. The authors concluded that the combined use of live sawing and unedged boards results in a 20-percent greater value yield of hardwood dimension stock than grade sawing followed by optimum edging. However, live sawing resulted in more than three times as much surface area with edge-grain as was produced with grade or taper sawing. Sawing around the log also produced 27 percent more surface area in sap cuttings than did live sawing; with live sawing sap and mixed color cuttings were almost equal and accounted for about two-thirds of the total yield.

Yield of dimension stock from bolts and short lumber.—In general, the yield of furniture cuttings from short lumber ranges from 70 to 85 percent; the yield from comparable lumber of standard length runs 60 percent (Bingham and Schroeder 1977).

One reason for the greater yield from short bolts is that the effects of crook and taper can be minimized when tree stems or long logs are cut into short bolt lengths before processing. For example, in a study of red maple logs from Florida, Huffman (1973) found that 4-, 5-, and 6-foot bolts produced more lumber and furniture cuttings than standard-length logs (fig. 18-113). The overrun for green lumber tally was about twice as much with bolt sawing as with conventional sawing, and the bolts produced a 16 percent greater yield of furniture cuttings than the sawlogs (table 27-116). The small, low-grade logs showed the greatest increases in yield. Large logs showed less increase, but because of the greater volumes of wood involved in the larger logs, even a small percentage increase may be worthwhile.

In a North Carolina study, bolter sawing 4- to 6-foot red oak logs with a total volume of 2,560 bd ft (International ¼-inch rule) produced a lumber tally of 2,850 bd ft—a 13 percent overrun (North Carolina Forest Service, no date). Lumber graded No. 3A common and better comprised 51 percent of the board-foot-volume; the rest was No. 3B common suitable for pallet stock. The number of clear faces on the bolt was highly significant in determining the quality of the lumber sawn (table 27-117). Bolts with two or more clear faces produced 72.6 percent of the No. 1 common lumber and 40.6 percent of the No. 2 common lumber, the grades usually considered necessary for furniture dimension stock. Bolts with one or zero clear faces produced more No. 3B lumber than No. 3A. Yields of clear-two-face furniture cuttings were as high with this short lumber as with standard length lumber of the same grade. The yield from No. 3A lumber was 48 percent, suggesting that No. 3A short lumber could be used as well as No. 1C and No. 2C short lumber for furniture parts.

Equations 18-35, 18-36, and 18-37 will predict square-foot yields of clear-one-face cuttings from low-quality yellow-poplar bolts. Equations 18-38, 18-39, and 18-40 give similar information for red maple.

Yield tables based on the red maple equations are presented here as tables 27-118 and 27-119. They give the maximum yields of clear-one-face, flat dimension from small low-quality trees and bolts removed in a stand improvement cut of 18- to 44-year-old red maples in southern Illinois (Landt 1974). The dimension recovery factor (described by equation 18-39) ranged from 2.70 for trees 10 feet high and 6 inches dbh to 4.67 for trees 60 feet high and 15 inches dbh. In this study, the square-foot area of dimension was measured by diagramming various size cuttings (1 to 6 inches wide, 12 to 72 inches long) on each flitch. Ripping to a specific width and then crosscutting out the defects rather than cutting random width and lengths would reduce the yield.

Yields of clear-one-face cuttings from oak, sweetgum, and yellow-poplar bolts (table 18-64) increased with increasing bolt diameter and with increasing number of clear faces on the bolt (bolt grade). Rift-sawing yielded significantly more cuttings than a modified live-sawing technique.

The volume, in board feet, of clear-one-face and better furniture cuttings produced from three grades of white oak bolts is given in table 12-33. In terms of percent of total bolt volume, maximum yield was 76 percent obtained with 12- and 13-inch bolts 4 feet long.

In addition, nomographs have been developed to predict cutting yields from 2- to 7-foot-long bolts of yellow-poplar and red maple (based on first ripping, then crosscutting, then re-ripping if required) as follows:

Yellow-poplar
- clear-two-face .... fig. 18-126
- clear-one-face .... fig. 18-127
- sound character marked .... fig. 18-128

Red maple
- clear-two-face .... fig. 18-129

See page 1982 for directions on how to use the nomographs.

Yield of clear-two-face cuttings from standard grades of long lumber.—Hallock (1980) developed nomograms (figs. 27-14A through 27-18B) to determine furniture cutting yields from hardwood lumber of various grades when that lumber is initially processed by gang ripping rather than by the more conventional crosscutting. The first one of the nomogram pair for each lumber grade shows in percent of total lumber surface area the yield of specified length, clear, two-face cuttings when the lumber is gang ripped into 1-inch widths. The second nomogram of each pair shows how to adjust yield values for gang rip widths other than 1 inch. A rip width table (table 27-120) shows the gang rip width that promises the highest yield for each cutting length.

The following example illustrates how to use the nomograms.[4]

Assume a relatively simple cutting bill is to be cut from No. 1C lumber. The cutting sizes and required numbers arranged in descending order of length are:

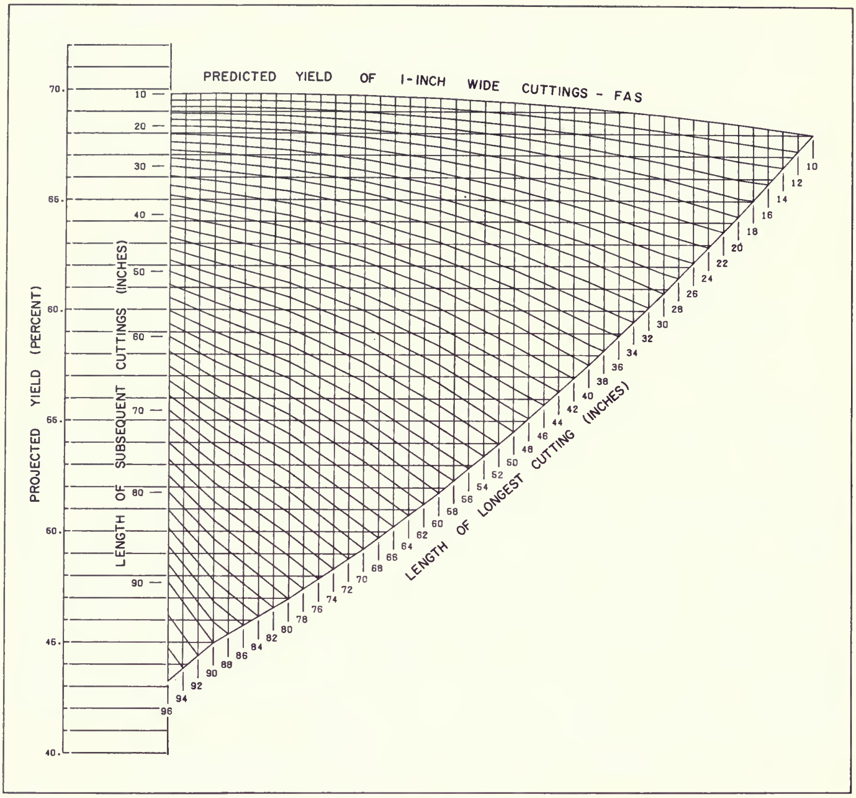
Length		Width	Number
-----*Inches*-----			
60	x	3.5	100
48	x	4.0	600
26	x	2.0	300
12	x	6.0	100

The longest cutting (60 inches) is known as the "primary" cutting and the other cuttings (48, 26, and 12 inches) as "subsequent" cuttings.

It is first necessary to refer to table 27-120 for the gang rip width which promises the highest yield for the primary (60-inch) cutting length from No. 1C lumber. Table 27-120 shows the 1.5-inch width to be best for all cutting lengths from 68 to 28 inches.

Use of a standardized data form similar to table 27-121 for recording observed and calculated values will greatly simplify the prediction computations. Consider first only that part of table 27-121 above the head "second calculation." Cutting sizes are entered sequentially with the longest first and the shortest last. The number of cuttings of each size is entered in the second column and total

[4]The example is reproduced from Hallock (1980).



M 148 576

Figure 27-14A.—FAS-predicted yield of 1-inch-wide cuttings when lumber is processed by gang ripping first. (Drawing after Hallock 1980.)

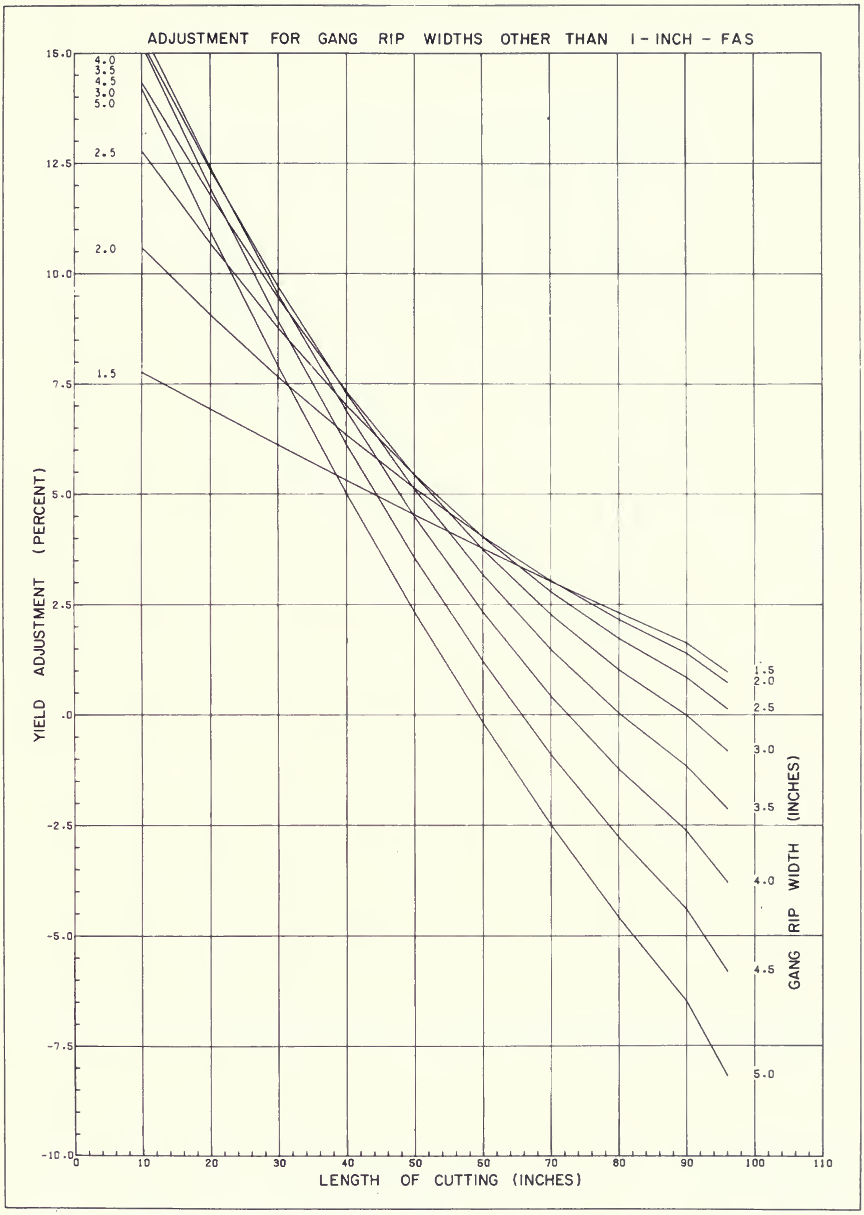
surface measure of each of the cuttings in column 3. The measure is calculated by multiplying the length and width in inches by the number of pieces and dividing by 144. For example,

$$\frac{60 \times 3.5 \times 100}{144} = 145.8$$

It is useful for the crosscut operation to know the actual number of ripped strip pieces of each given length that are required to yield the required cuttings of each length and width. Usually the rip width will differ from the cutting width so the number of pieces required will also differ. To calculate the number of pieces, the number of cuttings is multiplied by a factor obtained by dividing the cutting width by the rip width. For example:

$$\frac{3.5}{1.5} \times 100 = 233.3 \text{ pieces}$$

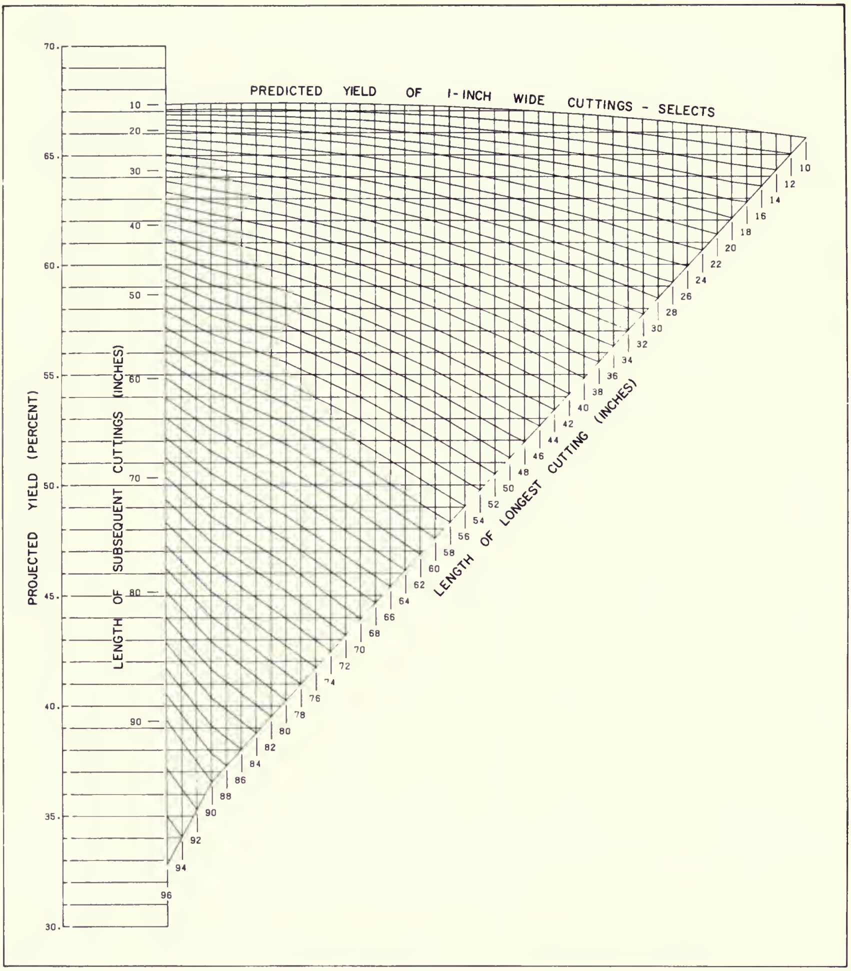
for the 60-inch cuttings. Since an extra piece is required to yield the 0.3, the actual requirement is 234 pieces.



M 148 577

Figure 27-14B.—FAS-yield adjustment for gang rip widths other than 1 inch. (Drawing after Hallock 1980.)

Now turn to the first of the nomogram pair for No. 1 Common lumber (fig. 27-16A). Begin by determining the yield for the longest cutting. Find the cutting length of 60 inches on the right-hand scale labeled "Length of Longest Cutting" and project this point horizontally to the far left scale labeled "Predicted Yield".



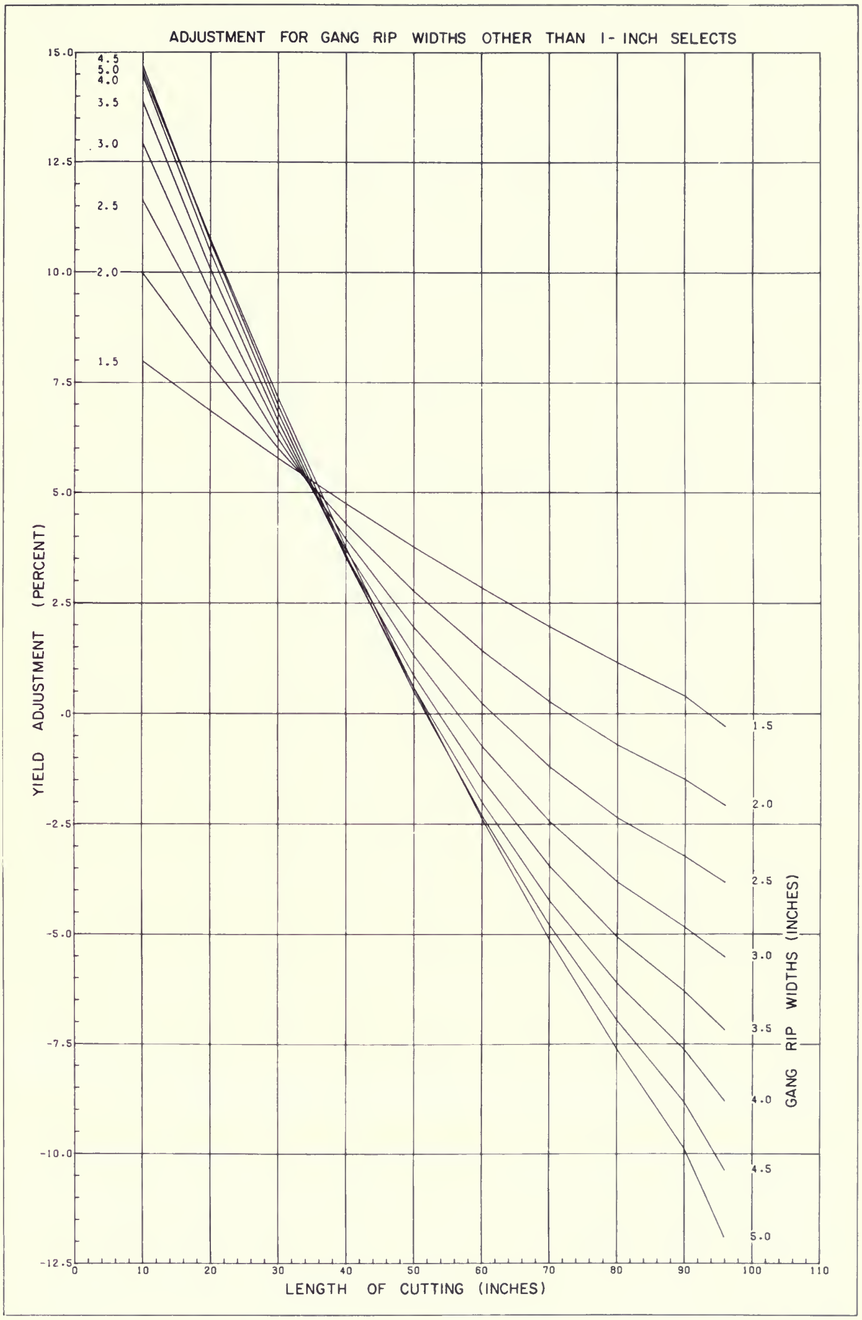
M 148 578

Figure 27-15A.—Selects—Predicted yield of 1-inch-wide cuttings when lumber is processed by gang ripping first. (Drawing after Hallock 1980.)

The indicated percent is 35.7. Now the yield for the next longest cutting will be predicted. This yield is determined by finding the intersection of a line projected vertically from the 60-inch primary cutting and the 48-inch "Length of Subsequent Cutting" curve. From this point, project a horizontal line to the far left scale. The percent yield is seen to be 45.0 percent. The other two subsequent length cuttings of 26 and 12 inches are determined in the same manner as the 48-inch cutting.

These yields will be found to be 57.4 percent and 61.8 percent, respectively. All values are entered in the calculation form, table 27-121.

The values shown on the nomogram are for a rip width of 1 inch. Rip widths other than 1 inch require adjustment by the use of the width adjustment nomogram (fig 27-16B). In this case, the rip width is 1.5 inches. Beginning with the



M 148 579

Figure 27-15B.—Selects—Yield adjustment for gang rip widths other than 1 inch. (Drawing after Hallock 1980.)

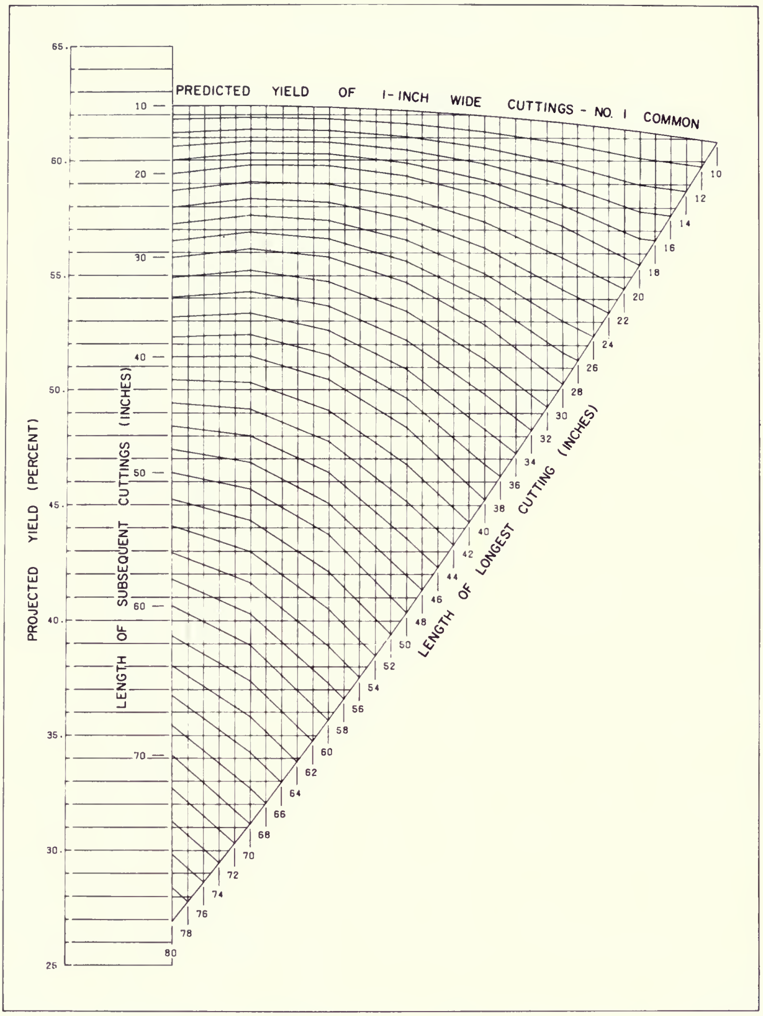


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Figure 27-16A.—No. 1 Common—Predicted yield of 1-inch-wide cuttings when lumber is processed by gang ripping first. (Drawing after Hallock 1980.)

longest cutting, locate the intersection of the 60-inch cutting length and the 1.5-inch rip width curve. Project this point horizontally to the left-hand scale labeled "Yield Adjustment" to obtain a value of +0.3 percent. Repeat this procedure for the 48-, 26-, and 12-inch cutting lengths. These yields are found to be +1.3 percent, +4.5 percent, and +7.5 percent, respectively. Enter all adjustment values in the calculation form, table 27-121. Adjusted yield values are now entered and are the sum for each cutting length of the basic value from the 1-inch nomogram and the width adjustment value.

The net yields for each cutting length can now be derived from the adjusted yield values. Since the values shown in the adjusted column are cumulative totals (the indicated length and all longer cuttings) the predicted yield for each

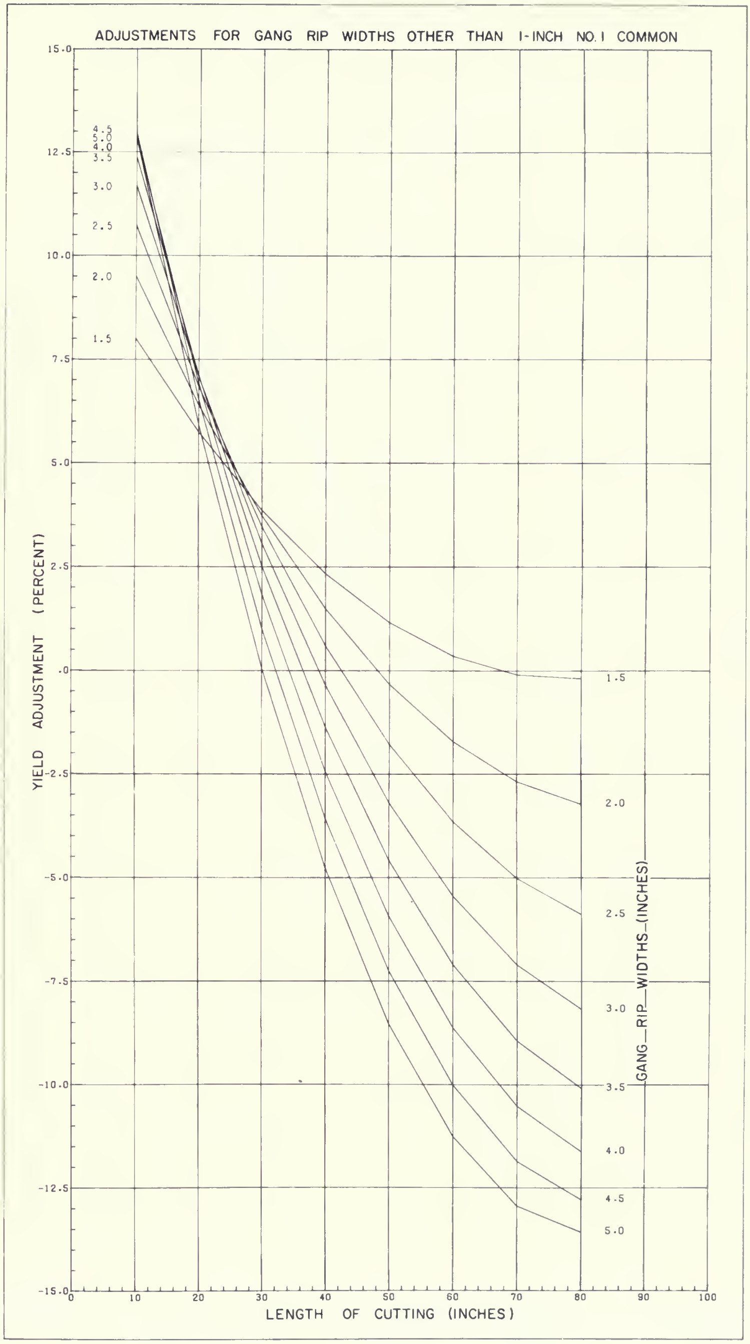

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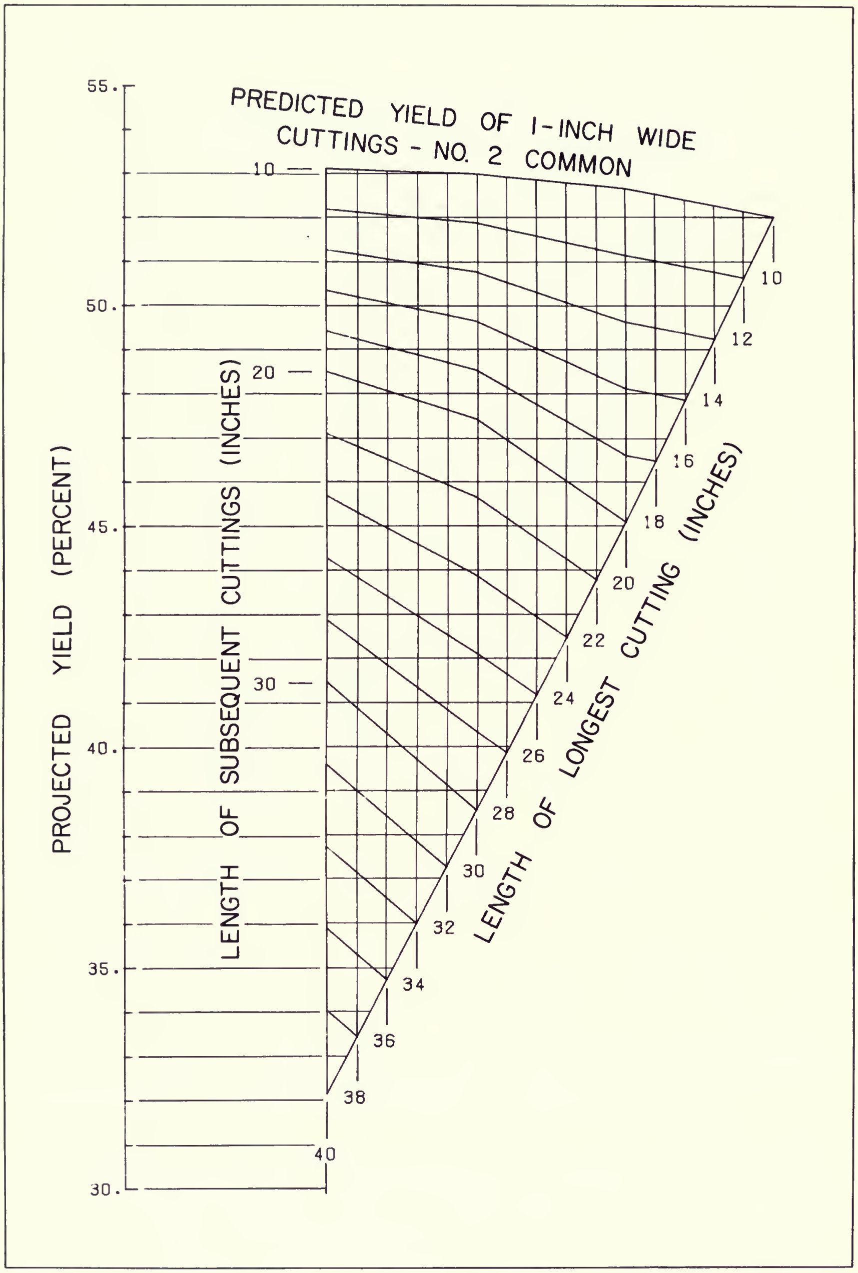
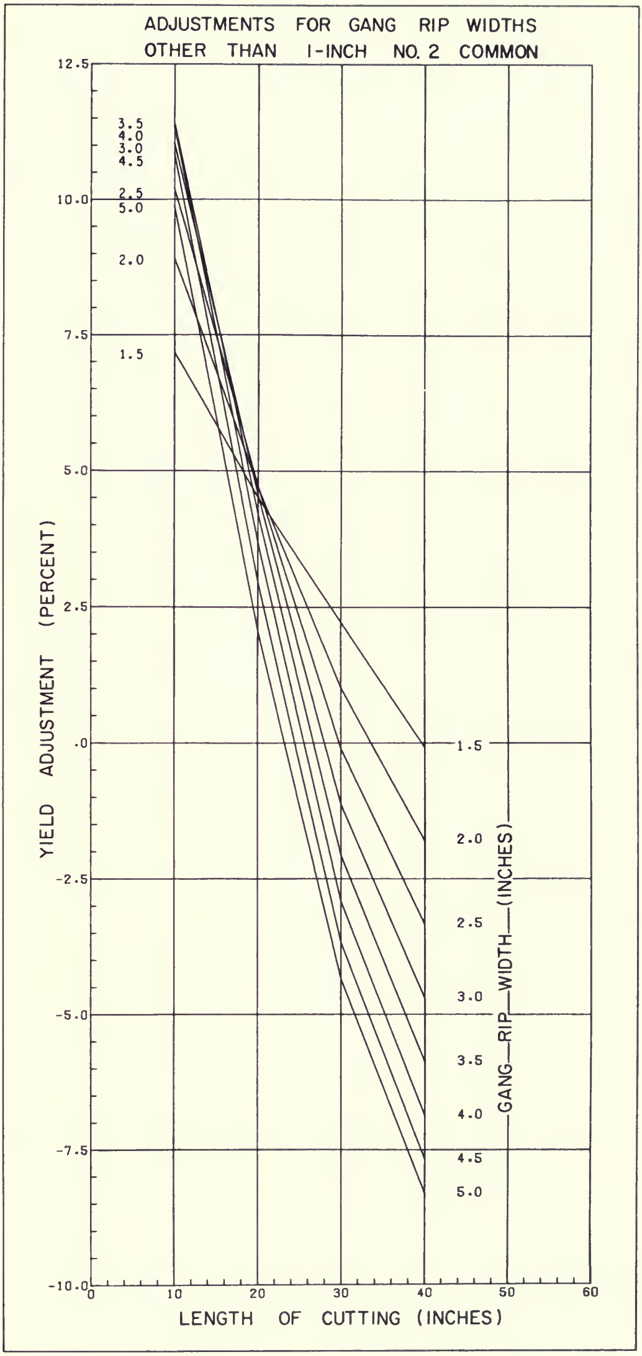
Figure 27-16B.—No. 1 Common—Yield adjustment for gang rip widths other than 1 inch. (Drawing after Hallock 1980.)



M 148 572

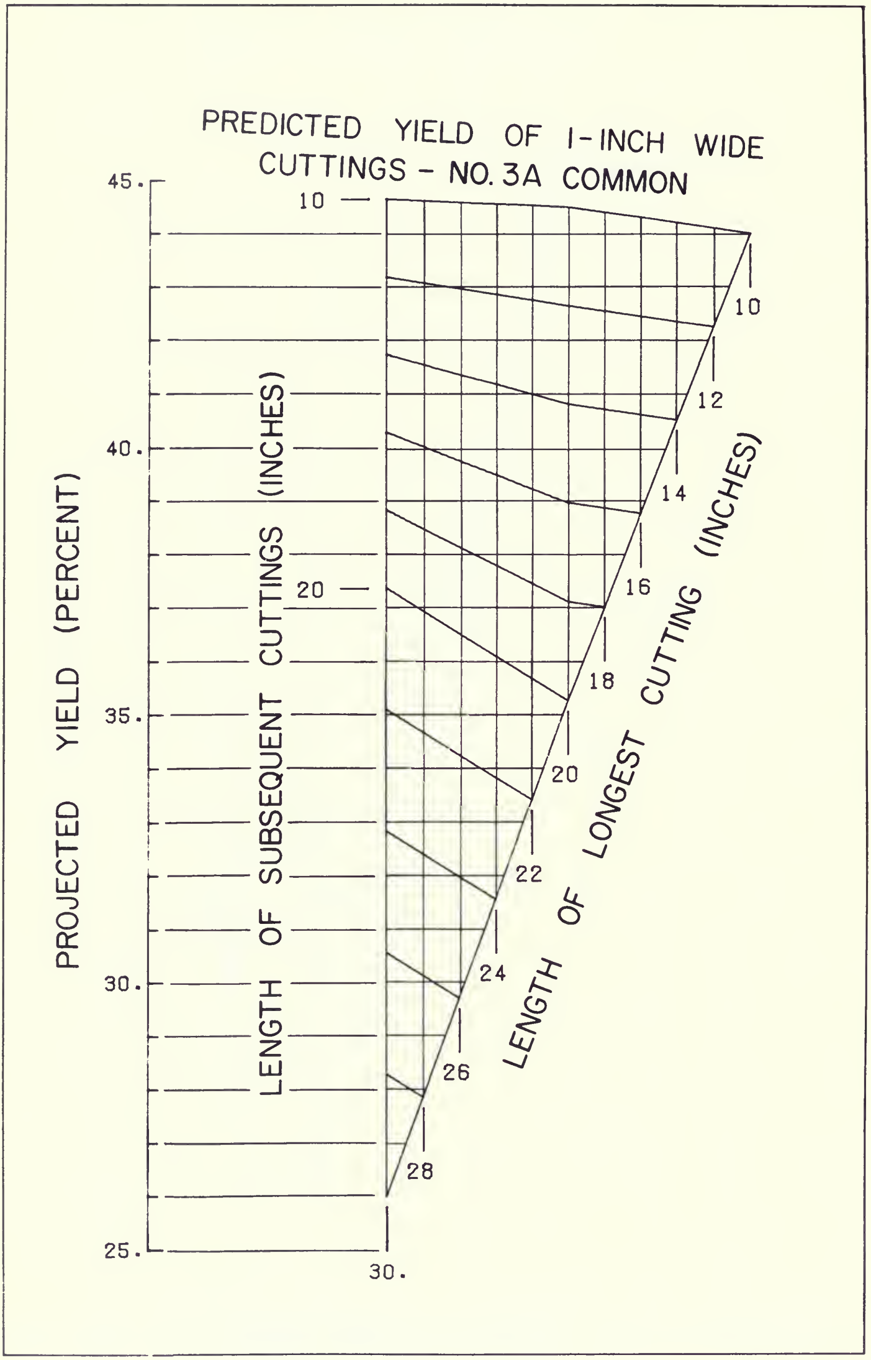
Figure 27-17A.—No. 2 Common—Predicted yield of 1-inch-wide cuttings when lumber is processed by gang ripping first. (Drawing after Hallock 1980.)

length other than the longest is obtained by subtraction. Thus, the 60-inch is 36 percent, the 48-inch is 10.3 percent (46.3 − 36.0), the 26-inch is 15.6 percent (61.9 − 46.3), and the 12-inch is 7.4 percent (69.3 − 61.9).



M 148 573

Figure 27-17B.—No. 2 Common—Yield adjustment for gang rip widths other than 1 inch. (Drawing after Hallock 1980.)



M 148 574

Figure 27-18A.—No. 3A Common—Predicted yield of 1-inch-wide cuttings when lumber is processed by gang ripping first. (Drawing after Hallock 1980.)

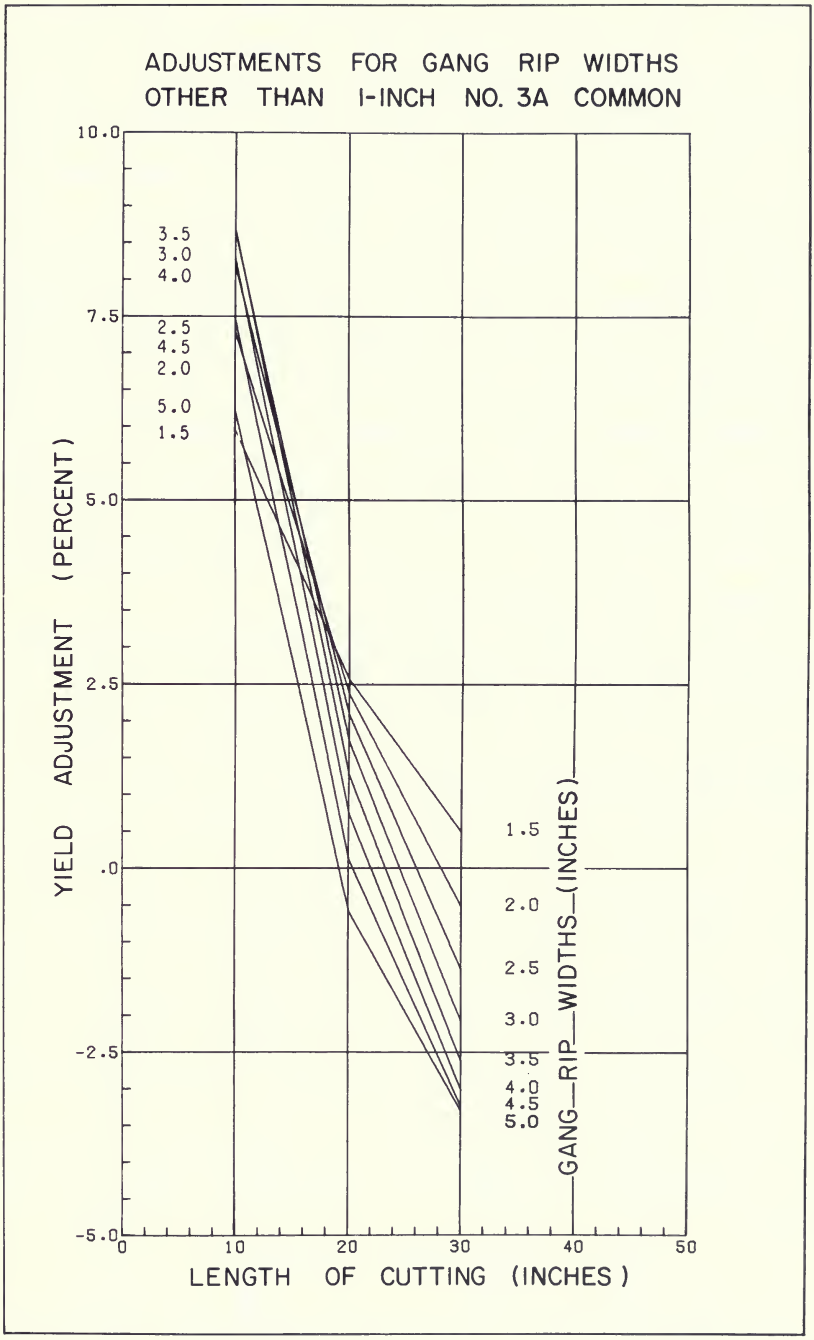


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Figure 27-18B.—No. 3A Common.—Yield adjustment for gang rip widths other than 1 inch. (Drawing after Hallock 1980.)

The next step is to determine how much lumber (No. 1 Common in this case) is required to produce the necessary ripped pieces for the longest cutting length. The 36 percent estimated yield is the same as 360 feet surface measure of cuttings from 1,000 feet surface measure of lumber. The required surface measure of 60-inch cuttings is 145.8 (column 3, table 27-121). When this figure is divided by 360 and multiplied by 1,000, 405 feet surface measure of lumber are found to be required to yield the 60-inch cuttings.

Yields for the other cutting lengths that will be developed in cutting 405 feet surface measure No. 1 Common lumber are next determined. Applying the percent values shown in column 8 to 1,000 feet surface measure indicates recoveries of 103, 156, and 74 feet surface measure for 48, 26, and 12-inch cutting lengths. Since only 405 feet surface measure are being cut, the predicted yields are found by dividing 405 by 1,000 and multiplying by the expected yield for 1,000 feet surface measure. Thus, the yield for 48 inches is 0.405 x 103 or 41.7 feet surface measure. The yields for all subsequent lengths are calculated and entered in column 10 of table 27-121. A summary of the cuttings still to be obtained is shown in column 11. All pieces required for the 60-inch length have been obtained so the balance is “0”. The balance for the other lengths is obtained by subtracting column 10 from column 3.

At this point the requirement for 60-inch cuttings has been met, and the requirements for the other subsequent cuttings have been met partially. A second calculation for the unfilled cutting requirements is initiated. It is nearly identical to the first calculation chart with respect to the determination of the values to be entered. Now the 48-inch cutting becomes the longest cutting and is used as the primary cutting length on the nomogram (fig. 27-16A). A new determination of the best rip width for the 48-inch length is made from table 27-120, and again, 1.5 inches is the best. No entries are needed in column 2. The figures in column 3 are the same as in column 11 in the first calculation chart. Figures in column 4 are determined by dividing the surface measure required from column 3 by the surface measure in one ripped piece. For example, with the 48-inch length the surface measure in one piece is 48 x 1.5 inches divided by 144, or 0.5. The required 758.3 feet surface measure divided by 0.5 equals 1,517 pieces, 48 x 1.5 inches, required. The values in column 5 are found from the nomogram (fig. 27-16A), using 48 inches as the primary cutting length in exactly the same manner as 60 inches was used in the first calculation.

Column 8 indicates an expected yield of 48-inch cuttings of 42.9 percent or 429 feet surface measure per 1,000 feet lumber surface measure. Since 758.3 feet surface measure are required, it is necessary to rip 1,768 feet surface measure

$$\frac{758.3}{429} \times 1{,}000 = 1{,}768$$

Using 1,768 feet surface measure as the new base, yields of 316.5 and 145.0 feet surface measure for 26-inch and 12-inch cuttings are available. Comparing these expected yields with the requirements in column 3 indicates they are more than met. In actual practice the crosscut saw operator would begin to develop cuttings for another cutting bill when he had 167 26-inch and 160 12-inch cuttings.

At this point all cutting requirements have been met. It is entirely possible with a longer and more complex cutting bill that more than the two calculation charts used in this example would be needed to fill all requirements. It is important to remember that, for each calculation chart, the longest remaining cutting becomes the primary cutting and that a best rip width for its length should be selected from table 27-120.

In this example a total of 2,173 feet (405 + 1,768) surface measure of No. 1 Common lumber would be required. However, 396.4 feet surface measure of cuttings (column 11, second calculation table 27-121, 271.4 + 125.0 = 396.4) would be either unused or used to develop short cuttings for another cutting bill.

Yield of dimension stock from flitches.—Flitches cut 1-½ or 2 inches thick from hardwood bolts are sometimes purchased by manufacturers of clear furniture squares and random-width stock. Yields of cuttings from such flitches can be predicted with the technique developed by Rast and Chebetar (1980). Basically, their procedure involves reducing the total possible yield (100 percent) by the percentage of defect, which is determined as follows:

1. Visualize a grid divided in thirds or in quarters superimposed over the flitch (fig. 27-19).
2. Select the grid in which the fewest compartments contain defects.
3. Deduct a percentage from total yield (100 percent) for the amount of defect (fig. 27-19). The minimum deduction for flitches divided into thirds is 15 percent; the minimum deduction for flitches divided into quarters is 10 percent.
4. If the defect deduction is 15 percent or less, deduct an additional 5 percent for cuttings and kerf. If the defect deduction is 20 percent or more, no additional deduction is needed.

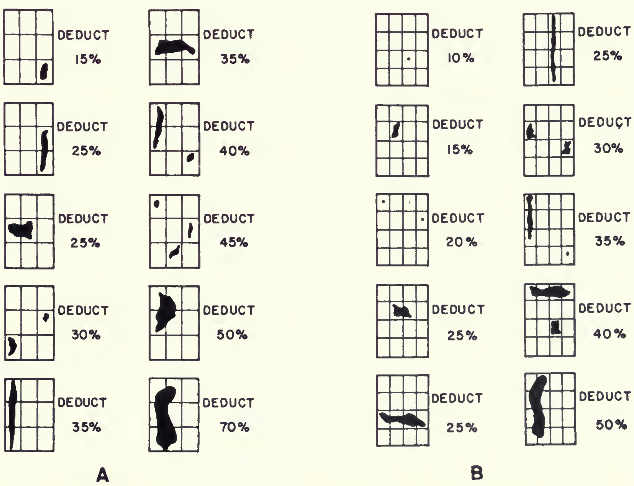


Figure 27-19.—Compartmentalization of defects in flitches by thirds (1/9 of area) or by quarters (1/16 of area), and percentage to deduct from total yield for various sized defects in flitches after compartmentalization by thirds (A) or by quarters (B). (Drawing after Rast and Chebator 1980.)

Two-ply cuttings.—With a laminated, 2-ply furniture cutting, defects on one face would not go through to the other face as they usually do in a conventional cutting (sect. 22-3, subsection LAMINATED LUMBER, page 2568). Losses from defects would be reduced and yields substantially increased (fig. 22-2).

Squares.—Anderson and Reynolds (1981) developed a computer program to determine the relationship between bolt diameter and yield of squares of various sizes. In developing the computer program they made two assumptions, which, while not true in actual sawing of bolts, clarify the relationship between the number of squares produced and the changes in square and bolt sizes. First, they assumed that the bolts were perfectly clear truncated cones, 4 feet long with a large-end diameter ½-inch larger than the small end. Second, they did not consider defects because their main interest was to find how many squares of a specific size could be obtained from a bolt with a given small-end diameter, considering bolt sawing patterns, cant sawing patterns, saw kerf, square size, and bolt diameter.

They also assumed that a turning square does not need four square corners, particularly if it is used to make a round. Thus, some wane was allowed. The wane was determined by calculating the size of a round that could be made from a given square. They calculated a width for each cant sawed from a bolt. Then they determined the maximum number of turning squares that could be sawed from the cant if some wane was allowed on the outside squares.

Two techniques for sawing bolts to squares were simulated: the boxed-pith method, in which a center cant containing the pith was sawed from the bolt, and the split-pith method, in which the bolt was sawed down the middle. In both cases, all of the bolts were sawed parallel to the pith. Outside slabs were resawed to cants if they were large enough to yield one or more squares. The simulation of sawing squares from cants was the same for both sawing methods. Squares were sawed from alternate sides of the cant and sawing was parallel to the bark. A tapered waste piece occurred in the inside of the cant. Square sizes were simulated in 0.5-inch increments from 3.0 to 6.0 inches. Saw kerfs were held constant for all runs with a headrig kerf allowance of 0.375 inch, a slab resaw kerf allowance of 0.3125 inch, and an edger kerf allowance of 0.1875 inch.

Seven different sizes of turning squares ranging from 3 to 6 inches in ½-inch increments were evaluated. Because the results were consistent throughout, they reported only on the 3- and 6-inch squares sizes since they represent the extremes tested. Data for each individual bolt diameter and square size are available from the Northeastern Forest Experiment Station, Forestry Sciences Laboratory, P.O. Box 152, Princeton, W. Va. 24740.

Neither sawing method was best for all sizes of squares or for all diameters of bolts. The total number and distribtuion of squares from each sawing method were not identical. However, they were too similar to show overall superiority of one method. Results are summarized as follows:

Bolt diameter class	Boxed pith: Number of squares	Boxed pith: Volumetric yield	Split pith: Number of squares	Split pith: Volumetric yield
Inches		*Percent*		*Percent*
3-INCH SQUARES				
6	1.4	40.2	0.4	11.5
7	2.0	42.8	2.0	42.8
8	2.0	33.2	3.8	63.0
9	2.2	29.1	4.0	52.9
10	4.8	51.7	4.6	49.6
11	7.0	62.7	6.0	53.7
12	7.6	57.5	6.0	45.4
13	10.0	64.7	7.8	50.4
14	10.0	56.0	12.0	67.2
15	11.6	56.7	13.4	65.5
16	13.2	56.9	14.8	63.8
17	16.8	64.2	17.4	66.5
18	20.4	69.7	18.0	61.5
19	21.8	67.0	19.2	59.0
20	24.4	67.8	25.0	69.4
21	26.2	66.1	27.4	69.1
22	28.4	65.4	30.4	70.0
23	31.4	66.2	34.0	71.7
24	37.6	72.9	35.2	68.2
6-INCH SQUARES				
6	0.6	69.0	0.0	00.0
7	1.0	85.7	0.0	00.0
8	1.0	66.0	0.0	00.0
9	1.0	52.9	0.0	00.0
10	1.0	43.1	0.0	00.0
11	1.0	35.8	0.0	00.0
12	1.4	42.3	0.4	12.1
13	2.0	51.7	2.0	51.7
14	2.0	44.8	2.0	44.8
15	2.0	39.1	3.4	66.5
16	2.0	34.4	4.0	68.9
17	2.0	30.6	4.0	61.2
18	2.2	30.1	4.0	54.7
19	4.6	56.5	4.0	49.2
20	5.8	64.4	5.2	57.8
21	7.0	70.7	6.0	60.6
22	7.0	64.5	6.0	55.2
23	7.0	59.0	6.0	50.6
24	8.6	66.7	6.0	46.5

PANELING AND FLOORING

Information on flooring yields is contained in section 22-3, subsection FLOORING, page 2571, and in figure 22-1.

Heebink and Compton (1966) provided data on paneling and flooring yields from small, low-grade (No. 3 or below) red oak logs. Logs were broken down at the headsaw to near the thickness of the finished product (7/16-inch). Yield from 12 logs (which totaled 350 bd ft Scribner Decimal C scale) was 406.20 sq ft of paneling and 63.40 sq ft of 8-½-inch flooring squares. Press-dried boards had a total yield of 60 percent of gross dry board weight (52 percent paneling, 8 percent flooring); kiln-dried boards had a total yield of 56 percent (48 percent paneling, 8 percent flooring). Changing the module length from 16 to 24 inches (so that end joints between panels would fall between studs) lowered total yield slightly. The authors suggested that using breakdown equipment with a smaller kerf (⅛-inch as opposed to 5/16-inch) would increase total yield 25 percent. Reducing the thickness of the finished product to ⅜-inch and using a saw with a kerf of 1/10-inch would raise yield another 14 percent.

HICKORY BOLTS FOR HANDLE STOCK

Hickory bolts generally 38 to 42 inches long and at least 7 inches in diameter are the traditional starting point for making handles. Yields of such bolts and additional sawlogs are shown by tree diameter in table 27-122.

Hickory bolts are commonly sold by the cord or by the board foot (Lehman 1958). One thousand board feet (Doyle scale) of 40-inch bolts yields about 650 forty-inch handle blanks and 250 fourteen- to twenty-inch blanks. The shorter blanks result from trimming for defects. A cord of hickory bolts yields about 275 long blanks, according to one company's records. For 40-inch bolts, a rick 4 feet high and 9-⅔ feet long constitutes a cord. For 38-inch bolts, the rick is 4 feet high and 10 feet long.

The number of handles that can be produced from hickory bolts of various diameters is listed in section 22-4.

Hickory is also purchased as split billets, which are usually 2 inches by 2 inches and come in six lengths (16, 18, 20, 26, 34, or 40 inches) and four grades (extra, 1, 2, and 3) (Lehman 1958).

For information on grades and specifications for hickory handle bolts, see section 22-4, figure 22-11, and tables 22-7, 22-8, and 22-9.

PALLETS

Size and performance standards for pallets are covered in section 22-7, subsection PALLET STANDARDS, page 2609.

Since most pallet parts are 30 to 48 inches in length and only a minor proportion exceed 72 inches in length, short bolts are suitable for pallet production. The SHOLO system for sawing 44- and 52-inch-long hardwood logs into pallet parts is discussed in section 18-11, subsection BOLT SAWING PATTERNS (page 1956), and illustrated in figures 18-114 and 18-115.

Lumber grades for deckboards and stringers are discussed in section 22-7. For quality distribution of hardwood pallet shook cut from three lumber grades by two cutting methods, see figure 22-33.

Weight of pallets made from pine-site hardwoods is also given in section 22-7; see page 2618.

Yield of pallet cants and lumber.—Craft and Emanuel (1981) processed hardwood sawbolts taken from poletimber thinnings from 36 sample plots of various timber types in West Virginia. They found that woods-run 4- and 6-foot long bolts from these thinnings were well suited for commercial pallet production. Bolts containing unsound heart defects and those containing sweep exceeding 1.5 inches should be eliminated. Resulting bolts (6- to 10-inches in scaling diameter) need not be segregated and should yield about 55 percent of cubic-foot volume in acceptable pallet cants and boards. When only 4- by 4- and 4- by 6-inch cants are produced (no side lumber), product yield is approximately 45 percent of the cubic foot volume. The quality of cants from such woods-run bolts is adequate for production of permanent or returnable warehouse pallets. Less than 3 percent of pallet parts produced were unusable.

Average yield per bolt, all species combined, of cants and side lumber varied with bolt diameter and length, as follows:

Diameter class	4-foot bolts	6-foot bolts
Inches	*Board feet*	
6	5.3	8.1
7	6.4	9.6
8	9.0	14.4
9	11.8	18.0
10	14.9	22.7

In this study, only 4-inch and wider lumber was tallied as usable; all 5-inch lumber was tallied as 4-inch widths, and all side lumber over 6 inches as 6-inch widths.

Average yield of pallet cants and side lumber decreased with increased sweep, as follows:

Sweep class	Yield from 4-foot bolts	Yield from 6-foot bolts
Inches	*Percent of volume*	
0-0.5	56	58
0.6-1.0	53	55
1.1-1.5	49	47

Some processes recover only pallet cants from boltwood (no side lumber); yield of pallet cants only from the sample bolts also varied with sweep class, as follows:

Sweep class	Yield from 4-foot bolts	Yield from 6-foot bolts
Inches	*Percent of volume*	
0-0.5	48	47
0.6-1.0	44	42
1.1-1.5	39	36

Table 27-122A shows the effect of sweep on pallet stock by bolt diameter class.

Material flow (yield) diagrams for eight other projected pallet operations are shown in figures 28-2, 28-13, 28-19, 28-21, 28-24, 28-26, 28-30, and 28-36.

TIGHT COOPERAGE

Specifications for tight cooperage generally require clear heartwood (see sect. 22-8). Therefore, to permit close inspection of the interior, logs are cut into short lengths of 23 to 39 inches for head and stave material, respectively, and then split into quarter sections called bolts.

Bolt volume is expressed in bolt feet, also called chord feet (Smith 1952). This measurement is taken from a point on one edge of the cross-section surface where heartwood and sapwood meet to the same point on the other edge. (In some localities, sapwood may be included.) When this linear distance is exactly 12 inches, the volume contained in the bolt is 1 bolt foot; for a distance of 15 inches, the volume would be 1.25 bolt feet.

The expected bolt foot yield from white oak trees 12 to 36 inches dbh is given in table 27-123.

The ratio of bolt foot volume to board foot volume (Doyle scale) was determined by Goebel (1956) using the following regression equations:

$$\text{Head Ratio} = [0.03354(D) + 0.00014(D^2)]\ L \qquad (27\text{-}43)$$

$$\text{Stave Ratio} = [0.059(D) + 0.00002(D^2)]\ L \qquad (27\text{-}44)$$

where:

D = log diameter, inches
L = log length, feet

The ratios for white oak logs 14 to 26 inches in diameter and 6 to 12 feet long are shown in figure 27-20 and in table 27-124.

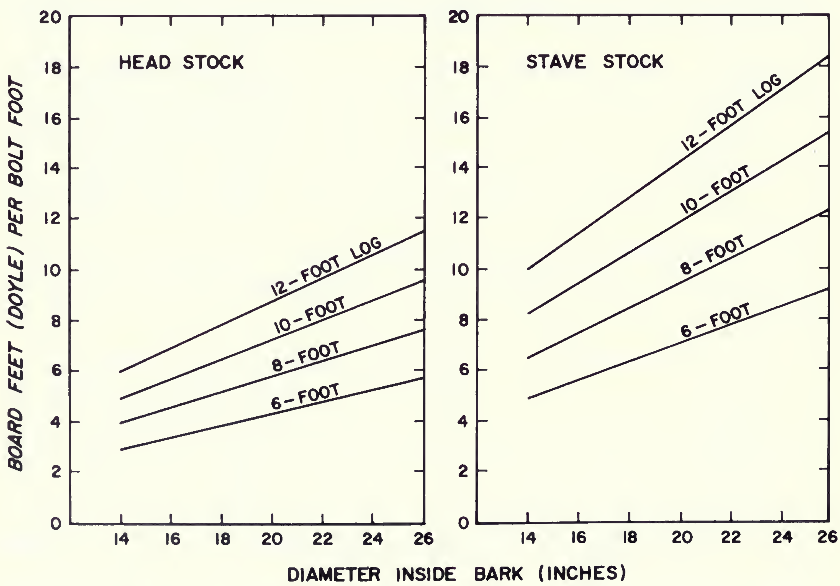


Figure 27-20.—Board foot/bolt foot ratio for white oak logs cut for head stock (left) and for stave stock (right). (Drawing after Goebel 1956.)

TIES AND TIMBERS

Sizes and specifications for crossties and switchties are explained in section 22-10 and table 22-20. The size of timber obtainable from a log is related to log diameter, sweep, and species (table 22-18, figs. 22-51, 22-52). Often low-grade logs will have a greater yield, both in terms of board feet and dollar value, when sawn for timber and lumber instead of just lumber (tables 27-125 and 22-17; fig. 22-50). Table 22-44 gives the yield of lumber and residues from 1,000 bd ft Doyle when red oak logs 13 inches in diameter and 8 feet long are cut for crossties and lumber.

Low-grade hardwoods, particularly logging residues and thinnings, can also be a source of mine timbers. Timson (1978) found that after a sawlog harvest, 44 percent of the logging residues measuring at least 4 feet long and 4 inches in diameter outside bark was suitable for mine timber production. Minimum characteristics of roundwood suitable for manufacturing sawn mine timbers and round and split props are discussed in section 22-10, table 22-25, and figure 22-62. Species preference is also covered in section 22-10.

PARALLEL-LAMINATED THICK VENEER

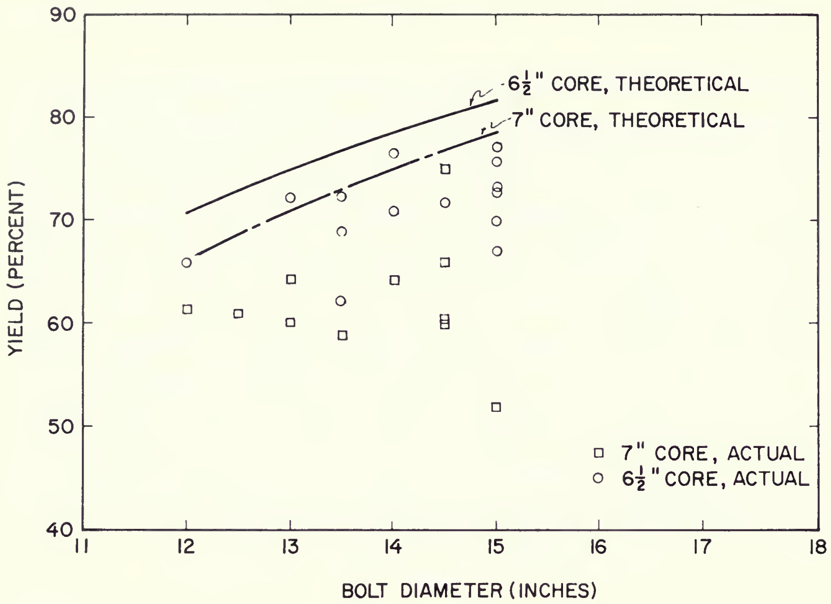
Subsection PARALLEL LAMINATED VENEER in section 22-10 (page 2705) lists literature related to the subject. Section 28-2 contains an economic analysis of a small scale operation to produce sawn veneer for parallel lamination into high-price furniture, and section 28-21 analyzes the economic feasibility of producing hardwood laminated-veneer flanges for fabrication with flakeboard webs into long-span I-beam joists. Both accounts estimate yield, but the literature contains little experimentally-derived data on yield of thick-peeled hardwood veneer.

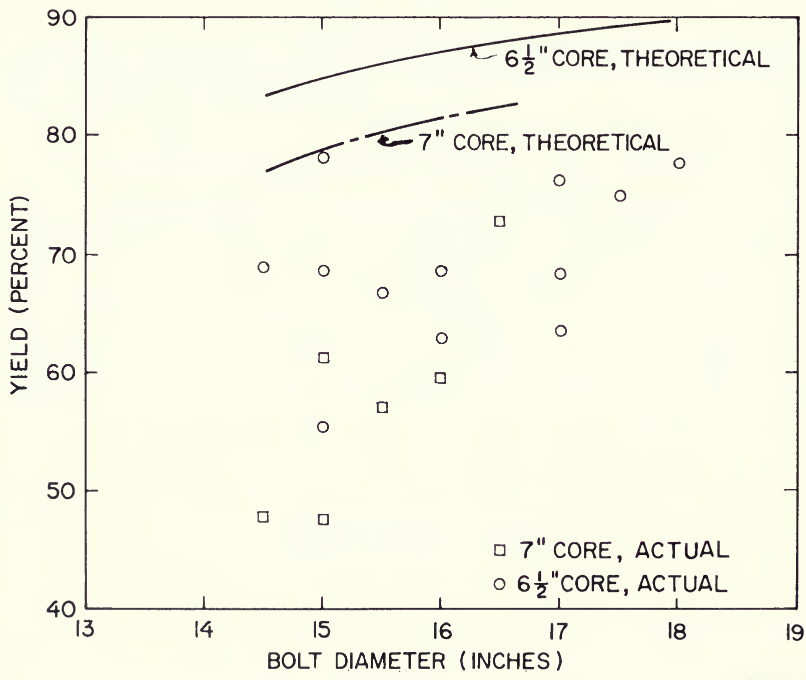
In a study with southern pine (Schaffer et al. 1972), 4-foot-long bolts cut at thicknesses of 0.431 or 0.500 averaged 66.6 percent yield of green veneer. Yield increased with bolt diameter (figure 27-21). Allowing for losses during drying and subsequent manufacturing, the dry product yield from logs 12 to 18 inches in diameter should average about 60 percent—about 1-½ times the yield typically obtained by sawing.

27-3 RESIDUES

LOGGING RESIDUES

In general, an upland hardwood tree has about 50 percent of its complete dry weight in the bark-free stem, 30 to 35 percent in tops (with foliage) and stem-bark, and 15 to 20 percent in the central stump-root system. These proportions vary significantly among species and between trees of a species as discussed at length in section 16-1 (e.g., see tables 16-2 and 16-10). Table 16-2, containing





M 140 209
M 140 211

Figure 27-21.—Volumetric yield of green southern pine veneer, 0.413 inch thick (top) and 0.500 inch thick (bottom), as a function of bolt diameter. The difference between theoretical and actual laboratory yield is due to roundup, lack of straightness in bolt, and occasional spinout of the partially rotary-cut bolt in the lathe. (Drawing after Schaffer et al. 1972.)

complete-tree biomass data on 67 six-inch-diameter pine-site hardwoods of 22 species, had average weight distribution as follows (lateral roots severed at a 3-foot radius):

Tree portion	Green weight	Ovendry weight
	----Percent of complete tree----	
Central stump-root system	21.7	20.6
Stem with bark	57.7	59.2
Branches 0.5-inch-diameter and larger	11.6	11.9
Twigs	5.2	5.3
Foliage	3.8	3.0
	100.0	100.0

A summary of weight distribution tables and equations in this text is given in table 27-97. For bark residue quantities see chapter 13, for roots chapter 14, and for foliage chapter 15.

Cost (1978) studied the volumes of bark-free above-ground wood in hardwood trees growing on about 4 million acres in the Mountain Region of North Carolina. He estimated the total volume of above-ground wood (bark-free) on this acreage at 7.5 billion cubic feet; 30 percent of this wood is in stumps, tops, limbs, and saplings. For both sawtimber and pole timber, about 80 percent of the wood volume is confined to the merchantable stem and abcut 20 percent is in the nonmerchantable portions. But the distribution of wood volume within the nonmerchantable portions varies with tree size: for sawtimber, 4 percent is in the stump, 2 percent in the top, and 13 percent in limbs; for poletimber, the corresponding proportions are 6, 8, and 6 percent (table 16-1).

In Louisiana and Alabama, hardwoods cut for pulpwood averaged 24 cubic feet in above-ground volume, excluding bark; 15 to 20 percent of that was in tree tops, 5 percent in lopped limbs, 5 percent in stumps, and only 70 to 75 percent was actually removed as pulpwood (Beltz 1976). **Lopped limbs** were those ≥ 1-inch diameter at limb collar and lopped from the portion of the bole used. **Tree tops** were residual crowns.

Measuring logging residues.—The first step toward utilization of logging residues is determining just how much is available. This can be done by weighing all logging residues on conventional sample plots. However, a much quicker procedure now in widespread use is the line intersect method.

In line intersect sampling (Martin 1976a), a line is established on the cutover area and the diamters of all logging residues that cross the line are measured at the point of intersection. Sample lines may be continuous or segmented, and they may be oriented either systematically or randomly. The volume of residue is then estimated by using the equation:

$$V = \frac{\pi \Sigma d^2}{8L} \times \frac{43,560}{144} \qquad (27\text{-}45)$$

where:

V = volume of residue per acre, cubic feet
d = diameter of residue point of intersection, inches
L = length of sample line, feet

If the sample line is measured in chains, the equation becomes

$$V = \frac{\Sigma(0.005454d^2)}{N} \times 1{,}037 \qquad (27\text{-}46)$$

where:

N = length of sample line, chains

Martin (1976b) verified that the line intersect method gives unbiased estimates of hardwood logging residues in the Appalachians and its reliability is little affected by species, type of cut, slope, road influence, or length of residue pieces. He also provided a computer program to expedite the required computations (Martin 1975a); the user's guide is available on request from the USDA Forest Products Marketing Laboratory, Princeton, West Virginia 24720.

Another approach is a series of photos showing various residue levels generated by different cutting practices in a given forest type and forest size class; information on residue quantities, sizes, and fuel ratings is given below each photo (Maxwell and Ward 1976). The user simply looks for the photo that most resembles his situation. As yet, however, such series are available only for softwood forests in the Pacific Northwest.

If logging residues are piled in windrows rather than scattered uniformly over the area, then the inventory technique developed by McNab (1980) can be applied. First, compute the wood ratio (proportion of the windrow profile area that is occupied by solid wood) using the following equation:

$$\text{Wood ratio} = (0.635 + 0.251/H - 1.625/D)^2 \qquad (27\text{-}47)$$

where:

H = maximum windrow height, feet
D = mean diameter of residues larger than 3 inches, inches

This equation has an R^2 of 0.88 and a standard error of estimate for wood ratio of 0.036.

Second, calculate the average cross-sectional area of the windrow, as follows:

$$\text{Area, sq ft} = 3.39 + 1.19(H \times L) \qquad (27\text{-}48)$$

where:

H = maximum windrow height, feet
L = horizontal distance from the near edge to point of maximum height, feet

The relationship between actual and predicted area was close, with an R^2 of 0.96.

Third, then the residue volume = wood ratio x average cross-sectional area x total length of windrows on the tract.

McNab's formulae are based on a total sample of 54 transects in 28 windrows in the lower Piedmont of Georgia. At these study sites, merchantable pines were harvested by tree-length logging to a 4-inch top and residual hardwoods were sheared at groundline and pushed into windrows with other debris by a crawler tractor equipped with a brush rake attachment.

Estimated amounts of logging residue.—For a discussion of logging residue per acre, see the subsection by this title in section 16-2.

Craft (1976) found that after the merchantable sawlogs were removed from an Appalachian hardwood stand by clearcutting, 69.3 tons per acre of green wood residue remained—about 1.8 times greater than the weight of the sawtimber removed. From these wastes, he produced an additional 4,800 bd ft of sawed products and 51.6 tons of chippable wood per acre (fig. 16-5).

Florida, Georgia, and South Carolina together generate an estimated 560 million cu ft of logging residues each year (Welch 1974). Harvesting West Virginia hardwood stands produces an average of 467 cu ft per acre of residue material 4 inches and larger dob at the small end and 4 feet long or longer (Martin 1975b). On Alabama clearcuts, about 8 cords per acre was left in residual trees, tops of cut trees, unused bole sections, and above-ground portions of stumps (Chappell and Beltz 1973).

According to a recent survey (Porterfield 1976), 9.3 percent of the softwood growing stock harvested in the United States and 17.5 percent of the hardwood growing stock is left behind in the woods. Corresponding figures for the South are 6.5 percent for softwood residues and 20.1 percent for hardwood residues. These figures do not include any cull trees or volume in trees less than 5 inches in dbh which might be present on the site. Neither do they include below-ground tree portions.

Residues related to type of harvest.—Of all logging operations, hardwood sawlog harvesting is the most wasteful. Logging only sawlogs to an 8-inch or merchantable top utilizes, on the average, only 60 to 67 percent of the above-ground wood in a deliquescent species like red oak (fig. 27-22) (Clark 1978). When both sawlogs and stem pulpwood are harvested, 70 to 80 percent of the red oak wood is utilized. However, whole tree chipping would increase wood utilization by 26 to 46 percent as compared to logging to a 4-inch top (fig. 27-23) and by up to 65 percent as compared to logging for sawlogs only. Increases for an excurrent hardwood like yellow-poplar are somewhat less dramatic.

A statewide study in Arkansas showed that hardwood sawlog operations utilized 72 percent of the bole to a 3-inch top, while hardwood pulpwood operations utilized 86 percent (Porterfield and von Segen 1976). For sawlogs, utilization averaged 13 percent higher for tree-length harvesting operations than for product-length operations where bucking was done in the woods.

Gibbons (1977) also found that longwood harvesting tends to leave less merchantable residue behind than shortwood operations. In a study of 3,000 acres of natural stands in the Midsouth, longwood harvesting left residues equalling 39.6 percent of the total preharvest hardwood inventory; shortwood harvesting left 43.2 percent; and a two-stage operation in which high value stock is removed first followed by shortwood operation left the highest residue—60.5 percent.

Martin (1977) compared various harvesting options for a 1.7-acre stand of predominantly yellow-poplar and red maple in southwest Virginia. "Near-complete removal," in which the timber was harvested for sawlogs and whole-tree chips, yielded 104 percent more salable material than would be expected if the area had been cut for sawlogs only and 27 percent more than a pure pulpwood harvest (table 27-126).

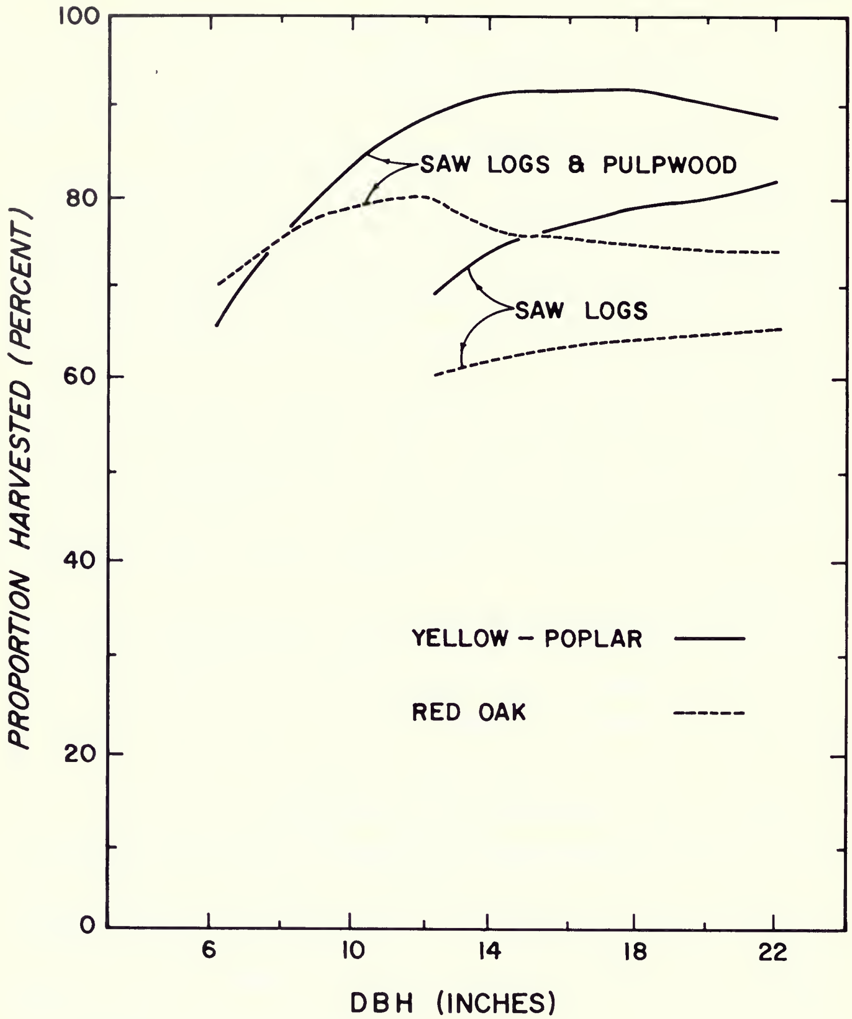


Figure 27-22.—Proportion of total-tree wood (above stump) harvested when saw logs of red oak sp. and yellow-poplar are logged to an 8-inch or merchantable top, compared to harvesting saw logs and pulpwood to a 4-inch top. (Drawing after Clark 1978.)

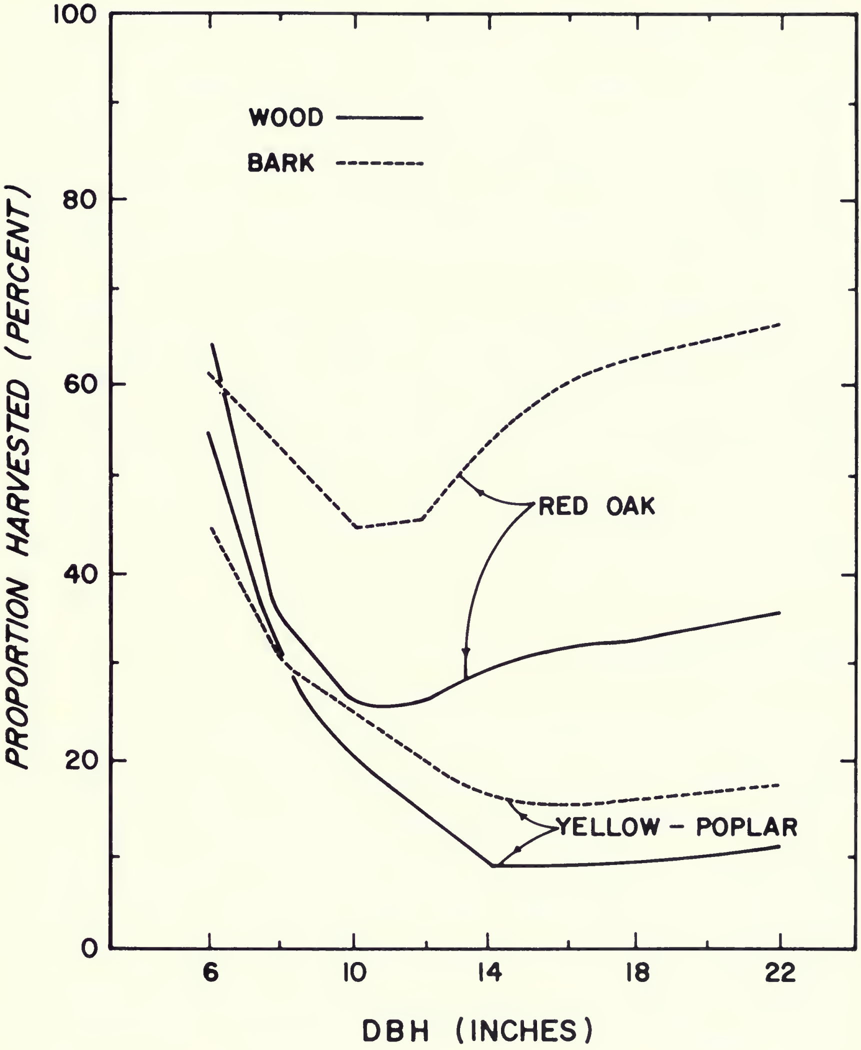


Figure 27-23.—Percent increase in red oak sp. and yellow-poplar wood and bark harvested when whole-tree chipping is compared to logging the stem to a 4-inch top. (Drawing after Clark 1978.)

Based on data collected on 20 timber sales in West Virginia and Virginia, Martin (1976b) prepared a residue yield table (table 16-33) for four cutting practices and various levels of basal area and stand age. Clearcutting for sawlogs only generates the most residues, followed by selection cut, clearcut for sawlogs and other products, and improvement cut.

Quality of logging residues.—The size and quality of logging residues can limit their possible uses. Timson (1980) established four quality levels for residues based on length, surface defects, and sweep. After examining 25 hardwood sawlog-only operations in West Virginia, Virginia, and Pennsylvania, he found that 74 percent of the residues would not qualify as "local use" logs. Eighty-six percent would not meet factory grade 3 standards. Timson concluded that hardwood logging residue can best be used when extracted in the primary harvesting operation and used for bulk products such as energy wood, chips, and pulpwood.

Another possible use is in mine timber production. Timson's (1978) study in the Appalachian coal region showed that 44 percent of the residue from sawlog-only harvests is physically suitable for mine timbers. In this study only residues at least 4 inches dob at the small end and at least 4 feet long were considered. Fifty-eight percent of the bolewood residue could be used in mine timbers, but only 26 percent of the limbwood residue was acceptable. The oaks and hickories—preferred species used for all purposes in mines—and yellow poplar—a nonpreferred species used primarily in noncritical areas—all had about 60 percent usable bolewood residue.

FOLIAGE AND SEED

Section 15-2, FOLIAGE QUANTITY, contains information on the number of leaves, leaf surface areas, foliage weights, and the proportion of complete-tree weight contributed by leaves (see tables 15-6 through 15-11, figs. 15-11 through 15-13). In general, ovendry foliage weights range from about 3 to 9 percent of the whole-tree weight (above-ground portions only), depending on tree size and species (table 15-7). When the complete-tree biomass is considered (including stump, taproot, and major lateral roots), leaves account for 2.1 to 6.9 percent of the total ovendry weight, and the variation appears to be a function more of tree dbh than of forest type (table 16-4). For 6-inch hardwoods growing on southern pine sites, foliage contributed from 1.4 to 4.5 percent of the complete-tree weight (ovendry basis); green ash had the least percent leaves, with 2.5 pounds per tree; red maple had the greatest, with 14.3 pounds per tree (table 15-9).

Annual production of foliage in southern upland hardwoods ranges from about 2,000 to 5,000 pounds per acre (ovendry basis), and the amount of litter in such stands is estimated at 5,000 to 11,000 pounds per acre (see sect. 15-2, table 15-12, and fig. 15-14). For a discussion of the volumes of deer browse contributed by leaves and twigs, see section 15-5, subsection WILDLIFE FOOD (page 1390).

Seed yield per tree and per acre for sweetgum, yellow-poplar, and the oaks is discussed in section 15-7 (see tables 15-24 through 15-26, figs. 15-21 through 15-24).

The number of acorns per pound varies considerably among oak species and also within species and with season. See table 15-23 and adjacent tabulations and text.

TOPS AND BRANCHES

One reason hardwood utilization lags behind softwood is that many hardwoods have large, spreading crowns. In hardwoods with excurrent branching, such as yellow-poplar, sweetgum, and black tupelo, the main stem outgrows the lateral branches, resulting in cone-shaped crowns with clearly defined central boles. In trees with deliquescent branching, the lateral branches grow almost as fast as the terminal stem, and the central stem becomes lost in the upper crown. Over 70 percent of the commercial hardwood volume in the southeastern United States—and most of the hardwood volume on southern pine sites—is in trees with deliquescent branching, such as oaks, elms, hickories, and maples. The marked difference in crown volume for excurrent and deliquescent species can be illustrated by a comparison of yellow-poplar and red oak (table 27-127). In 12-inch-dbh yellow-poplars, 11 percent of the wood and 16 percent of the bark is in the crown; in red oaks of this size, crowns contain 30 percent of the wood and 32 percent of the bark.

Section 16-1, DISTRIBUTION OF TREE BIOMASS, page 1428, provides detailed information on crown volumes and weights and on the proportion of total tree weight in the crown for various species. Perhaps the most pertinent data is that compiled for 6-inch-diameter hardwoods in the 23 species commonly found on southern pine sites. For these trees, branches 0.5 inch and larger in diameter contributed from 4.5 percent (yellow-poplar) to 27.4 percent (red maple) of the complete-tree ovendry weight (including stumps and roots); the average for all species was 11.9 percent (table 16-2). Branchwood and branch bark as a percentage of the foliage-free, whole-tree weight (above-ground portions only) is given in table 16-10. On the average, 9.7 percent of the whole-tree ovendry weight is in branchwood and 2.4 percent is in branch bark.

Other studies have also shown that crowns make up a significant portion of the biomass of small hardwoods. In the North Carolina mountains and Georgia Piedmont, six species with all sample trees between 1 and 5 inches in dbh had 12 to 33 percent of their above-ground volume in branches (table 16-7). Hickories under 20 inches in dbh were found to have more wood (by weight) in the crown than in the merchantable bole (Schnell 1978). For results of other studies on crown size and weight, see section 16-1 and tables 16-1, 16-4, 16-9, and 16-13 through 16-33.

Consequently, the amount of topwood available for use is large indeed. In hardwood saw log operations in Alabama and Louisiana, nearly two-thirds of all logging residue was in tops (Beltz 1976). Clearcuts in Alabama left behind about 3 cords per acre of pine and hardwood tops (Chappell and Beltz 1973).

The volume of topwood remaining after saw logs are removed varies substantially with tree size, and the greatest amount comes from large diameter trees that yield few saw logs (tables 27-8 and 16-31). For example, a 31-inch oak containing one 16-foot and one 8-foot saw log yielded 100 cubic feet of bark-free topwood (defined as the volume of upper stem and branches at least 5 inches in diameter inside bark and 5 feet long). A 20-inch tree with one saw log had about 30 cu ft of bark-free topwood, but a four-log tree of the same diameter had only 5.8 cu ft of topwood.

It is clear that tops and branches offer a substantial source of wood fiber. For example, in a 40-year-old upland oak stand, material 4 inches dob or less will account for 25 to 52 percent of the per-acre yield of wood—dry weight without bark (table 27-128). Even in a 100-year-old stand, at least 25 percent of the dry weight will be in this usually wasted material. The yield per acre from branches of trees 5 inches or more in dbh can be as much as 26,000 pounds (dry weight with bark) for a 40-year-old stand and as much as 40,000 pounds for a 100-year-old stand (table 27-129).

Estimating the volume in tops and branches.—Crown diameter can be estimated from dbh, as discussed in section 15-2. Volumes of tops in deliquescent hardwoods can be estimated from stem diameter outside bark at the base of the residual top or crown; figure 16-4 illustrates this relationship and gives the regression equation.

Crown volumes (cubic feet) in northern red oak can be reliably predicted from the squared value for diameter at base of crown $(DCr)^2$. The technique was developed by Phillips and Cost (1978) based on measurements of 62 trees 6 to 24 inches in dbh selected from natural, even-aged stands in the mountains of North Carolina. The equation is as follows:

$$CV = -0.88554 + 0.10874\,(DCr)^2 \qquad R^2 = 0.90 \qquad Sy \cdot x = 3.87 \text{ cu ft} \tag{27-49}$$

where:

CV = crown volume, wood only, cubic feet
DCr = diameter outside bark at base of live crown, inches

Equations for predicting the cubic-foot volume in yellow-poplar branches are given in table 16-30, and yields from trees 6 to 16 inches in dbh are listed in table 27-66D. The proportion of yellow-poplar crowns in small, medium, and large branches is illustrated in figure 16-3.

Regardless of crown type or species, the volume of a single hardwood branch can be estimated from the diameter of the limb just beyond the limb collar with equation 16-8.

Readers needing to estimate the volume that crowns of standing trees occupy in the forest, should find useful the work of Mawson et al. (1976) and Holsoe (1950).

Estimating the weight of tops and branches.—The relationship between branch weight and tree dbh is illustrated in figure 16-1.

Wartluft (1978) developed regression equations for predicting both green and ovendry weights of sawtimber tops for soft hardwoods (yellow-poplar, cucumbertree, and black tupelo), for hard hardwoods (white ash, hard maple, hickory, all oaks), and for both groups combined (table 27-130). Estimates of sawtimber top green weight ranged from 556 pounds for an 11-inch soft hardwood tree to 4,633 pounds for a 26-inch hard hardwood tree. Estimates of ovendry weight ranged from 308 to 2,993 pounds (table 16-32). The percent of treetop weight in material greater than 3 inches in diameter outside bark increased from 56 percent to 75 percent as dbh increased from 11 to 26 inches. Moisture content averaged 62 percent (ovendry basis) for the trees sampled.

A study of nine Appalachian species in West Virginia (Wiant et al. 1977) showed that northern red oak, black oak, scarlet oak, chestnut oak, and hickory sp. generally have high branch weights, while white oak, black cherry, red maple, and yellow-poplar have lower branch weights. Branch weights, green and dry, for trees 6 to 16 inches in dbh are given in tables 27-131 and 27-132. For dry weight of branchwood and stemwood in these trees see table 16-12; dry weights of branchbark and stembark are given in table 13-11.

Equations 27-30 and 27-32 predict the weight of the unmerchantable top, limbs, and foliage for mixed hardwood sawtimber and for mixed hardwood pulptimber, as determined in a Louisiana study (Hughes 1978).

Equation 16-4 and table 16-13 can be used to predict the crown weight (green or ovendry) from basal area and tree height for green ash, sugarberry, sweetgum, and American elm. Alternatively, crown weight (green) can be predicted from a knowledge of dbh and crown length using equation 16-5 for green ash, sugarberry, or sweetgum.

For black oak, total crown weight and the weight in limbs of various sizes can be estimated with the equations in table 27-81. Values for trees 12 to 36 inches in dbh are listed in tables 16-14 and 16-15.

Tabular data on crown weights of wood and bark in five important southern oaks are located as follows:

Species	Sample location	Table number for Wood	Table number for Bark
Chestnut oak	Western North Carolina	16-16	16-17
Northern red oak*	Western North Carolina	16-20, 16-21	13-13, 13-14
Scarlet oak	Tennessee Cumberland Plateau	16-22	13-15
Southern red oak	Highland Rim in Tennessee	16-23	13-16
White oak	Western North Carolina	16-24	13-17

For additional weight data on **mockernut hickory** and **white ash** see: Clark, Alexander, III, and W.H. McNab. 1982. Total tree weight tables for mockernut hickory and white ash in north Georgia. Ga For. Res. Pap. 33. Macon, Ga.: Georgia Forestry Commission, Research Division.

Equations are available to predict total branch weight for yellow-poplar (table 16-29), and values for trees 6 to 28 inches in dbh are listed in tables 27-133 and 27-134. Yellow-poplar branches make up 7 to 12 percent of the dry weight of the above-ground foliage-free tree, depending on tree size (table 16-27). On the average 77 percent of branch dry weight is wood and 23 percent is bark.

Branch density.—Branch densities vary widely among species and with tree diameter class as indicated by data in the following tables:

*See also: Loomis, Robert M.; Blank, Richard W.
How to estimate weights of northern red oak crowns in a stand.
Gen. Tech. Rep. NC-76 St. Paul, MN: U.S. Department of Agriculture, Forest Service, North Central Forest Experiment Station; 1982. 8 p.

Size class and description	Table number
Understory hardwoods less than 5 inches in dbh growing in the mountains of North Carolina on the Georgia Piedmont	16-7
Pine-site hardwoods 6 inches in dbh of 22 species samples throughout their southern ranges	7-2
Five oak species plus sweetgum and yellow-poplar 6 to 22 inches in dbh growing in the Southeast	7-2A

STUMPS AND ROOTS

Weights of stump-root systems are discussed in section 14-3 and in tables 14-1AB and 14-2AB. Figures 14-4 through 14-26 illustrate the typical stump-root shapes. Additional information is provided in section 16-1, DISTRIBUTION OF TREE BIOMASS (Page 1428).

The proportion of the complete-tree weight contributed by the stump-root system varies with species, as shown by a comparison of the 22 hardwood species most commonly found on southern pine sites (table 16-2). For trees 6 inches in dbh, the stump-roots (including lateral roots to a 3-foot radius) accounted for 15.4 to 25.1 percent of the complete-tree ovendry weight; the average for all species was 20.6 percent. Species with small proportions of their biomass in the stump-root system include yellow-poplar, the ashes, and water oak. Those with massive stump-root systems include hickory, black tupelo, sweetgum, and blackjack oak.

The proportion of the complete-tree weight contributed by the stump-root system also varies with tree size. In chestnut oak forests in east Tennessee, the stump-root system (including laterals to a radius of 60 cm) made up 9.4 percent of the complete-tree ovendry weight in trees more than 9.5 inches in dbh and 22.4 percent in trees between 0.5 and 3.5 inches in dbh (table 16-4). Similar ranges were found in oak-hickory stands (9.8 to 18.0 percent) and in yellow-poplar forests (10.7 to 16.9 percent). In a study of sawtimber-sized black oaks, the stump and roots accounted for one quarter of the complete tree dry weight (Tennessee Valley Authority 1972). Equations and a table for estimating stump and root weight for black oaks 12 to 36 inches dbh are given in tables 27-81 and 27-135.

Stump height.—The nominal stump height used by the Forest Survey in its inventories is 1 foot, but in actual practice the height at which stumps are cut varies. In a study of 200 logging operations in Alabama and Louisiana, mean stump heights ranged from 0.37 feet for softwood pulpwood to 1.15 feet for hardwood saw logs, and stump volume ranged from 0.22 to 2.51 cu ft (table 27-136).

Excessive stump heights can take a heavy toll on the volume of wood recovered, and tables are available for calculating the loss in terms of cubic feet and board feet (table 27-137). For example, if a stump 16 inches in diameter is cut 4 inches above the target height stated in the logging contract, 3.69 bd ft (International ¼-inch rule) is wasted. The tables are based on characteristics of southern pine stumps; on swell-butted hardwoods the losses may be greater.

Relation of stump dimensions to dbh.—Foresters and timber managers often need to estimate the volume of timber removed from a tract after cutting operations have been completed. To do this, they need to know the diameter at breast height of trees cut at various stump heights so that suitable volume tables can be applied. Several studies have explored the relationship of stump size to dbh. After measuring over 14,000 standing trees in the Carolinas and Virginia, McClure (1968) developed equations for predicting dbh from stump diameter and height for each of 53 southeastern tree species; his equations for 18 hardwoods are presented in table 27-138. Tables relating stump size to dbh were compiled by McCormack (1953) for hardwoods as a group in Georgia and North Carolina (table 27-139) and by Vimmerstedt (1957) for nine species and species groups in the southern Appalachians (table 27-140).

BARK

Data on bark are found principally in chapter 13 and in section 16-1. Briefly, for 6-inch hardwoods found on southern pine sites, stembark averages about 13.1 percent and branchbark about 2.4 percent of the foliage-free ovendry weight of above-ground tree portions (table 16-10). The range for stembark was from 8.1 percent (winged elm) to 19.3 percent (blackjack oak); the range for branchbark was from 1.9 percent (Shumard and cherrybark oaks) to 3.9 percent (post oak).

Bark volume and weight data are primarily in chapter 13 but some are also in section 16-1. Section 13-3, BARK VOLUME AND WEIGHT, contains the following subsections:

- BARK VOLUME AND WEIGHT PER ACRE, Page 1138
- BARK VOLUME AND WEIGHT PER TREE, Page 1141
- BARK VOLUME AND WEIGHT PER LOG, Page 1162
- BARK VOLUME AND WEIGHT PER STANDARD ROUGH CORD, Page 1167
- BARK WEIGHT PER Mbf LOG SCALE, Page 1171
- BARK WEIGHT PER Mbf LUMBER SCALE, Page 1174

Section 16-1 data on bark volume and weight can mainly be found in the following tables:

Subject and species	Table No.
Percentage of above-ground biomass/tree comprised of bark of 22 species; trees 6 inches in dbh	16-10
Weight per tree of stem bark	16-13
Ash, green	
Elm, American	
Sugarberry	
Sweetgum	
Weight per tree of bark in stem, crown, and complete tree	16-14
Black oak	
Weight per tree of bark in stem, branches, and whole tree above ground	16-17
Chestnut oak	
Same, but for:	
Sweetgum	16-26
Weight per tree of bark of whole tree above ground	16-27
Yellow-poplar	
Equations to predict weight per tree of bark in merchantable stem, stem to a 2-inch top, branches, and whole tree above ground	16-29
Yellow-poplar	
Same, but for volume	16-30
Yellow-poplar	

In a study of tops left after saw log harvesting, Wartluft (1978) found that bark accounted for an average of 23 percent of the green top weight. Some species of interest were:

Species	No. of trees	Bark moisture content (ovendry basis)	Bark proportion of green weight
		Percent	
Ash, sp.	1	49	19
Hickory sp.	2	40	26
Oak, chestnut	16	55	25
Oak, red sp.	31	67	20
Oak, white	6	48	22
Tupelo, black	3	89	24
Yellow-poplar	14	81	28
Hard hardwoods	57	59	22
Soft hardwoods	18	81	27

Data on bark **moisture content** are in section 13-4, and bark **specific gravity** data are in section 13-6. Bark **bulk density** is discussed in the paragraph *Bulk density of bark residue* in subsection SPECIFIC GRAVITY of section 13-6 (Page 1208).

Bark thickness data are in section 13-2 (Page 1124).

Bark thickness and tree diameter growth.—Foresters generally estimate tree diameter growth by taking increment cores at breast height to measure the rate of wood growth and by assuming that bark thickness remains constant. However, bark slowly increases in thickness over the years; so such estimates can be up to 17 percent low (McCormack 1955). To solve this problem, McCormack (1955) provides growth factors for several hardwood species measured in the Southeast (table 27-141). Note that this factor includes a multiplier of 2, which accounts for two bark thicknesses. One simply multiplies the measured radial wood growth for the period (as obtained by increment core) by the growth factor for that species to obtain total diameter growth. For examle, if we assume a 10-year radial wood growth measurement of 1.1 inches for a post oak that is now 13.2 inches in diameter, then the total diameter growth including bark is

$$(1.1)(2.19) = 2.4 \text{ inches}$$

The outside bark diameter of the tree at the beginning of the period would be computed as follows:

$$13.2 - 2.4 = 10.8 \text{ inches}$$

If no allowance were made for increase in bark thickness, the original diameter of the tree would be estimated at 11 inches, i.e., $(13.2) - (2)(1.1) = 11$, and actual tree diameter growth would be underestimated by 8 percent.

MILL RESIDUES—PROPORTION OF LOG VOLUME

Utilization of stems and logs varies greatly among mills and according to product manufactured. For example, fiberboard plants producing hardboard from whole-tree chips convert a high proportion of tree volume to primary product, whereas plants making hardwood flooring (fig. 22-1) or barrel staves convert a much lesser proportion into primary product. The material flow diagrams in chapter 28 permits ready comparison of utilization in a wide range of products.

Chapter 18 discusses the efficiency of various sawing methods and chapters 22 through 26, a wide range of products.

Readers needings a model to calculate the lumber and residue production at any sawmill—operating or proposed—with a minimum of data collection are referred to Steele and Hallock (1979). Their geometric model estimates volumes of green lumber, dry lumber, green chips, green sawdust, and dry planer shavings.

Average residue production at Georgia sawmills was reported by Page and Baxter (1974) as follows:

Type of residue	Residue/Mbf of lumber manufactured	
	Hardwood	Softwood
	Tons	
Bark (green weight)	0.44	0.44
Chips (green weight)	1.49	2.51
Sawdust (green weight)	1.09	0.44
Shavings (dry weight)	0.27	0.48

A canvass of mills in Florida, the Carolinas, and Georgia (Welch and Bellamy 1976) indicates the following utilization proportions in lumber and veneer production (data based on 893 sawmills and 97 veneer mills):

Mill type and species class	Proportion of log volume input ending as primary product	Proportion of residues utilized
	Percent	
Sawmills		
Hardwood	56	76
Softwood	37	89
Veneer mills		
Hardwood	60	79
Softwood	45	91

For all 1,102 mills in the study (including those that produced pulp, treated wood, or specialty wood), an average of 86 percent of the initial wood residues was utilized in 1973-74 as opposed to only 37 percent in 1962. Utilization rates varied by species type and by type of residue. Less than 11 percent of the softwood residues was wasted, but almost 24 percent of the hardwood residues was not used. Almost all of the coarse residues and planer shavings were utilized; over 35 percent of the finer residue was not. In addition, all but 25 percent of the bark residue was put to some use, mainly for industrial fuel.

A study of 25 Arkansas mills (Porterfield 1975) suggested that utilization efficiency is related more to sawmill size than to species sawn. Large and small mills produced from 55 to 62 percent of their total output as green lumber, but large mills tended to utilize sawdust and bark as fuel and to produce chips while small mills did not, as follows:

Species and sawmill size classes	Proportion of output volume in			
	Principal product	Pulp-chips	Utilized residue	Unutilized residue
	Percent			
Hardwood				
Small	59	2	16	23
Large	62	19	8	11
Southern pine				
Small	55	—	11	34
Large	55	31	13	1

In this study, small mills were defined as those producing 3 million bd ft of lumber, or less, annually.

Among specialty mills in Arkansas, Porterfield (1975) found that post mills had the largest percentage of raw material input converted to principal product (73 percent), followed by furniture stock mills (61 percent), handle-stock mills (51 percent), and lastly stave mills (40 percent), as follows.

Product of specialty mill	Proportion of roundwood input volume in		
	Principal product	Utilized residue	Unutilized residue
	Percent		
Furniture stock	61	20	19
Handle stock	51	49	0
Posts	73	10	17
Staves	40	31	29

Residues of nine pallet plants in the Tennessee Valley averaged 30 to 40 percent of the lumber input (by weight) (Perry 1976). A technique for estimating residue production is described in section 22-7, subsection RESIDUES FROM PALLET MANUFACTURE, and in figure 22-40.

SLABS, EDGINGS, AND TRIM

The newest mills equipped with both chipping headrigs and chipping edgers make neither slabs nor edgings but instead convert their equivalent volumes directly into pulp chips (see sect. 18-9). The information below is applicable only to sawmills with conventional headrigs and edgers.

Slab yield per Mbf log scale.—Using the formulae on which the International ¼-inch and Scribner log rules are based, Bennett and Lloyd (1974) estimated the cubic-foot yield of slabs and edgings from one Mbf log scale. Condensed versions of their volume tables (tables 27-142 and 27-143) indicate that the yield of slabs and edgings from 1,000 bd ft of 6-inch logs is three to four times the yield from 12-inch logs.

A study in the Missouri Ozarks (Massengale 1971) produced information on the weight yield of green slabs and edgings from 8-foot logs of mixed oaks. The range was from 1,790 pounds per Mbf Doyle scale for 16-inch-diameter logs to 4,155 pounds for 9-inch logs (table 27-144). Each log was sawn for maximum yield of 4/4 lumber, and the solid-toothed saw had a 3/16-inch kerf.

Slab yield per Mbf lumber scale.—Eight-foot-long mixed oak logs from the Missouri Ozarks produced from 1,530 to 3,300 pounds of green slabs and edgings per Mbf of lumber sawn (table 27-145).

With yellow-poplar, the green weight of chippable residues (slabs, edgings, and end trim) per board foot of lumber decreased as tree size increased (Clark et al. 1974). In this study, 47 yellow-poplar trees 12 to 28 inches in dbh were bucked into 8- to 16-foot logs, debarked, and sawn into 4/4 lumber on a bandsw. Weight of chips per board foot of lumber ranged from 3.0 pounds for the 12-inch trees to 1.4 pounds for the 28-inch trees and averaged 1.6 pounds (table 27-100).

Slab yield per log or tree.—Tables 27-142 and 27-143 give cubic-foot yields of slabs and edgings from logs 6 to 20 inches in diameter and 8 to 16 feet long. These estimates were developed by Bennett and Lloyd (1974) by an extension of the International ¼-inch and Scribner log rules. The authors caution that slab and edging estimates based on the International ¼-inch rule represent the minimum to expect; they apply if the logs are bucked into lengths that eliminate most of the sweep and crook and are carefully and properly sawn.

Tables 18-57 through 18-62 tally predicted cubic-foot yields of chippable residues from 10 to 24-inch-diameter trees in six species: red maple, black oak, chestnut oak, northern red oak, white oak, and yellow-poplar. In this study by Hanks (1977) sawmill residue volume was defined as the cubic-foot volume of a tree—including rot and voids—that reaches the mill and is not converted to lumber or sawdust. Most of this residue is suitable for pulp chips, but 2 to 4 percent is not usable because of rot (see page 1954).

In Massengale's (1971) study of mixed oak logs from the Missouri Ozarks, he projected the average weight of green slabs and edgings per log—ranging from 34 pounds for 8-inch-diameter logs 8 feet long to 347 pounds for 16-inch-diameter logs 16 feet long (table 27-146).

Chippable residues (slabs, edgings, and end trim) accounted for an average of 20 percent of the green weight of black oak saw logs processed in western North Carolina (Phillips 1975). As scaling diameter increased, chippable residue decreased, ranging from 25.6 percent of small-diameter logs to only 16.4 percent of large-diameter logs (table 27-147). In this study, 130 sample logs were cut from 40 trees 12 to 26 inches in dbh, bucked into logs 8 to 16 feet long with a minimum scaling diameter of 8 inches inside bark, and debarked with a rosser-head debarker. Logs were sawn in a mill with a thin-kerf band headsaw, an in-line edger, and end-trim saws for maximum grade yield of 4/4 and 5/4 lumber. Predicted residue yields are given by log diameter and log length in table 27-148 and by tree dbh and merchantable height in table 27-149.

A comparable study with yellow-poplar (Clark et al. 1974; Clark 1976) showed that 18 percent of the saw log green weight ends up as chippable residue. As in the black oak study, the yield of chippable residue decreased with increasing log size, ranging from 33 percent for 7-inch logs to 14 to 17 percent for large logs (table 27-150). The study sample was 230 saw logs from 47 yellow-poplar trees 12 to 28 inches in dbh cut in western North Carolina. Stems were bucked into 8- to 16-foot logs with a minimum scaling diameter of 8 inches inside bark. After debarking in a rosserhead debarker, logs were sawn into 4/4 lumber in a conventional hardwood mill with a 3/16-inch-kerf band headsaw and in-line edger and trim saws. Predicted residue yields are given by log size in table 27-151 and by tree size in table 27-152.

PULP CHIPS

Pulp chip yield per Mbf log scale, per Mbf lumber scale, per log, and per tree can be estimated from data in the preceding sub-section: SLABS, EDGINGS, AND TRIM.

Dry yield of wood and bark per green ton of whole-tree chips.—In a study of small hardwoods (1 to 5 inches in dbh) growing in the Georgia Piedmont and North Carolina mountains, Phillips and McClure (1976) computed the yields of dry wood and bark that could be expected from one green ton of chips for each species (table 27-153). Yellow-poplar yielded about 850 pounds of dry wood and bark out of 2,000 pounds of green wood and bark; hickory yielded about 1,250. The other species were intermediate in yield, with values of 1,000 to 1,250 pounds. (Details on the sample trees used in this study are given in tables 7-3 and 16-7).

Wood and bark content of whole-tree chips.—Whole-tree chips from aboveground, foliage-free portions of northern red oak and yellow-poplar trees are about 84 percent wood and 16 percent bark (Clark 1978). Bark content of whole-tree chips of other species can be approximated from data in sections 13-3 and 16-1.

Chip bulk density.—See tables 16-44 and 16-44A with related discussion in section 16-3.

SAWDUST

Circular saws produce more sawdust than bandsaws, which have thinner kerfs. For example, when yellow-poplar was sawn into 4/4 lumber with a 3/16-inch-kerf band headsaw, sawdust averaged 12 to 13 percent of log green weight, regardless of log size (table 27-150). Similarly, black oak of all diameters sawn with a thin-kerf band headsaw yielded 10 to 12 percent sawdust (table 27-147). However, when mixed oak logs were processed with a circular saw, sawdust percentages were 17 to 22 (Massengale 1971).

Sawdust yields from processing trees 10 to 24 inches in dbh are given in tables 18-57 through 18-62 for red maple, black oak, chestnut oak, northern red oak, white oak, and yellow-poplar.

In producing these tables, Hanks (1977) used a kerf size of 10/64 for bandsaws and 17/64 for circular saws. For a different kerf size, adjust the sawdust volume as follows:

$$\text{Adjusted sawdust volume} = \text{sawdust volume in table} \times \frac{\text{new kerf}}{10/64 \text{ or } 17/64} \qquad (27\text{-}51)$$

For mixed oak logs sawn with a circular saw in Missouri (Massengale 1971), sawdust green weights ranged from 50 pounds for an 8-inch 8-foot-long log to 406 pounds for a 16-inch, 16-foot-long log (table 27-146). Massengale also provided data on sawdust production per Mbf Doyle log scale (table 27-144) and per Mbf lumber scale (table 27-145).

For black oak sawn with a band saw, tallies of sawdust production by log size and by tree size are in tables 27-147 through 27-149. Comparable data for yellow-poplar are in tables 27-150 through 27-152.

Bulk density.—The bulk density of sawdust depends in large part on the wood species, the moisture content of the sawdust, and its degree of compaction. Fresh sawdust has higher bulk density than air-dried sawdust; sawdust which has been blown or packed into a container has higher bulk density than sawdust which has merely fallen in by gravity. See tables 16-44 and 16-45 and related discussion in section 16-3 for data.

TABLE 27-1—*Solid content (wood and bark) per stacked standard cord) of 4- and 8-ft-long rough hardwood pulpwood in three diameter classes* (Redman 1957)[1]

Character of bolts	Bold mid-length diameter outside bark (inches)					
	Less than 6		6 to 12		More than 12	
	4 ft	8 ft	4 ft	8 ft	4 ft	8 ft
	Cubic feet					
Straight						
Smooth	85	82	91	88	98	95
Slightly rough	82	78	89	86	96	93
Slightly rough and knotty	78	73	85	82	92	90
Not straight						
Slightly crooked and rough	75	70	82	79	89	86
Considerably crooked	70	65	79	75	85	82
Crooked, rough and knotty	67	60	75	70	78	75
Tops and branches	58	50	—	—	—	—

[1]Original data from: Forest Research Digest, Lake States Forest Experiment Station, May 1935. (Mimeographed.) Values shown are for the standard cord, 4 by 4 by 8 ft.

TABLE 27-2—*Volume of solid wood, excluding bark, in standard rough cords cut in the North Carolina Piedmont from trees in 10 dbh classes* (Welch 1975)

Dbh (inches)	All species	Pine	Other softwood	Hardwood
	Cubic feet			
6	60.6	61.0	68.2	60.0
8	68.4	68.1	76.0	68.4
10	73.3	73.1	81.4	73.4
12	76.5	76.7	85.2	76.4
14	78.8	79.4	88.2	78.4
16	80.3	81.6	90.4	79.8
18	81.4	83.3	92.3	80.8
20	82.1	84.8	93.8	81.5
22	82.6	86.0	95.1	82.1
24+	83.5	88.1	97.9	83.0
Average	72.9	71.5	77.4	73.8

TABLE 27-3—*Bark volume in cordwood (as percent of unpeeled wood) for different average values of the ratio (k) of diameter outside bark to diameter inside bark* (Chamberlain and Meyer 1950)

Ratio (k)	Bark volume in percent of unpeeled wood[1]
0.85	22.2
.86	20.8
.87	19.4
.88	18.0
.89	16.6
.90	15.2
.91	13.8
.92	12.3
.93	10.8
.94	9.3
.95	7.8

[1]Computed by formula $80(1-k^2)$.

TABLE 27-4—*Number of standard cords of unpeeled wood required to make one standard cord or one long cord of peeled wood* (After Worley 1958)

Species type	Number of standard cords of unpeeled wood for: One cord peeled	One long cord peeled
Thin-barked trees such as red maple, beech	1.12	1.40
Medium-bark trees such as red, scarlet, and white oak	1.17	1.47
Thick-barked trees, such as black and chestnut oak	1.23	1.55

TABLE 27-5—*Number of pulpwood bolts*[1] *of various lengths and diameters to make a standard rough cord* (Hawes 1940)

Bolt diameter[2] (inches)	Bolt length in feet				
	4	5	5.25	5.66	6
	Number				
5	152	122	116	108	102
6	109	87	84	78	73
7	82	66	62	58	55
8	64	51	49	45	43
9	51	41	39	36	34
10	42	33	32	30	28
11	35	28	27	25	23
12	30	24	23	21	20

[1]Bolts of better than average straightens and surface smoothness.
[2]D i b at midlength.

TABLE 27-6—*Number of veneer cores per nominal cord*[1] (Williams and Hopkins, 1969, p. 9)

Core diameter (inches)	Core length in inches	
	102[2]	54[3]
	Number	
3.5	191	402
4.0	148	312
4.5	117	245
5.0	93	196
5.5	78	163
6.0	64	135
6.5	55	116

[1]Calculations based on volumes of true cylinders.
[2]This cord measures 48 by 48 by 102 inches (136 cu ft gross).
[3]This cord measures 48 by 96 by 54 inches (144 cu ft gross).

TABLE 27-7—*Number of trees to make a standard rough cord by dbh and merchantable height* (Worley 1958)[1]

Dbh (inches)	Merchantable height (feet)					
	8	16	24	32	40	48
FORM CLASS 75						
8	33.0	18.2	13.5			
10		11.6	8.8	7.3		
12		8.1	6.0	5.0	4.5	
14		6.0	4.6	3.8	3.3	3.1
FORM CLASS 80						
8	32.0	17.3	12.5			
10		11.0	8.1	6.4		
12		7.8	5.7	4.6	3.9	
14		5.6	4.0	3.2	2.7	2.5

[1]Assuming the solid content in a cord = 90 cu ft of wood and bark.

TABLE 27-8—*Pulpwood volume in mixed oak topwood remaining after removal of sawlogs. Volume is given in 160-cu ft stacked units of sticks 5-ft-long, peeled and large sticks split. To obtain volume in standard cords (128 cu ft) of rough wood, multiply values by 1.44; for volume in standard cords of peeled wood, multiply by 1.15* (Barrett and Buell 1941)[1,2]

Tree dbh (inches	Number of 16.3-ft logs in tree								
	½	1	1½	2	2½	3	3½	4	Basis
	Number of 160-cu-ft cords, peeled topwood								*Number of trees*
9	.024	.017	.013	.010					
10	.035	.026	.019	.014	.010				1
11	.049	.036	.027	.020	.015				2
12	.067	.049	.037	.027	.020				3
13	.089	.066	.049	.036	.027				5
14	.116	.086	.064	.047	.035	.026			10
15	.150	.111	.082	.061	.045	.033			11
16	.189	.140	.104	.077	.057	.042	.031		12
17	.235	.174	.129	.096	.071	.053	.039		20
18	.289	.214	.159	.118	.087	.065	.048	.036	31
19		.260	.193	.143	.106	.079	.058	.043	26

See Footnote at end of Table.

TABLE 27-8—*Pulpwood volume in mixed oak topwood remaining after removal of sawlogs. Volume is given in 160-cu ft stacked units of sticks 5-ft-long, peeled and large sticks split. To obtain volume in standard cords (128 cu ft) of rough wood, multiply values by 1.44; for volume in standard cords of peeled wood, multiply by 1.15* (Barrett and Buell 1941)[1,2]—Continued

Tree dbh (inches	Number of 16.3-ft logs in tree								
	½	1	1½	2	2½	3	3½	4	Basis
	Number of 160-cu-ft cords, peeled topwood								*Number of trees*
20		.313	.232	.172	.128	.095	.070	.052	27
21		.374	.277	.205	.152	.113	.084	.062	24
22		.442	.328	.243	.180	.133	.099	.073	17
23		.519	.385	.285	.211	.157	.116	.086	12
24		.606	.449	.333	.247	.183	.135	.100	7
25			.520	.386	.286	.212	.157	.116	7
26			.600	.445	.329	.244	.181	.134	2
27			.687	.509	.378	.280	.207	.154	6
28			.784	.581	.431	.319	.237	.175	1
29			.890	.659	.489	.362	.268	.199	2
30			1.006	.745	.552	.409	.303	.225	2
31			1.133	.839	.622	.461	.342	.253	2
32			1.269	.941	.697	.517	.383	.284	
33							.428	.317	1
34							.477	.354	
Basis (No. trees)	3	19	53	63	57	28	6	2	231

[1]Volume includes topwood above limit of sawlog merchantability to 5-in diameter inside bark in branches.

[2]Field data collected on Bent Creek Experimental Forest, N.C. Block indicates extent of basic data.

TABLE 27-9—*Upland oak yield per acre of merchantable stem, in standard rough cords, to a 4-inch top outside bark* (Schnur 1937)[1]

Total age (years)	Yield per acre of merchantable stem by site index[2]				
	40	50	60	70	80
	Cords				
10	0.0	0.0	0.0	0.12	0.24
15	.0	.24	.47	.94	2.24
20	.24	.82	2.00	4.24	7.29
25	1.18	2.94	6.00	9.65	13.76
30	3.18	6.35	10.35	14.94	19.88
35	5.65	9.65	14.59	19.88	25.41
40	8.00	12.82	18.59	24.59	30.71
45	10.24	15.88	22.47	29.06	35.76

See Footnote at end of Table.

TABLE 27-9—*Upland oak yield per acre of merchantable stem, in standard rough cords, to a 4-inch top outside bark* (Schnur 1937)[1]—Continued

Total age (years)	Yield per acre of merchantable stem by site index[2]				
	40	50	60	70	80
	Cords				
50	12.47	18.82	26.24	33.29	40.59
55	14.59	21.65	29.65	37.41	44.94
60	16.71	24.47	32.94	40.94	48.94
65	18.71	26.94	35.88	44.35	52.71
70	20.59	29.53	38.71	47.41	56.12
75	22.35	31.88	41.29	50.35	59.53
80	24.12	34.12	43.88	53.06	62.82
85	25.88	36.12	46.12	55.76	65.88
90	27.41	38.00	48.47	58.35	69.06
95	28.94	39.36	50.59	60.94	72.12
100	30.47	41.41	52.71	63.53	75.06

[1]Based on a rangewide study of upland oaks.
[2]Site index = tree height in feet at age 50 years.

TABLE 27-10—*Total cordwood volume per acre of upland oak for all trees over 4.5 inches dbh, by age and basal area* (Evans et al. 1975)[1]

Basal area	Average stand age—years									
	20	30	40	50	60	70	80	90	100	110
	Standard rough cords per acre									
	SITE INDEX 55[2]									
20	0.8	2.6	4.0	4.9	5.4	5.7	5.9	6.1	6.2	6.3
30	1.3	3.9	6.1	7.4	8.2	8.7	9.0	9.2	9.4	9.6
40	1.5	5.0	8.1	9.9	11.0	11.7	12.1	12.5	12.7	13.0
50	1.7	5.9	9.9	12.4	13.8	14.7	15.3	15.7	16.1	16.4
60	1.8	6.7	11.6	14.8	16.6	17.7	18.4	19.0	19.4	19.8
70	1.8	7.3	13.0	17.0	19.4	20.7	21.6	22.3	22.8	23.2
80	—	7.7	14.4	19.2	22.1	23.8	24.8	25.6	26.2	26.7
90	—	—	15.6	21.3	24.7	26.8	28.0	28.9	29.6	30.1
100	—	—	—	—	27.4	29.8	31.2	32.2	33.0	33.6
110	—	—	—	—	—	—	34.4	35.6	36.4	37.1
120	—	—	—	—	—	—	—	—	—	40.6

See Footnote at end of Table.

TABLE 27-10—*Total cordwood volume per acre of upland oak for all trees over 4.5 inches dbh, by age and basal area* (Evans et al. 1975)[1]—Continued

Basal area	Average stand age—years									
	20	30	40	50	60	70	80	90	100	110
	Standard rough cords per acre									
	SITE INDEX 65									
20	1.4	3.4	4.8	5.5	5.9	6.2	6.5	6.7	6.8	6.9
30	2.0	5.1	7.2	8.4	9.1	9.5	9.9	10.1	10.4	10.6
40	2.5	6.7	9.7	11.3	12.2	12.8	13.3	13.7	14.0	14.2
50	2.9	8.1	12.0	14.2	15.4	16.2	16.8	17.2	17.6	18.0
60	3.2	9.4	14.3	17.0	18.5	19.5	20.3	20.8	21.3	21.7
70	3.3	10.5	16.4	19.8	21.7	22.9	23.8	24.5	25.0	25.5
80	—	11.4	18.4	22.6	24.9	26.3	27.3	28.1	28.7	29.3
90	—	—	20.3	25.3	28.0	29.7	30.9	31.7	32.5	33.1
100	—	—	—	27.9	31.2	33.1	34.4	35.4	36.2	36.9
110	—	—	—	—	—	36.5	38.0	39.1	40.0	40.7
120	—	—	—	—	—	—	—	42.8	43.8	44.6
130	—	—	—	—	—	—	—	—	—	48.4
	SITE INDEX 75									
20	1.9	4.1	5.4	6.1	6.5	6.8	7.1	7.3	7.5	7.6
30	2.9	6.3	8.2	9.3	9.9	10.4	10.8	11.1	11.4	11.6
40	3.7	8.3	11.1	12.5	13.4	14.1	14.6	15.0	15.3	15.6
50	4.3	10.2	13.8	15.7	16.9	17.7	18.4	18.9	19.3	19.7
60	4.8	12.0	16.6	19.0	20.4	21.4	22.2	22.9	23.4	23.8
70	5.2	13.6	19.2	22.2	24.0	25.2	26.1	26.8	27.4	27.9
80	5.4	15.0	21.8	25.4	27.5	28.9	30.0	30.8	31.5	32.1
90	—	16.3	24.3	28.6	31.1	32.7	33.9	34.8	35.6	36.3
100	—	—	26.8	31.8	34.6	36.5	37.8	38.9	39.8	40.5
110	—	—	—	—	38.2	40.2	41.7	42.9	43.9	44.7
120	—	—	—	—	—	—	45.7	47.0	48.0	48.9
130	—	—	—	—	—	—	—	—	52.2	53.2
	SITE INDEX 85									
20	2.5	4.8	6.0	6.7	7.2	7.5	7.8	8.0	8.2	8.3
30	3.8	7.3	9.2	10.2	10.9	11.5	11.9	12.2	12.5	12.7
40	4.9	9.8	12.3	13.8	14.7	15.4	16.0	16.5	16.8	17.1
50	5.9	12.1	15.5	17.3	18.6	19.5	20.2	20.8	21.2	21.6
60	6.7	14.4	18.7	21.0	22.4	23.5	24.4	25.1	25.7	26.1
70	7.3	16.5	21.8	24.6	26.3	27.6	28.6	29.5	30.1	30.7
80	7.8	18.5	24.9	28.2	30.2	31.7	32.9	33.8	34.6	35.2
90	—	20.3	27.9	31.8	34.2	35.9	37.2	38.2	39.1	39.8
100	—	—	30.9	35.4	38.1	40.0	41.5	42.7	43.6	44.4
110	—	—	—	39.1	42.1	44.2	45.8	47.1	48.2	49.1
120	—	—	—	—	—	48.4	50.1	51.6	52.7	53.7
130	—	—	—	—	—	—	—	56.0	57.3	58.4

[1]Source: Dale, Martin E. 1972. Growth and yield predictions for upland oak stands 10 years after initial thinning. U.S.F.S. Northeastern Forest Exp. Sta., Res. Paper NE-241. 21p.

[2]Site index = Tree height in feet at age 50 years.

TABLE 27-11—*Yields per acre for upland oaks; no thinning* (Gingrich 1971)

Age (years)	Basal area per acre	Trees	Average tree diameter[1]	Yields		
	Square feet	*Number*	*Inches*	*Cubic feet*[2]	*Cords*[3]	*Board feet*[4]
			SITE INDEX 55[5]			
20	55	2,500	2.0	60	0.6	—
30	75	1,260	3.3	583	5.3	—
40	87	790	4.5	1,320	12.1	—
50	97	480	6.1	2,150	19.7	400
60	104	357	7.3	2,520	22.9	900
70	108	295	8.2	2,730	24.4	2,800
80	112	242	9.2	2,880	25.6	5,400
			SITE INDEX 65			
20	59	1,880	2.4	178	1.6	—
30	81	930	4.0	1,200	10.6	—
40	96	505	5.9	1,840	18.2	440
50	105	342	7.5	2,800	26.9	2,150
60	111	262	8.8	3,300	30.8	5,160
70	115	215	9.9	3,700	33.3	7,200
80	117	187	10.7	3,950	35.6	8,200
			SITE INDEX 75			
20	70	1,425	3.0	694	6.4	—
30	89	680	4.9	1,670	16.7	—
40	101	400	6.8	2,440	23.7	1,380
50	110	279	8.5	3,315	30.1	4,100
60	114	222	9.7	4,140	37.7	9,288
70	117	187	10.7	4,760	43.0	11,200
80	120	166	11.5	5,160	46.5	12,500

[1]The diameter of the tree of average basal area.

[2]Total cubic-root volume of entire stem, including bark, tip, stump, but no branches. The equation: Cubic volume = $0.60 + 0.00249\ D^2H$.

[3]Standard cords to a 4-inch top inside bark, excluding bark and branches. The equation: Cord volume = $0.00532 + 0.02275\ D^2H/1000$.

[4]Board-foot volume, International ¼-inch rule, to an 8.5-inch top, outside bark. The equation: Board-foot volume = $-41.046 + 0.01161\ D^2H$.

[5]Site index = tree height in feet at age 50 years.

TABLE 27-12—*Cordwood volume in mixed hardwood stands on a variety of sites throughout the South* (Derived from Porterfield 1972)[1]

Location and years (age)	Volume
	Standard rough cords per acre
Upland slopes and ridges, mountains	
23	11.9
26	13.6
31	16.1
Upland slopes and ridges, Piedmont	
18	8.8
20	10.1
25	13.1
Branch bottoms	
19	15.8
22	19.6
26	24.1
Wet flats	
23	19.0
26	22.7
33	30.4

[1]Porterfield's data on nine types of locations, of which only four are shown here (the others were bottomlands and swamps), were based on 541 one-fifth-acre plots from Delaware to east Texas.

TABLE 27-13—*Doyle log scale, contents of logs in board feet*

Scaling diameter (inches)	Log length in feet					
	6	8	10	12	14	16
	Board feet					
6	2	2	3	3	4	4
7	3	5	6	7	8	9
8	6	8	10	12	14	16
9	9	13	16	19	22	25
10	14	18	23	27	32	36
11	18	25	31	37	43	49
12	24	32	40	48	56	64
13	30	41	51	61	71	81
14	38	50	63	75	88	100
15	45	61	76	91	106	121

See Footnote at end of Table.

TABLE 27-13—*Doyle log scale, contents of logs in board feet*—Continued

Scaling diameter (inches)	Log length in feet					
	6	8	10	12	14	16
	Board feet					
16	54	72	90	108	126	144
17	63	85	106	127	148	169
18	74	98	123	147	172	196
19	84	113	141	169	197	225
20	96	128	160	192	224	256
21	108	145	181	217	253	289
22	122	162	203	243	284	324
23	135	181	226	271	316	361
24	150	200	250	300	350	400
25	165	221	276	331	386	441
26	182	242	303	363	424	484
27	198	265	331	397	463	529
28	216	288	360	432	504	576
29	234	313	391	469	547	625
30	254	338	423	507	592	676

TABLE 27-14—*Volume of 16-ft logs to nearest board foot by the Doyle log scale* (Mesavage and Girard 1956)

Scaling diameter (inches)	Scaling diameter in tenths of inches									
	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
	Board feet									
5	1	1	1	2	2	2	3	3	3	4
6	4	4	5	5	6	6	7	7	8	8
7	9	10	10	11	12	12	13	14	14	15
8	16	17	18	18	19	20	21	22	23	24
9	25	26	27	28	29	30	31	32	34	35
10	36	37	38	40	41	42	44	45	46	48
11	49	50	52	53	55	56	58	59	61	62
12	64	66	67	69	71	72	74	76	77	79
13	81	83	85	86	88	90	92	94	96	98
14	100	102	104	106	108	110	112	114	117	119
15	121	123	125	128	130	132	135	137	139	142
16	144	146	149	151	154	156	159	161	164	166
17	169	172	174	177	180	182	185	188	190	193
18	196	199	202	204	207	210	213	216	219	222
19	225	228	231	234	237	240	243	246	250	253
20	256	259	262	266	269	272	276	279	282	286
21	289	292	296	299	303	306	310	313	317	320
22	324	328	331	335	339	342	346	350	353	357
23	361	365	369	372	376	380	384	388	392	396
24	400	404	408	412	416	420	424	428	433	437
25	441	445	449	454	458	462	467	471	475	480
26	484	488	493	497	502	506	511	515	520	524
27	529	534	538	543	548	552	557	562	566	571
28	576	581	586	590	595	600	605	610	615	620

TABLE 27-14—*Volume of 16-ft logs to nearest board foot by the Doyle log scale* (Mesavage and Girard 1956)—Continued

Scaling diameter (inches)	Scaling diameter in tenths of inches									
	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
	Board feet									
29	625	630	635	640	645	650	655	660	666	671
30	676	681	686	692	697	702	708	713	718	724
31	729	734	740	745	751	756	762	767	773	778
32	784	790	795	801	807	812	818	824	829	835
33	841	847	853	858	864	870	876	882	888	894
34	900	906	912	918	924	930	936	942	949	955

TABLE 27-15—*Scribner Decimal C log scale, contents of logs in board feet*

Scaling diameter (inches)	Log length in feet					
	6	8	10	12	14	16
	Board feet					
6	5	5	10	10	10	20
7	5	10	10	20	20	30
8	10	10	20	20	20	30
9	10	20	30	30	30	40
10	20	30	30	30	40	60
11	20	30	40	40	50	70
12	30	40	50	60	70	80
13	40	50	60	70	80	100
14	40	60	70	90	100	110
15	50	70	90	110	120	140
16	60	80	100	120	140	160
17	70	90	120	140	160	180
18	80	110	130	160	190	210
19	90	120	150	180	210	240
20	110	140	170	210	240	280
21	120	150	190	230	270	300
22	130	170	210	250	290	330
23	140	190	230	280	330	380
24	150	210	250	300	350	400
25	170	230	290	340	400	460
26	190	250	310	370	440	500
27	210	270	340	410	480	550
28	220	290	360	440	510	580
29	230	310	380	460	530	610
30	250	330	410	490	570	660

TABLE 27-16—*Volume of 16-foot logs to the nearest board foot by the Scribner log scale*[1] (Mesavage and Girard 1956)

Scaling diameter (inches)	Scaling diameter in tenths of inches									
	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
	Board feet									
6	12	13	14	15	16	16	17	18	19	20
7	21	22	23	24	24	25	26	27	28	29
8	30	31	32	33	34	36	37	38	39	41
9	42	43	45	46	47	48	50	51	52	54
10	55	56	58	60	61	63	64	66	67	69
11	70	72	74	75	77	78	80	81	83	84
12	86	88	90	91	93	95	97	99	101	102
13	104	106	108	110	111	113	115	117	119	121
14	123	125	127	129	131	133	135	137	140	142
15	144	146	148	150	153	155	157	159	161	164
16	166	168	171	173	175	177	180	182	185	187
17	189	191	194	196	199	202	204	207	210	213
18	216	218	221	224	227	229	231	234	237	240
19	243	245	248	251	254	257	260	263	266	269
20	272	275	278	281	284	287	290	293	296	299
21	302	305	308	311	314	317	320	323	327	330
22	334	337	340	344	348	351	354	358	361	365
23	368	372	375	379	382	386	390	394	397	400
24	403	406	410	414	418	422	426	429	432	436
25	440	444	448	452	456	460	464	468	472	475
26	478	482	486	490	494	498	502	506	510	514
27	518	522	526	530	534	538	542	546	550	554
28	559	563	567	571	575	579	583	587	592	597
29	602	606	611	615	620	624	629	633	638	642
30	647	651	656	660	665	669	674	678	683	688
31	693	698	703	708	712	717	722	726	731	736
32	741	746	751	756	761	766	770	775	780	785
33	790	795	800	805	810	815	820	825	830	835
34	841	846	851	856	862	867	872	877	883	888
35	894	900	905	910	915	921	926	931	937	942

[1]Computed from equation 27-6.

TABLE 27-17—*Deductions for defect*[1] *from Scribner Decimal C log scale* (U.S. Department of Agriculture, Forest Service 1965b)

Defect length (feet)	Deduction in board feet																			
	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
	Cross-sectional area of defect in square inches																			
2	38	113	188	263	338	413	488	563	638											
4	19	57	94	132	169	207	244	282	319	357	394	432	469	507	544	582	619	657		
6	13	38		88	113	138	163	188	213	238	263	288	313	338	363	388	413	438	463	488
8	10	29	47	66	85	104	122	141	160	179	197	216	235	254	272	291	310	329	347	366
10	8	23	38	53	68	83	98	113	128	143	158	173	188	203	218	233	248	263	278	293
12	7	19	32	44	57	69	82	94	107	119	132	144	157	169	182	194	207	219	232	244
14	6	17	27	38	49	59	70	81	92	102	113	124	134	145	156	167	177	188	199	209
16	5	15	24	33	43	52	61	71	80	90	99	108	118	127	136	146	155	165	174	183
18	5	13	21	30	38	46	55	63	71	80	88	96	105	113	121	130	138	146	155	163
20	4	12	19	27	34	42	49	57	64	72	79	87	94	102	109	117	124	132	139	147

[1]Example: If the end of the defect measures 9 by 11 inches (99 sq in), and the length is 12 feet, read horizontally from defect length of 12 feet to 99 sq in or next lower number found (in this case 94); read up to find the deduction of 80 bd ft at column head.

TABLE 27-18—*International 1/4-inch log scale, contents of logs in board feet*

Scaling diameter (inches)	Log length in feet					
	6	8	10	12	14	16
	Board feet					
6	5	10	10	15	15	20
7	10	10	15	20	25	30
8	10	15	20	25	35	40
9	15	20	30	35	45	50
10	20	30	35	45	55	65
11	25	35	45	55	70	80
12	30	45	55	70	85	95
13	40	55	70	85	100	115
14	45	65	80	100	115	135
15	55	75	95	115	135	160
16	60	85	110	130	155	180
17	70	95	125	150	180	205
18	80	110	140	170	200	230
19	90	125	155	190	225	260
20	100	135	175	210	250	290
21	115	155	195	235	280	320
22	125	170	215	260	305	355
23	140	185	235	285	335	390
24	150	205	255	310	370	425
25	165	220	280	340	400	460
26	180	240	305	370	435	500
27	195	260	330	400	470	540
28	210	280	355	430	510	585
29	225	305	385	465	545	630
30	245	325	410	495	585	675

TABLE 27-19—*Volumes of 8- and 16-foot logs to the nearest board foot by the International 1/4-inch log scale*

Scaling length (feet) and diameter (inches)	Scaling diameter in tenths of inches									
	.0	.1	.2	.3	.4	.5	.6	.7	.8	.9
	Board feet									
8 foot[1]										
6.	8	8	9	9	9	10	10	10	11	11
7.	12	12	13	13	13	14	14	15	16	16
8.	17	17	18	18	19	19	20	20	21	22
9.	22	23	23	24	25	25	26	27	27	28
10.	29	29	30	31	31	31	32	33	34	35
11.	36	37	38	38	39	40	41	42	42	43
12.	44	45	46	47	47	48	49	50	51	52
13.	53	54	55	56	57	58	59	60	61	62
14.	63	66	65	66	67	68	69	70	71	72
15.	73	74	75	76	77	79	80	81	82	83
16.	84	85	87	88	88	90	91	93	94	95
17.	96	98	99	100	101	103	104	105	107	108

See Footnote at end of Table.

TABLE 27-19—*Volumes of 8- and 16-foot logs to the nearest board foot by the International ¼-inch log scale*—Continued

Scaling length (feet) and diameter (inches)	Scaling diameter in tenths of inches .0	.1	.2	.3	.4	.5	.6	.7	.8	.9
	Board feet									
8 foot[1]										
18	109	110	112	113	115	116	117	119	120	121
19	123	124	126	127	129	130	131	133	134	136
20	137	139	140	142	143	145	146	148	149	151
21	152	154	156	157	159	160	162	164	165	167
22	169	170	172	174	175	179	179	180	182	184
23	185	187	189	191	192	194	196	198	200	201
24	203	205	207	208	210	212	214	216	217	220
25	221	224	225	227	229	231	233	235	237	239
26	241	243	245	247	249	251	253	255	257	259
27	262	264	265	266	269	271	273	275	277	279
28	282	284	286	288	290	292	294	296	299	301
29	303	305	307	310	312	314	316	319	321	323
30	325	329	330	332	334	337	339	342	343	346
16 foot[2]										
6	19	20	21	22	23	23	24	25	26	27
7	28	29	30	31	32	33	34	35	36	38
8	39	40	41	42	43	45	46	47	48	50
9	51	52	54	55	56	58	59	60	62	63
10	65	66	68	69	71	72	74	75	77	78
11	80	82	83	85	87	88	90	92	93	95
12	97	99	100	102	104	106	108	110	112	114
13	115	117	119	121	123	125	127	129	131	133
14	136	138	140	142	144	146	148	151	153	155
15	157	160	162	164	166	169	171	173	176	178
16	181	183	185	188	190	193	195	198	200	203
17	205	208	211	213	216	219	221	224	227	229
18	232	235	237	240	243	246	249	251	254	257
19	260	263	266	269	272	275	278	281	284	287
20	290	293	296	299	302	305	308	311	315	318
21	321	324	327	331	334	337	341	344	347	351
22	354	357	361	364	367	371	374	378	381	385
23	388	392	395	399	403	406	410	413	417	421
24	424	428	432	435	439	443	447	451	454	458
25	462	466	470	474	478	481	485	489	493	497
26	501	505	509	513	517	521	526	530	534	538
27	542	546	550	555	559	563	567	572	576	580
28	584	589	593	598	602	606	611	615	620	624
29	628	633	637	642	647	651	656	660	665	669
30	674	679	683	688	693	697	702	707	712	716
31	721	726	731	736	741	745	750	755	760	765
32	770	775	780	785	790	795	800	805	810	815
33	820	826	831	836	841	846	851	857	862	867
34	872	878	883	888	894	899	904	910	915	921
35	926	931	937	942	948	953	959	964	970	976

[1]Computed from equation 27-10. [2]Computed from equation 27-9.

TABLE 27-20—*Board-foot volume (International ¼-inch rule) for individual 16-foot logs in trees of mixed hardwood species, form class*[1] 78 (U.S. Department of Agriculture, Forest Service 1965a)

Dbh class (inches)	Position of log in tree				
	1	2	3	4	5
	Board feet				
12	56	36	28	—	—
14	78	54	42	—	—
16	106	74	61	—	—
18	136	97	81	60	—
20	171	125	105	79	62
22	211	157	132	103	88
24	251	190	164	118	117
26	299	229	197	152	144
28	347	269	234	177	174
30	403	315	273	207	217

[1]Defined by equation 27-2.

TABLE 27-21—*Average upper-log taper for hardwoods* (U.S. Department of Agriculture, Forest Service 1965a)

Number of 16-foot logs in tree and log position	Tree dbh (inches)	
	12 to 18	20+
	Inches	
Two-log tree		
Second log	2.0	2.5
Three-log tree		
Second log	1.5	2.0
Third log	2.0	2.5
Four-log tree		
Second log	1.0	1.5
Third log	1.5	2.0
Fourth log	2.0	2.5

TABLE 27-22—*Gross volume of tree by form class*[1], *diameter, and number of 16-foot logs, International ¼-inch log scale* (Mesavage and Girard 1956)

Tree diameter (inches)	Volume, by number of usable 16-foot logs										
	1	1½	2	2½	3	3½	4	4½	5	5½	6
	Board feet										
	FORM CLASS 65										
10	23	29	35	—	—	—	—	—	—	—	—
12	36	46	57	64	71	—	—	—	—	—	—
14	52	68	84	96	107	—	—	—	—	—	—
16	71	94	116	134	151	162	174	—	—	—	—
18	92	122	152	176	200	216	233	—	—	—	—
20	115	154	193	224	256	278	299	316	332	—	—
22	142	192	241	280	320	348	377	401	425	—	—
24	171	232	292	342	392	426	459	492	526	—	—
	FORM CLASS 75										
10	33	43	53	—	—	—	—	—	—	—	—
12	51	67	83	95	107	—	—	—	—	—	—
14	72	96	120	138	157	169	181	—	—	—	—
16	97	130	163	190	217	237	257	—	—	—	—
18	125	169	213	250	286	312	339	—	—	—	—
20	157	214	271	318	365	399	433	460	488	—	—
22	193	264	335	394	454	499	544	582	620	—	—
24	232	318	405	479	553	606	659	712	764	—	—
	FORM CLASS 85										
10	45	60	74	84	94	—	—	—	—	—	—
12	68	91	114	132	150	162	173	—	—	—	—
14	95	129	163	190	217	236	254	—	—	—	—
16	127	173	219	258	297	326	355	—	—	—	—
18	164	224	285	336	388	428	468	—	—	—	—
20	205	282	360	426	492	543	594	636	678	—	—
22	251	348	444	526	609	674	740	796	852	—	—
24	302	420	537	639	741	818	895	971	1,047	—	—
	FORM CLASS 90										
10	51	68	85	98	110	—	—	—	—	—	—
12	77	104	131	152	174	188	202	—	—	—	—
14	108	147	186	218	250	273	296	—	—	—	—
16	144	197	250	296	341	376	411	—	—	—	—
18	185	255	325	385	445	492	539	—	—	—	—
20	232	321	410	487	564	624	684	734	784	—	—
22	284	394	505	601	697	774	850	917	984	—	—
24	341	476	610	728	846	936	1,027	1,116	1,204	—	—

[1]Defined by equation 27-2.

TABLE 27-23—*Coefficients for estimating board-foot or cubic-foot volume in the principal hardwood species of the Southeast* (Data from Bryan and McClure 1962)

COEFFICIENTS FOR BOARD-FOOT VOLUME EQUATION[1]

Species	Number of trees used	a	b_1	b_2
Ash sp.	45	− 2.44	0.038834	−0.7236
Hickory sp.	72	− 5.26	.038061	− .4626
Maple, red	67	− .42	.040385	−1.0743
Oak, chestnut	109	− 8.61	.039357	− .4924
Oak, northern red	59	− 4.60	.040752	− .8123
Oak, scarlet	117	− 5.44	.039133	− .6653
Oak, white	77	− 4.02	.039088	− .6716
Sweetgum	133	− 7.52	.040328	− .7234
Tupelo, black	98	−12.86	.037147	− .3387
Yellow-poplar	83	−14.93	.041232	− .5470

COEFFICIENTS FOR CUBIC-FOOT VOLUME EQUATION[2]

Species	Number of trees used	b_1	b_2	b_3
Ash, sp.	56	0.005304	0.01861	0.00003298
Hickory, sp.	73	.005218	.02099	.00002196
Maple, red	71	.005407	.02291	.00001495
Oak, chestnut	112	.005127	.02191	.00002040
Oak, northern red	60	.005331	.01970	.00002550
Oak, scarlet	125	.005224	.01907	.00002712
Oak, white	92	.005312	.01907	.00002843
Sweetgum	139	.005285	.02244	.00002658
Tupelo, black	141	.005056	.01617	.00006025
Yellow-poplar	125	.005307	.01949	.00002839

[1] $V_B = a + b_1DSH + b_2H$

where: V_B = gross board-foot volume (International ¼-inch rule)

D = diameter at breast height or 1.5 feet above point of bottleneck for normally swell-butted trees, inches.

S = scaling diameter (dib) at the top of the lower section, which is defined as the point of noticeable change in stem taper (also top of saw log portion in sawtimber trees), inches

H = length of lower section (also saw log section in sawtimber trees), feet.

[2] $V_C = b_1DSH + b_2SU + b_3(SU)^2$

where:

V_C = gross cubic-foot volume to a 4.0-inch top outside bark, excluding bark volume.

U = upper section length in feet. This is the section from the top of the lower section to the 4.0-inch o.b. top, and D, S, and H are as defined in footnote 1.

TABLE 27-24—*Gross volume in white ash trees of outside-bark form class[1] 87 by International ¼-inch log scale* (Buell 1942)[2,3]

Dbh (inches)	Number of 16.3-foot logs									
	½	1	1½	2	2½	3	3½	4	4½	5
	Board feet									
10	21	36	48	60	72	82				
11	26	44	61	75	90	103				
12	32	54	74	92	110	126				
13	39	66	89	111	132	152				
14	46	78	106	132	157	181	203			
15	54	92	125	156	184	212	239			
16	63	106	145	181	214	247	277			
17	72	123	167	208	247	284	320			
18	83	140	191	238	282	324	366	405		
19	94	159	217	270	321	368	415	459		
20	105	180	244	305	361	415	467	518		
21		201	274	341	405	466	524	579		
22		224	306	380	451	519	583	646	706	766
23			339	422	500	575	647	716	783	849
24			374	466	553	635	714	792	867	940

[1]Outside bark form class = (100) $\left[\frac{\text{Dob at top of 16.3-foot butt log}}{\text{Dbh}}\right]$

The table above is for the average outside-bark form class for all trees sampled. Factors for determining volumes for trees in other form classes (both outside-bark and inside-bark) are given in Buell (1942).

[2]Volume as utilized to a variable top diameter.

[3]Basic data: 52 trees from Pisgah and Nantahala National Forests and Tucker County, W. Va.

TABLE 27-25—*Gross volume in red maple trees of outside-bark form class[1] 84, by International ¼-inch log scale* (Buell 1942)[2,3]

Dbh (inches)	Number of 16.3-foot logs									
	½	1	1½	2	2½	3	3½	4	4½	5
	Board feet									
10	23	37	49	59						
11	28	46	60	74	86					
12	34	56	74	90	105	120				
13	41	67	89	108	126	144				
14	49	79	105	128	150	171	190	208		
15	57	93	123	151	176	200	222	244		
16	67	108	143	175	204	232	258	283		

See Footnote at end of Table.

TABLE 27-25—*Gross volume in red maple trees of outside-bark form class*[1] *84, by International ¼-inch log scale* (Buell 1942)[2,3]—Continued

Dbh (inches)	Number of 16.3-foot logs									
	½	1	1½	2	2½	3	3½	4	4½	5
	Board feet									
17	76	124	164	201	234	266	296	325		
18	87	141	188	229	267	304	338	372		
19	99	160	212	259	303	344	383	421		
20	111	180	239	292	341	387	430	473		
21		201	267	327	381	432	482	528		
22		224	297	363	425	482	537	589		
23		248	329	402	470	533	594	652		
24		274	363	444	519	589	656	719		

[1]Outside bark form class = $(100)\left[\frac{\text{Dob at top of 16.3-foot butt log}}{\text{Dbh}}\right]$

The table above is for the average outside-bark form class for all trees sampled. Factors for determining volumes for trees in other form classes (both outside-bark and inside-bark) are given in Buell (1942).

[2]Volume as utilized to a variable top diameter.

[3]Basic data: 88 trees from Pisgah and Nantahala National Forests; Tucker County, W. Va.; and Bland County, Va.

TABLE 27-26—*Gross volume in black oak trees of outside-bark form class*[1] *84, by International ¼-inch log scale* (Buell 1942)[2,3]

Dbh (inches)	Number of 16.3-foot logs									
	½	1	1½	2	2½	3	3½	4	4½	5
	Board feet									
10	20	33	45	56	66	76				
11	24	41	56	69	82	94				
12	30	50	68	84	100	115	128			
13	36	60	81	101	120	137	154	171		
14	42	71	96	120	142	163	182	202	220	
15	49	83	113	140	166	190	213	236	258	
16	57	96	131	162	192	220	247	274	298	
17	65	110	150	186	220	252	284	313	343	
18	74	126	171	212	251	288	323	357	390	
19	84	142	193	239	283	325	366	404	442	
20	95	160	217	269	318	365	410	454	496	
21		178	242	301	356	408	458	507	553	
22		198	269	334	395	454	509	564	615	
23		219	298	370	438	501	564	622	681	
24		242	328	407	482	552	621	686	750	

[1]Outside bark form class = $(100)\left[\frac{\text{Dob at top of 16.3-foot butt log}}{\text{Dbh}}\right]$

The table above is for the average outside-bark form class for all trees sampled. Factors for determining volumes for trees in other form classes (both outside-bark and inside-bark) are given in Buell (1942).

[2]Volume as utilized to a variable top diameter.

[3]Basic data: 150 trees from Cherokee, Nantahala, and Chattahoochee National Forests; Jackson County, Ohio; and Bland County, Va.

TABLE 27-27—*Gross volume of black oak trees, Scribner log scale* (Schnur 1937)[1,2,3]

Dbh (inches)		Volume (to an 8.0-inch top inside bark), by total height in feet								
Outside bark	Inside bark	40	50	60	70	80	90	100	110	Basis
		Board feet								*Trees*
10	9.0	0	0	4	13	30	47	61		27
11	9.9	0	4	20	45	63	80	93		51
12	10.9	1	14	50	73	92	109	127		45
13	11.8	4	36	72	95	116	140	164		34
14	12.7	10	54	90	116	144	173	202		15
15	13.7	21	70	107	140	173	208	240		19
16	14.7		84	125	163	203	240	278	318	12
17	15.6		96	144	190	233	277	321	367	12
18	16.6			163	214	263	312	362	418	7
19	17.5			184	240	295	352	409	472	10
20	18.5			206	266	330	394	456	525	6
21	19.5			228	292	365	435	507	584	4
22	20.5			250	326	401	480	560	644	3
23	21.4			272	358	442	528	615	708	
Basis (trees)			12	46	81	74	31	1		245

[1]Scaled in 16-foot log lengths with trimming allowance of 0.3 foot; additional top sections scaled as fractions of a 16-foot, 8.0-inch log. Stump height 1.0 foot.

[2]Heavy lines indicate limits of basic data.

[3]Trees measured were in Connecticut, Maryland, New Jersey, New York, Ohio, Tennessee, and West Virginia.

TABLE 27-28—*Gross volume in chestnut oak trees of outside-bark form class*[1] *86, by International ¼-inch log scale* (Buell 1942)[2,3]

Dbh (inches)	Number of 16.3-foot logs									
	½	1	1½	2	2½	3	3½	4	4½	5
	Board feet									
10	20	33	44							
11	25	41	55	67	79	90				
12	31	50	67	82	96	110				
13	37	61	81	99	116	133				
14	44	72	96	118	139	158				
15	52	85	113	139	163	186	208			
16	60	99	132	162	190	216	242			
17	70	114	152	187	219	249	278			
18	80	131	175	214	251	286	319			
19	90	148	198	243	284	324	361	398		

See Footnote at end of Table.

TABLE 27-28—*Gross volume in chestnut oak trees of outside-bark form class*[1] *86, by International ¼-inch log scale* (Buell 1942)[2,3]—Continued

Dbh (inches)	Number of 16.3-foot logs									
	½	1	1½	2	2½	3	3½	4	4½	5
	Board feet									
20	102	167	223	274	321	366	408	449		
21	114	188	250	307	360	410	458	504		
22	128	209	279	343	402	457	510	562		
23	142	232	310	380	446	508	568	624	678	
24	156	256	343	421	493	561	627	689	750	

[1]Outside bark form class = (100) $\left[\frac{\text{Dob at top of 16.3-foot butt log}}{\text{Dbh}}\right]$

The table above is for the average outside-bark form class for all trees sampled. Factors for determining volumes for trees in other form classes (both outside-bark and inside-bark) are given in Buell (1942.

[2]Volume as utilized to a variable top diameter.

[3]Basic data: 150 trees from Cherokee, Pisgah, and Nantahala Forests; Jackson County, Ohio; and Bland County, Va.

TABLE 27-29—*Gross volume of chestnut oak trees, Scribner log scale* (Schnur 1937)[1,2,3]

Dbh (inches) Outside bark	Dbh (inches) Inside bark	Volume (to an 8.0-inch top inside bark), by total height in feet: 40	50	60	70	80	90	100	110	Basis
		Board feet								*Trees*
10	8.7	0	0	6	21	34				33
11	9.6	2	16	29	44	59	77	96		49
12	10.5	18	33	48	65	84	105	130		54
13	11.4	32	48	65	85	108	135	162		32
14	12.3		62	83	107	133	164	197		24
15	13.2		77	101	128	158	194	234		6
16	14.1		92	118	148	185	226	270		2
17	15.1		107	136	172	210	258	309		3
18	16.0				194	240	290	347		1
19	16.9				219	268	324	387		
20	17.8				241	296	359	426		1
21	18.7				269	328	396	470	544	
22	19.7				296	360	434	515	595	
23	20.6				325	395	475	562	652	1
24	21.5				357	430	520	618	712	
Basis (trees)		1	37	106	47	13	1	1		206

[1]Scaled in 16-foot log lengths with trimming allowance of 0.3 foot; additional top sections scaled as fractions of a 16-foot, 8.0-inch log. Stump height 1.0 foot.

[2]Heavy lines indicate limits of basic data.

[3]Trees measured were in Connecticut, Maryland, New York, Ohio, and Pennsylvania.

TABLE 27-30—*Gross volume in red oak (sp) trees of outside-bark form class[1] 85, by International ¼-inch log scale* (Buell 1942)[2,3]

Dbh (inches)	½	1	1½	2	2½	3	3½	4	4½	5
	Board feet									
10	20	34	46	57	68	78				
11	25	42	58	71	84	96				
12	31	52	70	87	103	118				
13	37	62	'84	104	123	141	158			
14	44	73	100	123	146	167	187			
15	51	86	116	144	170	195	219	242		
16	59	100	135	167	197	226	254	280		
17	68	114	154	191	226	259	291	321		
18	78	130	176	218	258	296	331	366	400	
19	88	147	199	247	292	334	375	414	452	
20	99	166	224	277	327	375	421	466	508	
21		185	250	310	366	420	471	520	568	614
22		206	278	344	406	467	524	578	631	682
23		228	308	381	450	515	578	640	698	755
24		251	339	420	496	569	637	703	769	832

Column heading: Number of 16.3-foot logs

[1]Outside bark form class $= (100) \left[\frac{\text{Dob at top of 16.3-foot butt log}}{\text{Dbh}}\right]$

The table above is for the average outside-bark form class for all trees sampled. Factors for determining volumes for trees in other form classes (both outside-bark and inside-bark) are given in Buell (1942).

[2]Volume as utilized to a variable top diameter.

[3]Basic data: 280 trees from Cherokee, Pisgah, and Nantahala National Forests; Jackson County, Ohio; Garrett County, Md.; Tucker County, W. Va.; and Bland County, Va.

TABLE 27-31—*Gross volume of red oak (sp.) trees, Scribner log scale* (Schnur 1937)[1,2,3]

Dbh (inches)		Volume (to an 8.0-inch top inside bark), by total height in feet								
Outside bark	Inside bark	40	50	60	70	80	90	100	110	Basis
		Board feet								*Trees*
12	10.9	34	52	67	81	96	112			31
13	11.9	54	71	87	102	118	138	163		21
14	12.8	70	88	105	123	142	167	198		22
15	13.7	84	104	123	143	167	198	236		14
16	14.7		119	141	166	195	231	276		15
17	15.6		134	161	190	223	266	317		9
18	16.6		151	181	215	254	301	360		7
19	17.6		168	203	240	284	340	408	487	7

See Footnote at end of Table.

TABLE 27-31—*Gross volume of red oak (sp.) trees, Scribner log scale* (Schnur 1937)[1,2,3]—Continued

Dbh (inches)		Volume (to an 8.0-inch top inside bark), by total height in feet								
Outside bark	Inside bark	40	50	60	70	80	90	100	110	Basis
		Board feet								*Trees*
20	18.6		186	226	270	319	380	455	545	4
21	19.6		208	252	300	358	428	512	615	3
22	20.6					398	474	570	682	
23	21.6					440	528	633	760	
24	22.5					487	581	700	840	1
25	23.4						640	765	920	
26	24.4						700	840	1,005	
27	25.4						765	920	1,090	
28	26.4						830	995	1,180	1
29	27.4						895	1,070	1,275	
Basis (trees)			7	41	37	32	16	2		135

[1]Scaled in 16-foot log lengths with trimming allowance of 0.3 foot; additional top sections scaled as fractions of a 16-foot, 8.0-inch log. Stump height 1.0 foot.

[2]Heavy lines indicate limits of basic data.

[3]Trees measured were in Connecticut, Maryland, New York, Ohio, Virginia, and West Virginia.

TABLE 27-32—*Gross volume in scarlet oak trees of outside-bark form class*[1] *87, by International ¼-inch log scale* (Buell 1942)[2,3]

Dbh (inches)	Number of 16.3-foot logs									
	½	1	1½	2	2½	3	3½	4	4½	5
	Board feet									
10	23	38	52	64	76	87				
11	28	47	64	80	94	108	121			
12	34	58	78	97	115	131	147	163		
13	41	69	94	116	137	157	177	195		
14	49	82	111	137	162	186	209	231	252	
15	57	96	130	161	190	218	244	270	295	
16	66	111	150	186	220	252	282	313	341	369

See Footnote at end of Table.

TABLE 27-32—*Gross volume in scarlet oak trees of outside-bark form class*[1] *87, by International 1/4-inch log scale* (Buell 1942)[2,3]—Continued

Dbh (inches)	Number of 16.3-foot logs									
	½	1	1½	2	2½	3	3½	4	4½	5
	Board feet									
17	76	127	172	213	252	289	324	358	392	424
18	86	145	196	243	287	330	370	408	446	482
19	98	164	222	275	325	372	418	461	504	546
20	110	184	249	309	365	418	469	519	566	612
21	122	206	278	345	407	467	524	579	632	684
22	136	228	309	384	453	519	582	643	703	760
23	150	252	342	424	501	574	644	711	778	841
24	166	278	377	467	552	632	710	783	857	927

[1]Outside bark form class = $(100)\left[\frac{\text{Dob at top of 16.3-foot butt log}}{\text{Dbh}}\right]$

The table above is for the average outside-bark form class for all trees sampled. Factors for determining volumes for trees in other form classes (both outside-bark and inside-bark) are given in Buell (1942.)

[2]Volume as utilized to a variable top diameter.

[3]Basic data: 213 trees from Cherokee, Pisgah, Nantahala, and Chatahoochee National Forests; Bland County, Va.; and Chatham County, N.C.

TABLE 27-33—*Gross volume of scarlet oak trees, Scribner log scale* (Schnur 1937)[1,2,3]

Dbh (inches)		Volume (to an 8.0-inch top inside bark), by total height in feet					
Outside bark	Inside bark	50	60	70	80	90	Basis
		Board feet					*Trees*
10	9.2	8	14	30	51	69	35
11	10.2	22	45	66	82	95	49
12	11.1	57	77	92	108	127	70
13	12.0	79	94	113	133	157	41
14	13.0	95	113	134	159	188	28
15	13.9	110	131	156	185	219	12
16	14.8	127	152	180	212	250	11
17	15.8	145	174	206	241	285	5
18	16.7		197	232	273	319	1
19	17.6		219	258	303	352	2
20	18.6		243	285	333	388	2
21	19.5		268	312	364	420	
22	20.4		291	339	394	453	1
Basis (trees)		10	67	119	48	13	257

[1]Scaled in 16-foot log lengths with trimming allowance of 0.3 foot; additional top sections scaled as fractions of a 16-foot, 8.0-inch log. Stump height 1.0 foot.

[2]Heavy lines indicate limits of basic data.

[3]Trees measured were in Connecticut, Indiana, Maryland, New Jersey, Ohio, Pennsylvania, Tennessee, and West Virginia.

TABLE 27-34—*Gross volume in white oak trees of outside-bark form class*[1] *84, by International ¼-inch log scale* (Buell 1942)[2,3]

Dbh (inches)	Number of 16.3-foot logs									
	½	1	1½	2	2½	3	3½	4	4½	5
	Board feet									
10	22	35	46	56	65					
11	27	43	58	70	82	93				
12	33	53	71	86	100	114				
13	40	65	85	104	121	137	153			
14	48	77	102	124	144	164	182			
15	56	91	120	146	170	193	215			
16	65	105	139	170	198	224	250	274		
17	75	122	161	196	229	259	288	316		
18	86	139	184	224	262	296	330	362	393	
19	98	158	209	255	298	337	375	411	446	
20	111	179	236	288	336	380	424	463	504	541
21	124	200	265	323	377	427	475	521	565	608
22	139	223	296	361	421	476	530	581	631	678
23	154	248	328	400	467	530	589	646	700	753
24	170	275	363	443	516	585	652	713	774	832

[1]Outside bark form class = $(100)\left[\frac{\text{Dob at top of 16.3-foot butt log}}{\text{Dbh}}\right]$

The table above is for the average outside-bark form class for all trees sampled. Factors for determining volumes for trees in other form classes (both outside-bark and inside-bark) are given in Buell (1942).

[2]Volume as utilized to a variable top diameter.

[3]Basic data: 688 trees from Cherokee, Pisgah, Nantahala, and Chatahoochee National Forests; Jackson County, Ohio; Garrett County, Maryland; Hardy County, W. Va.; Bland County, Va.; and Chatham County, N.C.

TABLE 27-35—*Gross volume of white oak trees, Scribner log scale* (Schnur 1937)[1,2,3]

Dbh (inches)		Volume (to an 8.0-inch top inside bark), by total height in feet								
Outside bark	Inside bark	40	50	60	70	80	90	100	110	Basis
		Board feet								*Trees*
10	9.1	0	1	9	22	33				41
11	10.0	2	16	34	46	57	67	77		36
12	10.9	14	36	53	66	80	93	105		33
13	11.8	31	53	71	88	103	122	138		33
14	12.8	44	68	90	111	133	156	175		29
15	13.7		83	109	137	163	190	213	241	15
16	14.6		98	130	162	192	224	252	287	15

See Footnote at end of Table.

TABLE 27-35—*Gross volume of white oak trees, Scribner log scale* (Schnur 1937)[1,2,3]—Continued

Dbh (inches)		Volume (to an 8.0-inch top inside bark), by total height in feet								
Outside bark	Inside bark	40	50	60	70	80	90	100	110	Basis
		Board feet								*Trees*
17	15.5		116	154	192	226	264	297	338	13
18	16.5		134	178	219	260	303	342	390	5
19	17.4		154	203	252	298	350	395	449	2
20	18.3				287	342	400	450	510	
21	19.2				324	386	450	505	574	1
22	20.1				362	430	500	560	640	
Basis (trees)			33	76	24	47	40	3		223

[1]Scaled in 16-foot log lengths with trimming allowance of 0.3 foot; additional top sections scaled as fractions of a 16-foot, 8.0-inch log. Stump height 1.0 foot.

[2]Heavy lines indicate limits of basic data.

[3]Trees measured were in Connecticut, Maryland, New York, Ohio, Tennessee, Virginia, and West Virginia.

TABLE 27-36—*Gross volume of sweetgum trees, Scribner log scale* (Schnur 1937)[1,2,3]

Dbh (inches)		Volume (to an 8.0-inch top inside bark), by total height in feet								
Outside bark	Inside bark	50	60	70	80	90	100	110	120	Basis
		Board feet								*Trees*
11	10.1	14	20	27	35	43	50	59		20
12	11.1	28	41	55	68	81	94	102		25
13	12.1	43	62	79	95	110	125	139		34
14	13.0	58	79	98	117	136	152	172	190	27
15	14.0		97	119	141	162	187	209	230	19
16	14.9		115	142	170	195	220	250	278	23
17	15.9		136	167	198	230	263	294	328	22
18	16.9		158	193	230	269	302	344	380	12
19	17.8			220	260	305	350	392	439	9
20	18.7			250	298	350	398	448	500	7
21	19.7			280	340	394	450	510	563	9
22	20.6			320	380	448	510	575	640	3
23	21.6			360	430	500	570	645	720	2
24	22.6			400	480	560	640	720	800	5
25	23.6			442	530	620	710	800	900	
Basis (trees)			3	9	57	60	71	14	3	217

[1]Scaled in 16-foot log lengths with trimming allowance of 0.3 foot; additional top sections scaled as fractions of a 16-foot, 8.0-inch log. Stump height 1.0 foot.

[2]Heavy lines indicate limits of basic data.

[3]Trees measured were in Indiana, Missouri, and South Carolina.

TABLE 27-37—*Gross volume in sweetgum trees, Doyle-Scribner log scale* (Chittenden and Hatt 1905)[1,2]

Dbh (inches)	South Carolina	Missouri
	Board feet	
13	20	15
14	65	45
15	110	80
16	155	110
17	200	145
18	250	180
19	300	215
20	350	250
21	405	295
22	460	340
23	515	400
24	570	465
25	625	535
26	685	610
27	745	685
28	805	760
29	875	840
30	955	900

[1]Logs were scaled, where the clear lengths would permit, to a 10-inch top.
[2]Based on measurements of 849 trees in South Carolina and 801 trees in Missouri; their data, not reproduced here, also included trees 31 to 48 inches in dbh.

TABLE 27-38—*Gross volume in yellow-poplar trees of outside-bark form class*[1] *88, by International ¼-inch log scale* (Buell 1942)[2,3]

Dbh (inches)	Number of 16.3-foot logs										
	½	1	1½	2	2½	3	3½	4	4½	5	5½
	Board feet										
10	23	38	50	62	72	82	92	101			
11	29	47	63	77	90	102	114	125			
12	35	57	76	93	109	124	139	152			
13	42	68	91	112	131	149	166	182			
14	50	81	108	132	154	176	196	215	234		
15	58	95	126	154	181	206	229	252	274		
16	67	109	146	179	209	238	265	291	316		

See Footnote at end of Table.

TABLE 27-38—*Gross volume in yellow-poplar trees of outside-bark form class*[1] *88, by International ¼-inch log scale* (Buell 1942)[2,3]—Continued

Dbh (inches)	½	1	1½	2	2½	3	3½	4	4½	5	5½
						Board feet					
17	77	125	167	205	239	272	304	334	363		
18		143	190	233	273	310	346	380	413		
19		161	215	263	308	351	391	430	467	502	
20		181	241	295	346	394	438	482	524	564	
21		202	269	330	386	438	490	538	585	630	
22		224	298	366	428	488	543	597	649	700	
23			330	405	474	540	601	661	718	773	828
24			364	446	521	593	662	728	791	851	910

[1]Outside bark form class = $(100)\left[\frac{\text{Dob at top of 16.3-foot butt log}}{\text{Dbh}}\right]$

The table above is for the average outside-bark form class for all trees sampled. Factors for determining volumes for trees in other form classes (both outside-bark and inside-bark) are given in Buell (1942.)

[2]Volume as utilized to a variable top diameter.

[3]Basic data: 334 trees from George Washington, Cherokee, Pisgah, and Nantahala National Forests; Jackson County, Ohio; Tucker County, W. Va.; Bland County, Va.; and Chatham County, N.C.

TABLE 27-39—*International ¼-inch board-foot volumes for southern Appalachian yellow-poplar*[1] *to a top diameter of 8.0 inches outside bark* (Beck 1964)

Dbh (inches)	Total tree height (feet)															
	65	70	75	80	85	90	95	100	105	110	115	120	125	130	135	140
	Board feet															
11	51	59	67	76	84	92	101	109	118	127	135	144				
12	67	77	87	97	107	117	127	137	147	158	168	179				
13	85	97	108	120	132	144	156	168	180	193	205	217	229	242		
14	105	119	133	146	161	174	189	203	217	231	245	260	274	288		
15		144	160	176	192	208	224	241	257	273	290	306	323	339		
16		171	190	208	227	245	264	282	301	320	339	357	376	394		
17		202	222	243	264	286	307	327	348	370	391	412	433	455		
18				282	306	329	353	377	400	424	448	472	495	519	543	
19				324	351	376	404	429	456	482	509	536	562	589	615	643
20					399	428	458	487	516	546	575	604	634	663	692	
21							515	548	581	613	646	678	710	743	776	
22							578	614	650	685	721	756	792	828	864	
23								684	723	762	801	840	879	919	957	
24								758	801	844	887	928	972	1,013	1,057	
25								838	884	929	976	1,022	1,070	1,115	1,162	
26								921	972	1,022	1,071	1,121	1,171	1,221	1,272	
27									1,065	1,119	1,173	1,226	1,280	1,335		
28										1,220	1,279	1,336	1,395	1,453		
29											1,390	1,452	1,517	1,578		
30											1,510	1,577	1,644	1,711		

[1]Derived from board-foot/cubic-foot ratios.

TABLE 27-40—*Gross volume of yellow-poplar trees, Scribner log scale to an 8-inch top diameter inside bark, related to dbh and total tree height* (Schnur 1937)[1,2,3]

Dbh (inches)		Total tree height (feet)								
Outside bark	Inside bark	40	50	60	70	80	90	100	110	Basis
		Board feet								*Trees*
10	9.2	29	32	37	42	48	55			10
11	10.1	33	37	42	51	66	78	82		26
12	11.0	38	43	52	71	94	109	115	119	20
13	12.0	43	50	68	93	120	140	148	158	21
14	12.9	48	60	84	112	147	168	177	185	18
15	13.8		72	99	131	169	198	209	217	7
16	14.8		84	114	150	196	229	243	251	4
17	15.7		95	129	170	223	261	277	289	
18	16.6		108	146	192	253	297	313	327	1
19	17.5		119	161	215	282	332	350	365	
20	18.5				240	318	370	389	405	
21	19.4				265	348	408	430	445	1
22	20.4				290	382	445	470	488	
Basis (trees)			2	18	61	19	3	5		108

[1]Scaled in 16-foot log lengths with trimming allowance of 0.3 foot; additional top sections scaled as fractions of a 16-foot, 8.0-inch log. Stump height 1.0 foot.

[2]Heavy lines indicate limits of basic data.

[3]Trees measured were in Ohio, Pennsylvania, Virginia, and West Virginia.

TABLE 27-41—*Board foot volumes by Scribner rule in second-growth yellow-poplar trees of six heights* (McCarthy 1933)[1,2]

Dbh outside bark (inches)	Tree height (feet)						Basis
	50	60	70	80	90	100	
	Board feet						*Trees*
8	15	20	27				62
9	22	30	38	45			66
10	30	40	51	61	71		55
11	37	51	65	78	91		75
12	46	62	80	96	112	129	49
13	56	74	95	115	135	155	51
14		86	112	136	160	184	27
15		100	129	157	187	217	16
16			147	180	216	251	20
17			165	205	246	287	12
18			184	231	278	325	5
19				259	312	367	5
20				289	348	409	
21					386	453	
22					427	501	1
Total							444

[1]Volume scaled by Scribner rule from taper diagrams. Stump 1 foot high and top 6 inches in diameter inside bark.

[2]Trees sampled in Fairfax County, Va. and Pike County, Ohio.

TABLE 27-42—*Total tree height and dbh related to board foot volumes by Scribner Decimal C rule in yellow-poplar trees over 100 years old in the southern Appalachians* (McCarthy 1933)[1]

Dbh (inches)	Total tree height (feet) 70	80	90	100	110	120	130	140	Top dib	Basis
	Board feet/10								*Inches*	*Trees*
10	6	7							6	1
11	7	9							7	1
12	9	11	14						7	4
13	11	14	17						8	3
14	13	17	20	22					8	3
15	16	20	23	26					8	4
16	19	23	27	30	31				8	8
17	22	27	31	34	37				9	16
18	25	31	36	39	43	47			9	16
19	29	35	41	45	50	54			9	18
20	33	39	46	52	58	63	68		10	20
21		44	52	59	66	72	77		10	20
22		49	58	67	74	81	86	91	10	27
23		54	64	75	83	91	96	101	11	27
24		60	71	84	91	101	106	112	11	22
25		66	78	93	102	111	117	123	12	32
26		73	86	102	112	122	129	136	12	29
27		80	94	111	123	133	141	148	12	21
28		87	103	121	134	145	154	162	13	21
29		95	113	132	145	158	168	176	13	19
30		104	124	144	158	171	181	190	14	22
31		113	135	155	171	185	195	205	14	14
32		123	146	168	184	199	210	220	14	13
33		133	158	181	198	214	225	235	15	14
34			171	194	213	228	239	250	15	10
35			183	207	226	243	254	265	16	5
36			196	220	240	257	269	281	16	3
37			209	233	254	272	285	297	16	
38			222	246	268	286	301	314	17	5
39			235	260	281	300	317	331	17	7
40			248	273	295	314	334	348	17	2
Total										407

[1]Derived from taper curves by scaling the merchantable length in log lengths to the top diameters shown. Logs were 16.3 feet long whenever possible, with some 14.3 feet, 12.3 feet, and 10.3 feet long to avoid waste. The assumed stump height was 2 feet.

TABLE 27-43—*Number of 16-foot logs in tree and dbh related to board foot volumes by Scribner Decimal C rule in yellow-poplar trees over 100 years old in the southern Appalachians* (McCarthy 1933)[1]

Dbh (inches)	Number of 16-foot logs in tree						Top dib	Basis
	1	2	3	4	5	6		
	Board feet/10						*Inches*	*Trees*
10	2	5	8				6	1
11	3	6	10				7	1
12	3	7	12	18			7	4
13	3	8	15	21			8	3
14	3	9	17	24			8	3
15	3	10	19	27			8	4
16	3	12	22	31			8	8
17	4	13	24	35	42		9	16
18	4	15	27	39	47		9	16
19	5	16	30	44	54		9	18
20	5	18	33	48	61	75	10	20
21		20	36	54	69	84	10	20
22		22	39	59	76	93	10	27
23		25	42	65	85	103	11	27
24		27	46	72	94	113	11	22
25		30	50	79	103	123	12	32
26		32	54	86	112	135	12	29
27		35	58	94	122	147	12	21
28		38	63	102	133	159	13	21
29		40	68	110	144	172	13	19
30		43	74	118	156	185	14	22
31			79	127	168	199	14	14
32			85	136	181	214	14	13
33			91	146	193	228	15	14
34			98	156	206	244	15	10
35			104	167	219	259	16	5
36			112	178	232	275	16	3
37			119	191	245	291	16	
38			126	204	258	307	17	5
39			133	216	271	322	17	7
40			140	230	284	338	17	2
Total								407

[1]Table based on taper curves; height of stump, 2 feet.

TABLE 27-44—*Estimates of height, basal area, and yield for mixed hardwoods growing on a variety of sites* (Smith et al. 1975) (See footnote 1 for an explanation of numerical code used in table headings.)[1,2]

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
		Basal area					Volume					Weight					
												Total		Residues		Trees 3.5-5.5	
Age (years)	Total height	Total	Mer-chantable	Saw-timber	Saw-timber	Mer-chantable timber	Total timber	Total wood bark-free	Total residues	Trees <3.5	Trees 3.5-5.5	Dry	Green	Dry	Green	Dry	Green
	Feet	*Square feet/acre*			*Board feet/acre*	*Cubic feet/acre*						*Tons/acre*					
UPLAND SLOPES AND RIDGE SITES																	
20	52	84	36	7	34	481	1,554	1,215	690	237	16	–	37	20	39	4	7
30	56	109	61	12	253	1,069	2,897	2,334	1,561	438	14	–	72	37	69	7	13
40	60	124	79	16	691	1,593	3,956	3,235	2,349	597	13	–	100	51	92	9	18
50	64	134	93	19	1,263	2,024	4,768	3,935	3,002	718	12	–	121	61	109	11	22
60	68	141	103	21	1,889	2,375	5,400	4,484	3,534	813	11	–	138	69	122	13	24
COVES, GULFS, AND LOWER SLOPE SITES																	
20	56	86	53	10	571	888	1,757	1,393	1,777	274	11	26	52	26	52	4	8
30	62	108	84	16	2,436	1,764	3,299	2,698	3,056	509	12	49	96	45	87	8	15
40	68	121	103	20	5,032	2,437	4,520	3,755	3,945	695	13	66	128	57	111	11	21
50	76	129	116	23	7,777	2,940	5,459	4,579	4,575	838	14	78	151	67	128	13	25
60	84	135	125	26	10,396	3,322	6,192	5,227	5,039	950	14	88	169	73	140	15	29
WET FLAT SITES IN NORTH CAROLINA, TENNESSEE, VIRGINIA																	
20	56	103	68	14	541	1,268	2,383	1,911	2,540	374	21	39	78	38	77	6	11
30	60	132	105	21	2,520	2,169	4,095	3,376	3,882	613	19	65	129	59	117	10	18
40	64	149	131	26	5,438	2,837	5,369	4,488	4,800	791	17	85	165	74	144	12	24
50	69	160	149	30	8,626	3,333	6,316	5,324	5,451	923	16	100	192	85	163	14	28
60	74	168	163	33	11,733	3,711	7,038	5,965	5,934	1,025	15	111	212	92	177	16	31
WET FLATS IN OTHER STATES																	
20	56	96	58	12	360	1,092	2,194	1,760	2,195	347	21	33	67	33	67	5	10
30	60	123	90	18	1,677	1,868	3,770	3,110	3,355	568	19	57	110	52	101	9	17
40	64	139	112	22	3,618	2,443	4,942	4,134	4,148	731	18	74	142	65	124	11	22
50	69	149	127	25	5,739	2,870	5,814	4,904	4,712	853	17	86	165	74	141	13	26
60	74	157	139	28	7,805	3,196	6,479	5,495	4,129	946	16	96	182	81	153	15	28

See Footnote at end of Table.

TABLE 27-44—*Estimates of height, basal area, and yield for mixed hardwoods growing on a variety of sites* (Smith et al. 1975) (See footnote 1 for an explanation of numerical code used in table headings)[1,2]—Continued

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
		Basal area					Volume					Weight					
												Total		Residues		Trees 3.5-5.5	
Age (years)	Total height	Total	Mer-chantable	Saw-timber	Saw-timber	Mer-chantable timber	Total timber	Total wood bark-free	Total residues	Trees <3.5	Trees 3.5-5.5	Dry	Green	Dry	Green	Dry	Green
	Feet	*Square feet/acre*			*Board feet/acre*	*Cubic feet/acre*						*Tons/acre*					
BRANCH BOTTOM SITES IN NORTH CAROLINA, TENNESSEE, VIRGINIA																	
20	61	120	89	18	1,509	1,735	3,330	2,715	3,366	496	19	51	109	49	103	8	15
30	62	124	102	20	3,004	2,091	4,068	3,368	3,904	590	17	64	128	58	117	9	18
40	64	142	129	26	5,073	2,716	5,135	4,273	4,901	726	15	82	162	74	145	11	22
50	66	160	157	31	7,359	3,353	6,161	5,138	5,900	856	13	101	196	89	174	13	26
60	68	176	183	37	9,659	3,947	7,081	5,912	6,814	973	12	117	227	103	200	15	29
BRANCH BOTTOM SITES IN OTHER STATES																	
20	60	101	71	14	568	1,335	2,781	2,309	2,717	423	18	41	82	40	78	7	13
30	64	121	95	20	2,695	2,003	4,039	3,387	3,569	609	16	58	114	53	103	9	18
40	68	133	117	24	5,869	2,638	4,868	4,103	4,327	731	14	73	142	64	124	11	22
50	72	140	135	26	9,363	3,183	5,444	4,603	4,946	816	13	86	166	74	142	13	24
60	76	145	150	28	12,783	3,643	5,866	4,969	5,448	879	13	96	186	81	156	14	26

[1] 1 = Average total height of all trees ≥5.5 inches dbh (feet).
2 = Total basal area of all trees in stand (sq ft/acre)
3 = Basal area of all trees ≥5.5 inches dbh (sq ft/acre)
4 = Basal area of all trees ≥11.0 inches dbh (sq ft/acre)
5 = Board-foot volume per acre (International ¼-inch) in trees ≥11.0 dbh to a 9-inch top outside bark.
6 = Inside-bark cubic-foot volume per acre of apparent sound wood in main stems of trees ≥5.5 inches dbh to a 4-inch top outside bark.
7 = Total biomass—wood and bark in all live trees, assuming no cull, and excluding only twigs and small branch material not in bolts 5 feet and longer to an outside bark diameter of 4 inches (cu ft/acre)
8 = Biomass without bark—as defined in #7 but excluding bark (cu ft/acre)
9 = Residual biomass—tops, limbs, slabs, edgings, sawdust, and bark remaining after subtracting the board-foot component of the stand (cu ft/acre)
10 = Biomass in trees less than 3.5 inches dbh (cu ft/acre)
11 = Biomass in trees between 3.5 and 5.5 inches dbh (cu ft/acre)
12 = Ovendry weight of total biomass (#7) (tons/acre)
13 = Green weight of total biomass (#7) (tons/acre)
14 = Ovendry weight of residual biomass (#9) (tons/acre)
15 = Fresh green weight of residual biomass (#9) (tons/acre)
16 = Ovendry weight of biomass in trees between 3.5 and 5.5 inches dbh (tons/acre)
17 = Fresh green weight of biomass in trees between 3.5 and 5.5 inches dbh (tons/acre)

[2] Only above-ground tree portions are considered in this tabulation. Data based on 641 plots in nine forest site types extending from Virginia to Florida and west to Louisiana and Arkansas. Data on three of the bottomland sites were omitted from this tabulation.

TABLE 27-45—*Yield of second-growth upland oak stands, including all trees 0.6-inch dbh and larger* (Schnur 1937)

Age (years)	Total height, average dominant and co-dominant oak	Trees per acre	Basal area per acre	Average diameter breast height	Yield per acre: Entire stem inside bark	Yield per acre: Merchantable stem to a 4-inch top outside bark[1]		Yield per acre: Scribner rule[2]
	Feet	*Number*	*Square feet*	*Inches*	*Cubic feet*	*Cubic feet*	*Cords*	*Board feet*
			SITE INDEX[3] 40—POOR SITE					
10	8	6,850	36	1.0	205	—	—	—
20	17	3,260	60	1.8	485	20	0.24	—
30	25	1,610	75	2.9	755	270	3.18	—
40	33	1,020	82	3.8	1,030	680	8.00	50
50	40	802	89	4.5	1,300	1,060	12.47	150
60	45	651	96	5.2	1,540	1,420	16.71	400
70	48	541	102	5.8	1,765	1,750	20.59	800
80	50	483	109	6.4	1,975	2,050	24.12	1,450
90	52	447	115	6.9	2,175	2,330	27.41	2,200
100	53	411	122	7.4	2,375	2,590	30.47	3,350
			SITE INDEX 60—AVERAGE SITE					
10	17	4,060	41	1.4	345	—	—	—
20	30	1,945	68	2.5	805	170	2.00	—
30	41	965	84	4.0	1,265	880	10.35	50
40	51	611	93	5.3	1,725	1,580	18.59	500
50	60	482	100	6.3	2,165	2,230	26.24	1,400
60	67	390	108	7.2	2,590	2,800	32.94	3,150
70	71	326	115	8.0	2,970	3,290	38.71	5,650
80	75	292	123	8.8	3,325	3,730	43.88	8,350
90	77	268	130	9.4	3,655	4,120	48.47	11,050
100	79	248	138	10.1	3,970	4,480	52.71	13,700
			SITE INDEX 80—EXCELLENT SITE					
10	26	2,435	44	1.8	490	20	0.24	—
20	43	1,160	73	3.4	1,145	620	7.29	—
30	56	578	90	5.3	1,795	1,690	19.88	500
40	69	366	99	6.9	2,440	2,610	30.71	2,500
50	80	290	107	8.3	3,085	3,450	40.59	6,650
60	89	235	115	9.5	3,690	4,160	48.94	11,350
70	95	196	124	10.7	4,225	4,770	56.12	15,900
80	99	174	132	11.7	4,725	5,340	62.82	19,700
90	103	161	140	12.7	5,200	5,870	69.06	23,050
100	105	148	148	13.6	5,650	6,380	75.06	26,100

[1]Converting factor, 85 cu ft of solid wood free of bark and voids per cord.
[2]To an 8-inch top inside bark.
[3]Site index = height at age 50 years.

TABLE 27-46—*International ¼-inch board-foot yield to an 8-inch top, outside bark, for unthinned yellow-poplar stands of various stand densities, site indices,*[1] *and ages*[2] (Beck and Della-Bianca 1970)

Trees per acre (number)	Age (years)					
	20	30	40	50	60	70
	Board feet/acre					
SITE INDEX 90						
50	—	—	5,180	8,490	12,240	16,480
100	260	2,480	6,260	10,750	15,670	20,920
150	140	2,090	5,960	10,690	15,730	20,830
200	80	1,630	5,210	9,750	14,530	19,120
250	40	1,230	4,370	8,540	12,920	17,000
300	20	880	3,520	7,230	—	—
350	10	590	2,670	—	—	—
SITE INDEX 110						
50	—	—	9,400	15,310	22,370	30,720
100	750	5,340	12,380	20,810	30,520	41,580
150	520	5,160	13,070	22,580	33,190	44,760
200	370	4,750	12,950	22,890	33,740	45,150
250	270	4,330	12,550	22,670	33,550	44,630
300	210	3,940	12,050	22,230	—	—
350	170	3,550	11,450	—	—	—
SITE INDEX 130						
50	—	—	15,160	24,950	37,190	52,270
100	1,600	9,500	21,120	35,590	53,220	74,650
150	1,310	10,070	23,880	40,940	61,220	—
200	1,100	10,270	25,560	44,350	—	—
250	990	10,470	26,960	47,180	—	—
300	940	10,740	28,320	—	—	—
350	920	11,050	—	—	—	—

[1]Site index = height at age 50.
[2]Only trees 11.0 inches dbh and larger are included.

TABLE 27-47—*Normal yield per acre for second-growth yellow-poplar in board feet* (Scribner) *and cubic feet on four sites* (McCarthy 1933)[1,2]

Dbh class and age (years)	Site index[3]			
	60	80	100	120
Trees 9 inches in dbh and larger (board feet Scribner scale)[4]				
10	—	—	150	360
15	50	210	870	1,960
20	190	1,030	2,920	5,800
25	450	2,370	6,180	10,810
30	930	4,430	9,900	15,810
35	1,540	6,800	13,700	21,050
40	2,370	9,270	17,500	26,500
45	3,380	11,850	21,400	31,560
50	4,580	14,410	25,300	36,600
Trees 5 inches in dbh and larger (cubic feet)[5]				
10	—	—	135	360
15	80	415	800	1,180
20	320	880	1,475	2,040
25	570	1,340	2,145	2,900
30	825	1,800	2,800	3,770
35	1,080	2,250	3,450	4,600
40	1,335	2,690	4,085	5,410
45	1,590	3,130	4,710	6,200
50	1,840	3,570	5,330	6,970

[1]Based on 89 plots scattered well over the species range and representing the best stocked areas that could be found.

[2]Stump height, 1 foot.

[3]Site index = height at age 50.

[4]Top diameter outside bark, 6 inches.

[5]Peeled volume of the merchantable stem, excluding stump and top less than 3 inches inside bark.

TABLE 27-48—*Age related to volume per acre in pure, even-aged, well stocked stands of ash on sites of three qualities* (Sterrett 1915)[1]

Age (years)	Trees per acre[2]	Average dbh[2]	Volume per acre: Trees 7 inches dbh and larger	Volume per acre: Trees 3 inches dbh and larger	Volume per acre: Cords
	Number	*Inches*	*Board feet*[3]	*Cubic feet*[4]	*Cords*[5]
			QUALITY I		
20	427	5.4	2,000	2,200	24.4
30	375	7.5	6,500	3,900	43.3
40	341	9.1	11,700	5,250	58.3
50	288	10.5	18,000	6,350	70.6
60	224	11.8	25,700	7,220	80.2
70	188	13.0	32,800	7,950	88.3
80	166	14.0	38,000	8,600	95.6
			QUALITY II		
20	482	4.0	—	850	9.4
30	415	5.8	2,200	2,400	26.7
40	378	7.4	5,300	3,630	46.3
50	361	8.7	9,900	4,590	51.0
60	340	9.8	15,700	5,380	59.8
70	309	10.9	22,600	6,010	66.8
80	268	12.0	28,000	6,520	72.4
			QUALITY III		
30	456	4.2	—	970	10.8
40	426	5.5	1,300	1,950	21.7
50	402	6.8	3,900	2,790	31.0
60	382	7.9	7,700	3,470	38.6
70	371	5.9	12,900	4,020	41.7
80	359	9.8	18,000	4,490	49.9

[1]Based on 18 plots, Quality I; 30 plots, Quality II; 14 plots, Quality III; with a total area of 16.9 acres.

[2]All trees 3 inches in dbh and larger.

[3]Scribner Decimal C rule.

[4]Top diameter limit not defined in source reference; volume assumed to be bark free.

[5]Standard rough cord.

TABLE 27-49—*Cordwood volume, excluding bark, by tree diameter, form class*[1], *and length of merchantable stem*[2] (Mesavage 1947)

Form class and tree diameter (inches)	Length of merchantable stem (feet)												
	12	16	20	24	28	32	36	40	44	48	52	56	60
	Cubic feet												
Form class 70													
5	1.1	1.4	1.6	1.9	2.1	2.3	2.6	2.8	3.1	3.3	3.5	3.8	4.0
6	1.5	1.9	2.2	2.5	2.8	3.2	3.5	3.8	4.1	4.4	4.7	5.1	5.4
7	2.1	2.6	3.0	3.4	3.8	4.2	4.6	5.0	5.4	5.8	6.2	6.6	7.0
8	2.6	3.4	3.9	4.4	4.9	5.4	5.9	6.4	6.9	7.4	7.9	8.4	8.9
9	3.2	4.2	4.8	5.4	6.0	6.6	7.1	7.7	8.3	8.9	9.5	10.1	10.7
10	4.0	5.0	5.7	6.4	7.1	7.7	8.4	9.1	9.8	10.5	11.2	11.8	12.5
Form class 80													
5	1.4	1.8	2.1	2.4	2.7	3.1	3.4	3.7	4.0	4.5	4.6	5.0	5.3
6	1.9	2.4	2.8	3.2	3.6	4.0	4.4	4.8	5.2	5.6	6.0	6.4	6.8
7	2.5	3.2	3.7	4.2	4.7	5.2	5.7	6.2	6.7	7.2	7.7	8.2	8.7
8	3.2	4.2	4.8	5.5	6.1	6.7	7.4	8.0	8.7	9.3	9.9	10.6	11.2
9	4.0	5.2	6.0	6.7	7.5	8.2	9.0	9.8	10.5	11.3	12.0	12.8	13.6
10	4.8	6.3	7.2	8.1	9.0	9.9	10.8	11.7	12.5	13.4	14.3	15.2	16.1
Form class 90													
5	1.6	2.1	2.5	2.9	3.3	3.7	4.1	4.5	4.9	5.3	5.7	6.1	6.5
6	2.3	2.9	3.4	3.9	4.5	5.0	5.5	6.0	6.6	7.1	7.6	8.1	8.7
7	3.0	3.9	4.6	5.2	5.9	6.5	7.2	7.9	8.5	9.2	9.8	10.5	11.2
8	3.9	5.0	5.8	6.6	7.4	8.2	9.1	9.9	10.7	11.5	12.3	13.1	13.9
9	4.8	6.3	7.3	8.2	9.2	10.1	11.1	12.0	13.0	13.9	14.9	15.8	16.8
10	5.9	7.7	8.8	10.0	11.1	12.2	13.4	14.5	15.6	16.8	17.9	19.0	20.2

[1]Defined by equation 27-2.
[2]To a minimum 3-inch top diameter outside bark.

TABLE 27-50—*Sawlog volume, excluding bark, and (scaling diameter of top sawlog, in inches in parentheses) by tree diameter, form class*[1], *and number of 16-foot logs* (Mesavage 1947)

Form class and tree diameter (inches)	Number of 16-foot logs			
	1	2	3	4
	Cubic feet			
Form class 70				
10	5.0 (7)	8.5 (6)	—	—
11	6.1 (8)	10.4 (6)	—	—
12	7.2 (8)	12.3 (7)	16.0 (6)	—
13	8.5 (9)	14.6 (7)	19.1 (6)	—
14	9.8 (10)	16.9 (8)	22.2 (7)	26.0 (5)
15	11.3 (10)	19.4 (9)	25.8 (7)	30.4 (6)
16	12.8 (11)	22.0 (9)	29.3 (8)	34.9 (6)
17	14.6 (12)	25.1 (10)	33.4 (9)	39.9 (7)
18	16.4 (13)	28.2 (11)	37.6 (9)	44.9 (7)
19	18.4 (13)	31.6 (11)	42.2 (10)	50.5 (8)
20	20.4 (14)	35.1 (12)	46.9 (10)	56.1 (8)
21	22.6 (15)	39.0 (13)	52.1 (11)	62.5 (9)
22	24.9 (15)	42.9 (13)	57.3 (12)	68.9 (10)
23	27.6 (16)	47.3 (14)	63.3 (12)	75.8 (10)
24	30.2 (17)	51.7 (14)	69.3 (13)	82.7 (10)
Form class 80				
10	6.3 (8)	11.0 (7)	14.4 (5)	—
11	7.6 (9)	13.4 (7)	17.7 (6)	—
12	8.9 (10)	15.7 (8)	21.0 (7)	24.8 (5)
13	10.5 (10)	18.6 (9)	25.0 (7)	29.6 (6)
14	12.1 (11)	21.5 (9)	28.9 (8)	34.4 (6)
15	14.0 (12)	24.8 (10)	33.6 (9)	40.3 (7)
16	15.9 (13)	28.2 (11)	38.2 (10)	46.2 (8)
17	18.0 (14)	32.1 (12)	43.5 (10)	52.8 (9)
18	20.2 (14)	36.0 (12)	48.8 (11)	59.3 (9)
19	22.7 (15)	40.4 (13)	54.8 (12)	66.6 (10)
20	25.2 (16)	44.8 (14)	60.9 (12)	74.0 (10)
21	28.0 (17)	49.8 (15)	67.6 (13)	82.4 (11)
22	30.8 (18)	54.7 (15)	74.4 (14)	90.8 (12)
23	33.9 (18)	60.2 (16)	82.0 (14)	99.8 (12)
24	37.0 (19)	65.6 (17)	89.6 (15)	108.7 (13)

See Footnote at end of Table.

TABLE 27-50—*Sawlog volume, excluding bark, and (scaling diameter of top sawlog, in inches in parentheses) by tree diameter, form class*[1], *and number of 16-foot logs* (Mesavage 1947)—Continued

Form class and tree diameter (inches)	Number of 16-foot logs			
	1	2	3	4
	Cubic feet			
Form class 90				
10	7.7 (9)	13.8 (8)	18.3 (6)	—
11	9.3 (10)	16.8 (8)	22.5 (7)	—
12	10.9 (11)	19.7 (9)	26.7 (8)	32.0 (6)
13	13.0 (12)	23.4 (10)	31.8 (9)	38.3 (7)
14	15.0 (13)	27.1 (11)	36.9 (10)	44.6 (8)
15	17.2 (13)	31.2 (12)	42.6 (10)	52.0 (9)
16	19.4 (14)	35.3 (12)	48.4 (11)	59.3 (9)
17	22.0 (15)	40.0 (13)	55.1 (12)	67.6 (10)
18	24.6 (16)	44.8 (14)	61.8 (13)	75.9 (11)
19	27.6 (17)	50.2 (15)	69.4 (14)	85.2 (12)
20	30.5 (18)	55.7 (16)	76.9 (14)	94.5 (12)
21	34.0 (19)	61.8 (17)	85.4 (15)	105.2 (13)
22	37.4 (20)	68.0 (18)	93.9 (16)	116.0 (14)
23	41.0 (21)	74.6 (18)	103.3 (17)	127.2 (15)
24	44.6 (22)	81.2 (19)	112.7 (18)	138.4 (15)

[1]Defined by equation 27-2.

TABLE 27-51—*Total cubic foot volumes for natural yellow-poplar*[1] (Beck 1963)

Dbh (inches)	Total tree height (feet) 15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120	125	130	135
	Cubic feet																								
1	0.03	0.05	0.06	0.07																					
2	0.15	0.20	0.25	0.30	0.35	0.40																			
3			0.56	0.67	0.78	0.90	1.01																		
4				1.2	1.4	1.6	1.8	2.0	2.2	2.4															
5					2.2	2.5	2.8	3.1	3.4	3.8	4.1	4.4													
6							4.0	4.5	5.0	5.4	5.8	6.3	6.8	7.2											
7							5.5	6.1	6.7	7.4	8.0	8.6	9.2	9.8	10.4	11.0	11.6	12.2							
8								8.0	8.8	9.6	10.4	11.2	12.0	12.8	13.6	14.4	15.2	16.0	16.8						
9									11.1	12.2	13.2	14.2	15.2	16.2	17.2	18.2	19.2	20.2	21.2						
10										15.0	16.2	17.5	18.8	20.0	21.2	22.5	23.8	25.0	26.2	27.5					
11											19.7	21.2	22.7	24.2	25.7	27.2	28.7	30.2	31.8	33.3	34.8	36.3			
12											23.4	25.2	27.0	28.8	30.6	32.4	34.2	36.0	37.8	39.6	41.4	43.2			
13											27.5	29.6	31.7	33.8	35.9	38.0	40.1	42.2	44.4	46.5	48.6	50.7	52.8	54.9	
14											31.8	34.3	36.8	39.2	41.6	44.1	46.6	49.0	51.4	53.9	56.4	58.8	61.2	63.7	
15												39.4	42.2	45.0	47.8	50.6	53.4	56.2	59.1	61.9	64.7	67.5	70.3	73.1	
16												44.8	48.0	51.2	54.4	57.6	60.8	64.0	67.2	70.4	73.6	76.8	80.0	83.2	
17														57.8	61.4	65.0	68.6	72.2	75.9	79.5	83.1	86.7	90.3	93.9	
18														64.8	68.8	72.9	77.0	81.0	85.0	89.1	93.2	97.2	101.2	105.3	109.4
19															76.7	81.2	85.7	90.2	94.8	99.3	103.8	108.3	112.8	117.3	121.8
20															85.0	90.0	95.0	100.0	105.0	110.0	115.0	120.0	125.0	130.0	135.0
21																	104.7	110.2	115.8	121.3	126.8	132.3	137.8	143.3	148.8
22																	115.0	121.0	127.0	133.1	139.2	145.2	151.2	157.3	163.4
23																		132.2	138.9	145.5	152.1	158.7	165.3	171.9	178.5
24																		144.0	151.2	158.4	165.6	172.8	180.0	187.2	194.4
25																		156.2	164.1	171.9	179.7	187.5	195.3	203.1	210.9
26																		169.0	177.4	185.9	194.4	202.8	211.2	219.7	228.2
27																			191.4	200.5	209.6	218.7	227.8	236.9	
28																				215.6	225.4	235.2	245.0	254.8	
29																					241.8	252.3	262.8	273.3	
30																					258.8	270.0	281.2	292.5	

[1]Includes wood and bark of entire stem from ground level to tree tip. Stump volume computed as a cylinder 1 foot high with a diameter equal to that at its top.

TABLE 27-52.—*Cubic foot volumes (outside bark) for natural yellow-poplar; top diameter 4.0 inches outside bark*[1] (Beck 1963)

Dbh (inches)	Total tree height (feet)																				
	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120	125	130	135
	Cubic feet																				
5	1.5	1.8	2.1	2.4	2.7	3.0	3.3	3.6													
6			3.2	3.7	4.1	4.5	5.0	5.4	5.8	6.3											
7			4.6	5.2	5.8	6.4	7.0	7.6	8.2	8.8	9.4	9.9	10.5	11.1							
8				7.0	7.8	8.6	9.3	10.1	10.9	11.6	12.4	13.2	14.0	14.7	15.5						
9					10.0	11.0	12.0	13.0	13.9	14.9	15.9	16.8	17.8	18.8	19.8						
10						13.8	15.0	16.2	17.4	18.6	19.8	21.0	22.2	23.4	24.6	25.8					
11							18.2	19.7	21.1	22.6	24.0	25.5	27.0	28.4	29.9	31.3	32.8	34.2			
12							21.8	23.6	25.3	27.0	28.7	30.5	32.2	33.9	35.6	37.4	39.1	40.8			
13							25.7	27.8	29.8	31.8	33.8	35.9	37.9	39.9	42.0	44.0	46.0	48.0	50.1	52.1	
14							29.9	32.3	34.6	37.0	39.3	41.7	44.0	46.4	48.8	51.1	53.4	55.8	58.2	60.5	
15								37.2	39.9	42.6	45.3	48.0	50.7	53.4	56.1	58.8	61.5	64.2	66.9	69.6	
16								42.4	45.4	48.5	51.6	54.7	57.7	60.8	63.9	66.9	70.0	73.1	76.2	79.2	
17								47.9	51.4	54.8	58.3	61.8	65.2	68.7	72.2	75.6	79.1	82.6	86.1	89.5	
18										61.6	65.4	69.3	73.2	77.1	81.0	84.9	88.8	92.7	96.6	100.4	104.3
19										68.7	73.0	77.3	81.7	86.0	90.3	94.7	99.0	103.3	107.7	112.0	116.3
20											81.0	85.8	90.6	95.4	100.2	105.0	109.8	114.6	119.4	124.2	129.0
21													99.9	105.2	110.5	115.8	121.1	126.4	131.7	137.0	142.4
22													109.7	115.5	121.3	127.1	132.9	138.8	144.6	150.4	156.2
23														126.3	132.7	139.0	145.4	151.7	158.1	164.4	170.8
24														137.6	144.5	151.4	158.3	165.2	172.2	179.1	186.0
25														149.4	156.9	164.4	171.9	179.4	186.9	194.4	201.9
26														161.6	169.7	177.8	185.9	194.0	202.2	210.3	218.4
27															183.1	191.8	200.6	209.3	218.1	226.8	
28																206.3	215.7	225.2	234.6	244.0	
29																	231.5	241.6	251.7	261.8	
30																	247.8	258.6	269.4	280.2	

[1]To obtain cubic-foot volume outside bark to an 8.0-inch (o.b.) top diameter in trees larger than 11.0 inches d.b.h., subtract 4.7 cubic-feet from tabular values.

TABLE 27-53.—*Cubic foot volumes (inside bark) for natural yellow-poplar; top diameter 4.0 inches outside bark*[1] (Beck 1963)

Dbh (inches)	Total tree height (feet)																				
	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120	125	130	135
	Cubic feet																				
5	1.1	1.3	1.6	1.8	2.1	2.3	2.6	2.8													
6			2.6	2.9	3.3	3.6	4.0	4.4	4.7	5.1											
7			3.7	4.2	4.7	5.2	5.7	6.2	6.8	7.2	7.6	8.1	8.6	9.1							
8				5.7	6.4	7.0	7.6	8.3	8.9	9.6	10.2	10.8	11.5	12.1	12.8						
9					8.2	9.0	9.8	10.7	11.5	12.3	13.1	13.9	14.7	15.5	16.3						
10						11.3	12.3	13.3	14.3	15.3	16.3	17.3	18.3	19.3	20.3	21.3					
11							15.0	16.3	17.5	18.7	19.9	21.1	22.3	23.5	24.7	25.9	27.2	28.4			
12							18.0	19.5	20.9	22.4	23.8	25.2	26.7	28.1	29.6	31.0	32.4	33.9			
13							21.3	23.0	24.7	26.4	28.0	29.7	31.4	33.1	34.8	36.5	38.2	39.9	41.6	43.3	
14							24.8	26.8	28.7	30.7	32.6	34.6	36.6	38.5	40.5	42.4	44.4	46.4	48.3	50.3	
15								30.8	33.1	35.3	37.6	39.8	42.1	44.3	46.6	48.8	51.1	53.3	55.6	57.8	
16								35.2	37.7	40.3	42.8	45.4	48.0	50.5	53.1	55.6	58.2	60.8	63.3	65.9	
17								39.8	42.7	45.6	48.4	51.3	54.2	57.1	60.0	62.9	65.8	68.7	71.6	74.5	
18										51.2	54.4	57.6	60.9	64.1	67.4	70.6	73.8	77.1	80.3	83.6	86.8
19										57.1	60.7	64.3	67.9	71.5	75.1	78.7	82.4	86.0	89.6	93.2	96.8
20											67.3	71.3	75.3	79.3	83.3	87.3	91.3	95.3	99.3	103.3	107.3
21													83.1	87.5	91.9	96.3	100.8	105.2	109.6	114.0	118.4
22													91.3	96.1	101.0	105.8	110.6	115.5	120.3	125.2	130.0
23														105.1	110.4	115.7	121.0	126.3	131.6	136.9	142.2
24														114.5	120.3	126.0	131.8	137.6	143.3	149.1	154.8
25														124.3	130.6	136.8	143.1	149.3	155.6	161.8	168.1
26														134.5	141.3	148.0	154.8	161.6	168.3	175.1	181.8
27														145.1	152.4	159.7	167.0	174.3	181.6	188.9	
28																171.8	179.6	187.5	195.3	203.2	
29																	192.8	201.2	209.6	218.0	
30																	206.3	215.3	224.3	233.3	

[1]To obtain cubic-foot volume inside bark to an 8.0-inch (o.b.) top diameter in trees larger than 11.0 inches d.b.h., subtract 4.4 cubic feet from tabular values.

TABLE 27-54—*Total cubic-foot volumes of entire stems (inside bark) for natural sweetgum in Alabama* (Lyle 1973)

Dbh	Total tree height[1] (feet)																				Diameter
(inches)	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	dist.
	Cubic feet																				
2	0.02	0.06	0.11	0.15	0.20																1
3	0.03	0.14	0.24	0.34	0.45	0.55	0.65														5
4		0.25	0.43	0.61	0.79	0.98	1.16	1.34	1.53												5
5			0.67	0.95	1.24	1.53	1.81	2.10	2.38	2.67	2.95										8
6				1.37	1.79	2.20	2.61	3.02	3.43	3.84	4.25	4.67	5.08								10
7						2.99	3.55	4.11	4.67	5.23	5.79	6.35	6.91	7.47	8.03						12
8								5.37	5.10	6.83	7.56	8.29	9.03	9.76	10.49	11.22					12
9								6.80	7.72	8.65	9.57	10.50	11.42	12.35	13.28	14.20	15.13				22
10									9.53	10.68	11.82	12.96	14.10	15.25	16.39	17.53	18.68	19.82			12
11										12.92	14.30	15.68	17.07	18.45	19.83	21.21	22.60	23.98			7
12										15.37	17.02	18.66	20.31	21.96	23.60	25.25	26.89	28.54	30.18		3
13										18.04	19.97	21.90	23.84	25.77	27.70	29.63	31.56	33.49	35.42	37.36	0
14												25.40	27.64	29.88	32.12	34.36	36.60	38.84	41.08	43.32	2
15														34.30	36.88	39.45	42.02	44.59	47.16	49.73	
Height dist.	2	0	1	4	3	3	6	4	8	8	9	12	10	15	7	6	0	2	0	0	

[1]Does not include a six inch stump.
Block shows extent of observed data.
Confidence limits per tree are ± 1.5 cu. ft. with 95% confidence.

TABLE 27-55—*Total cubic-foot volumes of entire stems (outside bark) for natural sweetgum in Alabama* (Lyle 1973)

Dbh	Total tree height[1] (feet)																				Diameter
(inches)	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	dist.
	Cubic feet																				
2	0.14	0.18	0.23	0.27	0.32																1
3	0.31	0.41	0.51	0.61	0.71	0.82	0.92														5
4		0.73	0.91	1.09	1.27	1.45	1.63	1.82	2.00												5
5			1.42	1.70	1.99	2.27	2.55	2.84	3.12	3.40	3.69										8
6				2.45	2.86	3.27	3.68	4.09	4.49	4.90	5.31	5.72	6.13								10
7						4.45	5.01	5.56	6.12	6.67	7.23	7.79	8.34	8.90	9.45						12
8								7.26	7.99	8.72	9.44	10.17	10.90	11.62	12.35	13.08					12
9								9.19	10.11	11.03	11.95	12.87	13.79	14.71	15.63	16.55	17.47				22
10									12.48	13.62	14.75	15.89	17.02	18.16	19.29	20.43	21.56	22.70			12
11										16.48	17.85	19.23	20.60	21.97	23.35	24.72	26.09	27.47			7
12										19.61	21.25	22.88	24.52	26.15	27.78	29.42	31.05	32.69	34.32		3
13										23.02	24.94	26.85	28.77	30.69	32.61	34.53	36.44	38.36	40.28	42.20	0
14												31.14	33.37	35.59	37.82	40.04	42.27	44.49	46.72	48.94	2
15														40.86	43.41	45.97	48.52	51.07	53.63	56.18	0
Height dist.	2	0	1	4	3	3	6	4	8	8	9	12	10	15	7	6	0	2	0	0	

[1]Does not include a six inch stump.
Block shows extent of observed data.
Confidence limits per tree are ± 1.5 cu. ft. with 95% confidence.

TABLE 27-56—*Bark-free cubic volume in entire stems and in merchantable stems of hickory* (Schnur 1937)[1,2,3]

Dbh (inches)		Total tree height (feet)										
Outside bark	Inside bark	10	20	30	40	50	60	70	80	90	100	Basis
		Cubic feet										Trees
		ENTIRE STEM										
1	0.9	0.04	0.07	0.10								47
2	1.8	.12	.22	.32	0.40							78
3	2.7	.25	.45	.65	.85	1.01						66
4	3.6	.41	.75	1.08	1.38	1.67						61
5	4.4		1.12	1.60	2.07	2.50	2.95					39
6	5.3		1.55	2.20	2.85	3.45	4.10					32
7	6.1		2.05	2.90	3.80	4.60	5.50	6.40	7.25			29
8	7.0		2.60	3.75	4.90	6.05	7.20	8.40	9.50			32
9	8.0				6.30	7.80	9.20	10.80	12.10	13.70		30
10	8.9				8.0	9.8	11.8	13.6	15.5	17.4		20
11	9.9				9.6	12.0	14.3	16.6	19.0	21.2		20
12	10.9				11.6	14.2	17.0	19.9	22.6	25.7		15
13	11.9				13.4	16.8	20.0	23.2	26.8	30.0		7
14	12.9				15.6	19.5	23.2	27.2	31.2	34.8		3
15	13.8				18	22	27	31	35	40	44	5
16	14.8				20	25	30	35	40	45	50	2
17	15.8					28	34	39	45	51	57	1
18	16.8						38	44	50	57	64	
19	17.8						42	49	56	64	72	
20	18.8							54	62	70		
21	19.8							60	69	78		
22	20.8							66	76	86		
23	21.8							72	84	95		
Basis (trees)		38	91	113	77	61	51	41	14	1	1	488

TABLE 27-56—*Bark-free cubic volume in entire stems and in merchantable stems of hickory* (Schnur 1937)[1,2,3]—Continued

Dbh (inches) Outside bark	Dbh (inches) Inside bark	Total tree height (feet) 10	20	30	40	50	60	70	80	90	100	Basis
		Cubic feet										*Trees*
		MERCHANTABLE STEM TO A 4-INCH TOP OUTSIDE BARK										
5		0.83	1.13	1.44	1.78	2.10	2.40					49
6		1.35	2.01	2.67	3.35	3.95	4.65	5.20				37
7		1.96	2.94	3.95	4.95	6.00	6.95	8.00				42
8			4.00	5.42	6.85	8.25	9.80	11.20	12.50			39
9			5.20	7.10	8.95	10.90	12.70	14.40	16.00			47
10			6.5	8.8	11.3	13.4	15.5	17.9	20.0	22.0		49
11			8.0	11.0	13.6	16.3	19.1	21.8	24.3	26.9		35
12				13.0	16.2	19.6	22.9	25.9	29.3	32.0		18
13				15.2	19.2	23.0	26.7	30.5	34.0	38.0		27
14				17.8	22.2	26.5	31.2	35.5	40.0	44.0		15
15				20.5	25.5	30.8	36.0	41.5	46.0	52.0	56.0	10
16				23.0	29.1	35.0	41.0	46.5	53.0	59.0	64.0	5
17					32.5	39.5	46.0	53.0	60.0	67.0	73.0	5
18					37.0	44.0	52.5	60.0	68.0	76.0	83.0	
19					41.5	50.0	59.0	67.5	77.0	86.0	94.0	
20						55.5	65.0	76.0	86.0	96.0	104.0	
21						62.0	73.0	85.0	96.0	106.0	115.0	
22						68.0	81.0	94.0	106.0	116.0	125.0	
23						76.0	89.0	102.0	115.0	126.0	137.0	1
Basis (trees)			13	52	87	86	80	39	19	2	1	379

[1]Volume computed from tree graphs by the panimeter method. Stump height 1.0 foot.
[2]Heavy lines indicate limits of basis data.
[3]Trees measured were in Alabama, Arkansas, Connecticut, Indiana, Kentucky, Maryland, Missouri, New York, Ohio, Tennessee, and West Virginia.

TABLE 27-57—*Bark-free cubic volume in entire stems and in merchantable stems of red maple* (Schnur 1937)[1,2,3]

Dbh (inches) Outside bark	Dbh (inches) Inside bark	Total tree height (feet) 10	20	30	40	50	60	70	80	90	Basis: Number of trees
		Cubic feet									
		ENTIRE STEM									
2	1.9	0.12	0.23	0.34	0.44	0.54					67
3	2.9	.27	.51	.73	.96	1.18	1.39				97
4	3.9		.87	1.25	1.65	2.04	2.39	2.78			58
5	4.8			1.89	2.48	3.08	3.60	4.18			38
6	5.7			2.63	3.42	4.25	5.05	5.80			37
7	6.6			3.48	4.55	5.65	6.60	7.70	8.70		55
8	7.5			4.42	5.80	7.20	8.50	10.00	11.10		64
9	8.4			5.60	7.25	9.00	10.60	12.10	13.80		43
10	9.3			6.6	8.7	10.8	12.7	14.5	16.5	18.4	25
11	10.2			8.0	10.6	12.9	15.1	17.5	20.0	22.2	18
12	11.2				12.5	15.2	18.0	21.0	23.8	26.4	11
13	12.2				14.5	17.9	21.2	24.8	27.8	31.0	10
14	13.2				16.8	20.8	24.7	28.3	31.8	35.6	4
15	14.1					24.0	28.2	32.4	36.8	40.8	2
16	15.1					26.9	31.8	36.4	41.5	46.0	1
17	16.1					30.1	35.6	41.0	46.2	51.8	2
18	17.1					33.5	39.8	45.8	51.6	57.8	
Basis (trees)			16	80	106	150	136	38	6		532

See Footnote at end of Table.

TABLE 27-57—*Bark-free cubic volume in entire stems and in merchantable stems of red maple* (Schnur 1937)[1,2,3]—Continued

Dbh (inches)		Total tree height (feet)									Basis:
Outside bark	Inside bark	10	20	30	40	50	60	70	80	90	Number of trees
		Cubic feet									
		MERCHANTABLE STEM TO A 4-INCH TOP OUTSIDE BARK									
5				1.38	1.78	2.15	2.52	2.90	3.25		38
6				2.47	3.18	3.88	4.50	5.25	5.80		37
7				3.52	4.56	5.64	6.55	7.55	8.50		55
8				4.68	6.10	7.50	8.80	10.10	11.50		65
9				5.90	7.70	9.50	11.20	12.80	14.60		42
10				7.2	9.4	11.5	13.6	15.7	17.8	19.8	25
11				8.6	11.3	13.9	16.3	18.9	21.6	24.0	18
12				10.1	13.2	16.3	19.3	22.5	25.5	28.6	11
13				11.6	15.4	19.0	22.6	26.1	29.8	33.3	10
14				13.4	17.7	22.0	26.0	30.2	34.5	38.8	4
15						25.2	30.0	34.8	39.5	44.4	2
16						28.3	34.0	39.2	44.8	50.0	1
17						31.5	37.8	44.0	50.2	57.0	2
18						35.5	42.3	49.5	57.0	63.0	
19						39.2	47.0	55.0	63.0	70.0	
Basis (trees)					15	117	136	36	6		310

[1]Volume computed from tree graphs by the planimeter method. Stump height 1.0 foot.
[2]Heavy lines indicate limits of basic data.
[3]Trees measured were in Connecticut, Maryland, Michigan, New York, Ohio, and Pennsylvania.

TABLE 27-58—*Bark-free cubic volume in entire stems and in merchantable stems of black oak* (Schnur 1937)[1,2,3]

Dbh (inches)		Total tree height (feet)									
Outside bark	Inside bark	20	30	40	50	60	70	80	90	100	Basis: Number of trees
		Cubic feet									
		ENTIRE STEM									
2	1.7	0.20	0.26	0.33	0.40						
3	2.6	.44	.58	.73	.89						16
4	3.5	.77	1.02	1.29	1.60	1.94					33
5	4.4	1.20	1.60	2.02	2.48	3.02					48
6	5.3	1.73	2.28	2.90	3.58	4.32	5.15				44
7	6.2	2.34	3.12	3.94	4.85	5.88	7.00				39
8	7.1	3.08	4.05	5.10	6.30	7.65	9.10	10.70			47
9	8.0	3.88	5.10	6.5	8.00	9.68	11.50	13.50	15.70		49
10	9.0		6.3	8.0	9.8	11.8	14.1	16.6	19.2	21.8	43
11	9.9			9.6	11.8	14.3	17.0	20.1	23.2	26.4	51
12	10.9			11.3	13.9	17.0	20.2	23.8	27.5	31.2	45
13	11.8			13.3	16.3	19.8	23.7	27.9	32.0	36.5	34
14	12.7			15.4	18.9	22.8	27.5	32.2	37.2	42.0	15
15	13.7			17.6	21.7	26.2	31.4	36.8	42.5	48.0	19
16	14.7				24.6	29.6	35.5	41.8	48.2	55.0	12
17	15.6				27.7	33.5	40.0	47.0	54.4	61.5	12
18	16.6					37.5	44.8	52.5	60.8	68.8	7
19	17.5					41.5	49.8	58.5	68.0	76.6	10
20	18.5					46.0	55.0	65.0	74.0	85.0	6
21	19.5					51.0	60.0	71.0	82.0	93.0	4
22	20.5					55.0	66.0	78.0	90.0	102.0	3
23	21.4					60.0	72.0	85.0	98.0	111.0	
Basis (trees)		6	75	57	79	111	102	76	30	1	537

See Footnote at end of Table.

TABLE 27-58—*Bark-free cubic volume in entire stems and in merchantable stems of black oak* (Schnur 1937)[1,2,3]—Continued

Dbh (inches) Outside bark	Dbh (inches) Inside bark	Total tree height (feet) 20	30	40	50	60	70	80	90	100	Basis: Number of trees
		Cubic feet									
		MERCHANTABLE STEM TO A 4-INCH TOP OUTSIDE BARK									
5		0.89	1.23	1.57	1.90	2.27					48
6		1.58	2.21	2.86	3.50	4.19	4.92				44
7		2.30	3.25	4.22	5.20	6.25	7.40				39
8		3.06	4.40	5.74	7.15	8.50	10.10	11.70			47
9		3.89	5.60	7.38	9.12	11.10	13.10	15.20	17.30		49
10			7.0	9.2	11.4	13.9	16.3	18.9	21.8	24.6	43
11				11.2	14.0	16.8	19.9	23.2	26.5	30.0	51
12				13.4	16.7	20.2	23.8	27.7	31.8	35.8	45
13				15.8	19.6	23.7	27.9	32.5	37.2	42.0	34
14				18.3	22.9	27.6	32.8	38.0	43.2	48.8	15
15				21.0	26.3	32.0	37.8	43.5	49.8	56.5	19
16				24.0	30.0	36.2	42.8	49.6	56.8	63.9	12
17					33.9	40.8	48.2	56.1	64.0	72.0	12
18						45.7	54.3	62.8	71.5	80.8	7
19						51.2	60.0	69.9	80.0	90.0	10
20						56	67	77	88	100	6
21						62	73	85	98	110	4
22						68	81	94	107	121	3
23						74	88	102	118	133	
Basis (trees)		2	43	45	78	111	101	76	31	1	488

[1]Volume computed from tree graphs by the planimeter method. Stump height 1.0 foot.
[2]Heavy lines indicate limits of basic data.
[3]Trees measured were in Connecticut, Maryland, New York, Ohio, Pennsylvania, Tennessee, and West Virginia.

TABLE 27-59—*Bark-free cubic volume in entire stems and in merchantable stems of chestnut oak* (Schnur 1937)[1,2,3]

Dbh (inches) Outside bark	Inside bark	Total tree height (feet) 20	30	40	50	60	70	80	90	100	Basis: Number of trees
		Cubic feet									
		ENTIRE STEM									
3	2.5	0.39	0.55	0.72	0.88	1.05					69
4	3.3	.73	1.00	1.30	1.60	1.91					87
5	4.2	1.16	1.60	2.08	2.55	3.01	3.60				77
6	5.1		2.33	3.01	3.70	4.40	5.20				63
7	6.0		3.20	4.16	5.08	6.00	7.15	8.35			71
8	6.9		4.22	5.42	6.62	7.95	9.28	10.70			56
9	7.8		5.35	6.95	8.40	9.85	11.60	13.70	16.3		59
10	8.7		6.7	8.6	10.2	12.2	14.6	17.5	20.6		54
11	9.6		8.0	10.1	12.4	14.9	17.9	21.3	24.5	28.2	49
12	10.5			12.0	14.8	18.0	21.6	25.2	29.1	33.5	54
13	11.4			14.3	17.9	21.4	25.3	29.6	34.1	39.2	32
14	12.3				20.9	24.8	29.3	34.0	39.2	45.0	24
15	13.2				24.0	28.5	33.5	39.0	45.0	52.0	6
16	14.1				27.1	32.2	37.9	44.0	51.0	58.8	2
17	15.1				30.8	36.1	42.7	49.6	57.4	66.0	3
18	16.0					40.2	47.8	55.8	64.0	74.0	1
19	16.9						52.8	61.8	71.2	82.0	
20	17.8						58.0	68.0	78.8	90.0	1
21	18.7						64.0	75.2	86.5	98.5	
22	19.7						70.0	82.0	94.0	107.0	
23	20.6						77.0	89.0	102.0	116.0	1
24	21.5						84.0	96.0	110.0	125.0	
Basis (trees)		7	95	147	177	195	72	14	1	1	709

See Footnote at end of Table.

TABLE 27-59—*Bark-free cubic volume in entire stems and in merchantable stems of chestnut oak* (Schnur 1937)[1,2,3]—Continued

Dbh (inches)		Total tree height (feet)									
Outside bark	Inside bark	20	30	40	50	60	70	80	90	100	Basis: Number of trees
		Cubic feet									
		MERCHANTABLE STEM TO A 4-INCH TOP OUTSIDE BARK									
4			0.09	0.51	0.94	1.48					83
5			1.00	1.69	2.41	3.20	4.00				77
6			2.20	3.08	4.08	5.22	6.30				63
7			3.55	4.70	6.00	7.50	8.88	10.25			71
8			5.05	6.55	8.20	9.95	11.60	13.30			56
9			6.68	8.50	10.45	12.55	14.55	16.50	18.6		59
10			8.5	10.5	12.8	15.5	17.5	20.3	22.8	25.2	54
11			10.2	12.6	15.3	18.4	21.1	24.0	27.0	29.9	49
12				14.9	18.0	21.6	25.0	28.4	31.5	35.0	54
13				17.2	20.9	25.0	28.8	32.5	36.2	40.2	32
14					24.0	28.6	32.9	37.2	41.7	45.8	24
15					27.3	32.2	37.2	42.3	46.8	51.8	6
16					30.5	36.0	42.0	47.0	52.0	57.0	2
17					34.0	40.0	46.0	52.0	58.0	64.0	3
18						45.0	51.0	58.0	64.0	70.0	1
19						49.0	56.0	63.0	70.0	77.0	
20							62	69	77	84	1
21							67	75	83	92	
22							72	81	90	99	
23							78	87	96	106	1
24							84	94	105	114	
(Basis) tree . . .			45	134	177	192	72	14	1	1	636

[1]Volume computed from tree graphs by the planimeter method. Stump height 1.0 foot. [2]Heavy lines indicate limits of basic data.
[3]Trees measured were in Connecticut, Maryland, New York, Ohio, and Pennsylvania.

TABLE 27-60—*Bark-free cubic volume in entire stems and in merchantable stems of northern red oak* (Schnur 1937)[1,2,3]

Dbh (inches)		Total tree height (feet)										Basis:
Outside bark	Inside bark	20	30	40	50	60	70	80	90	100	110	Number of trees
		Cubic feet										
		ENTIRE STEM										
2	1.9	0.18	0.27	0.36								7
3	2.8	.40	.60	.80	1.01							16
4	3.6	.72	1.06	1.42	1.78	2.13						12
5	4.5	1.12	1.66	2.22	2.77	3.32						12
6	5.4		2.39	3.20	3.96	4.75						6
7	6.3		3.25	4.34	5.40	6.45	7.50					16
8	7.2		4.28	5.70	7.08	8.50	9.85	11.20				29
9	8.1		5.38	7.15	8.95	10.65	12.30	14.05	15.70			40
10	9.0		6.7	8.8	11.0	13.0	15.1	17.2	19.3			34
11	10.0		8.1	10.6	13.2	15.8	18.3	20.8	23.3			25
12	10.9		9.6	12.6	15.6	18.6	21.6	24.7	27.5			31
13	11.9			14.7	18.3	21.8	25.3	28.6	32.0	35.5		21
14	12.8			16.9	20.9	25.2	29.0	33.0	36.8	40.8		22
15	13.7			19.4	24.0	28.7	33.2	37.5	42.2	46.6		14
16	14.7				27.2	32.5	37.4	42.6	47.5	52.8		15
17	15.6				30.7	36.5	42.2	48.0	53.6	59.4		9
18	16.6				34.2	40.8	47.0	53.5	60.0	66.5		7
19	17.6				37.8	45.2	52.0	59.5	66.5	74.0		7
20	18.6				42	50	58	66	74	82	89	4
21	19.6				46	55	64	72	81	90	98	3
22	20.6							79	88	98	107	
23	21.6							86	96	106	116	
24	22.5							93	104	115	125	
25	23.5							100	112	124	135	1
26	24.4								121	134	146	
27	25.4								130	144	157	
28	26.4								139	154	168	1
29	27.4								149	165	180	
Basis (trees)		9	20	26	70	104	46	39	16	2		332

See Footnote at end of Table.

TABLE 27-60—*Bark-free cubic volume in entire stems and in merchantable stems of northern red oak* (Schnur 1937)[1,2,3]—Continued

Dbh (inches) Outside bark	Dbh (inches) Inside bark	Total tree height (feet) 20	30	40	50	60	70	80	90	100	110	Basis: Number of trees
		Cubic feet										
		MERCHANTABLE STEM TO A 4-INCH TOP OUTSIDE BARK										
4			0.22	0.57	0.90	1.30						5
5			1.11	1.59	2.17	2.78						12
6			2.15	2.86	3.64	4.48						6
7			3.39	4.33	5.32	6.48	7.65					16
8			4.78	5.95	7.25	8.75	10.30	11.80				29
9			6.28	7.70	9.45	11.05	13.00	15.10	17.60			40
10			7.9	9.8	11.8	14.0	16.3	18.9	22.0			34
11			9.8	12.0	14.3	17.0	20.0	23.0	26.7			25
12			11.8	14.3	17.1	20.4	23.8	27.4	31.6	36.5		31
13				16.8	20.2	23.9	27.9	32.3	37.0	42.9		21
14				19.7	23.7	27.8	32.5	37.4	43.2	50.2		22
15				22.8	27.3	32.2	37.3	43.0	49.9	57.2		14
16					31.0	36.5	42.6	49.2	56.5	65.2		15
17					35.1	41.4	48.2	55.5	63.9	73.0		9
18					39.4	46.4	53.8	62.0	71.0	82.0		7
19					43.8	51.6	60.0	68.8	78.8	90.5	102.0	7
20					48.5	57.0	66.5	76.0	87.4	100.5	112.0	4
21					53.4	63.0	72.8	83.5	95.5	110.5	124.0	3
22								91.0	105.0	121.0	136.0	
23								100.0	115.0	132.0	148.0	
24								108.0	125.0	144.0	160.0	
25								117	135	156	174	1
26									145	168	188	
27									156	180	205	
28									168	195	232	1
29									180	218	262	
Basis (trees)			3	20	69	103	50	39	16	2		302

[1]Volume computed from tree graphs by the planimeter method. Stump height 1.0 foot.
[2]Heavy lines indicate limits of basic data.
[3]Trees measured were in Connecticut, Maryland, New York, Ohio, Virginia, and West Virginia.

TABLE 27-61—*Bark-free cubic volume in entire stems and in merchantable stems of scarlet oak* (Schnur 1937)[1,2,3]

Dbh (inches) Outside bark	Dbh (inches) Inside bark	Total tree height (feet) 20	30	40	50	60	70	80	90	Basis Number of trees
		Cubic feet								
		ENTIRE STEM								
3	2.6	0.49	0.68	0.85	1.04					13
4	3.6	.80	1.15	1.46	1.78	2.10				36
5	4.5	1.21	1.74	2.27	2.77	3.27	3.78			52
6	5.5	1.74	2.48	3.20	3.93	4.65	5.45			39
7	6.4	2.26	3.30	4.28	5.30	6.30	7.40	8.50		50
8	7.3	2.92	4.25	5.60	7.00	8.45	9.90	11.40		33
9	8.3	3.62	5.40	7.15	8.99	10.90	12.80	14.80	16.80	32
10	9.2		6.6	8.9	11.1	13.5	16.0	18.4	20.8	41
11	10.2		8.1	10.9	13.8	16.8	19.5	22.2	24.9	49
12	11.1			13.0	16.5	19.8	23.0	26.2	29.3	70
13	12.0			15.2	19.2	23.0	26.6	30.0	33.7	41
14	13.0				22.0	26.3	30.3	34.5	39.0	28
15	13.9				25.0	29.3	34.3	39.5	44.0	12
16	14.8				28.0	33.3	38.8	44.0	49.5	11
17	15.8				31.3	37.5	43.7	49.9	55.5	5
18	16.7					41.5	48.0	55.0	61.5	1
19	17.6					45.5	53.0	60.2	67.5	2
20	18.6					50.3	58.5	67.0	74.5	2
21	19.5					55.0	64.0	72.5	80.2	
22	20.4					59.5	69.0	78.0	88.0	1
Basis (trees)		14	75	55	66	111	134	50	13	518

See Footnote at end of Table.

TABLE 27-61—*Bark-free cubic volume in entire stems and in merchantable stems of scarlet oak* (Schnur 1937)[1,2,3]—Continued

Dbh (inches) Outside bark	Dbh (inches) Inside bark	Total tree height (feet) 20	30	40	50	60	70	80	90	Basis Number of trees
		Cubic feet								
		MERCHANTABLE STEM TO A 4-INCH TOP OUTSIDE BARK								
5		1.05	1.34	1.66	2.01	2.40	2.78			80
6		1.68	2.24	2.91	3.65	4.41	5.17			39
7		2.36	3.25	4.25	5.40	6.50	7.70	8.95		50
8		3.13	4.40	5.75	7.40	9.10	10.90	12.40		33
9		4.00	5.65	7.50	9.75	12.00	14.00	16.10	18.00	32
10			7.0	9.4	12.0	14.8	17.1	19.7	22.0	41
11			8.5	11.6	14.8	17.9	20.9	24.0	26.9	49
12				13.8	17.5	21.2	24.9	28.5	32.1	70
13				16.1	20.4	24.9	29.0	33.5	37.7	41
14					23.8	29.0	34.0	38.8	44.0	28
15					27.2	33.5	39.0	44.5	50.2	12
16					31.0	37.7	44.0	50.5	57.0	11
17					34.5	42.5	49.8	57.0	64.0	5
18						48.0	55.5	64.0	71.0	1
19						53.0	62.0	70.0	79.5	2
20						58.5	68.0	77.5	87.0	2
21						64.0	75.0	85.0	96.0	
22						70.0	82.0	93.5	104.0	1
Basis (trees)....		6	63	54	66	111	134	50	13	497

[1]Volume computed from tree graphs by the planimeter method. Stump height 1.0 foot.
[2]Heavy lines indicate limits of basic data.
[3]Trees measured were in Connecticut, Indiana, Maryland, New Jersey, Ohio, Pennsylvania, Tennessee, and West Virginia.

TABLE 27-62—*Bark-free cubic volume in entire stems and in merchantable stems of white oak* (Schnur 1937)[1,2,3]

Dbh (inches) Outside bark	Dbh (inches) Inside bark	Total tree height (feet) 20	30	40	50	60	70	80	90	100	Basis: Number of trees
		Cubic feet									
		ENTIRE STEM									
3	2.7	0.44	0.64	0.83							75
4	3.6	.76	1.09	1.43	1.76						66
5	4.5	1.15	1.68	2.20	2.71	3.21					54
6	5.4	1.63	2.40	3.12	3.81	4.54					44
7	6.3	2.19	3.20	4.18	5.14	6.08	6.96				73
8	7.3	2.83	4.12	5.40	6.62	7.82	9.04	10.20			72
9	8.2	3.55	5.15	6.72	8.25	9.80	11.35	12.90			48
10	9.1		6.3	8.2	10.2	12.1	14.1	16.0	18.1		41
11	10.0		7.6	9.9	12.3	14.7	17.1	19.5	22.0		34
12	10.9		9.0	11.8	14.6	17.6	20.4	23.3	26.2	29.0	38
13	11.8			13.9	17.2	20.7	23.9	27.4	30.8	34.0	30
14	12.8			16.2	20.0	24.1	27.9	31.8	35.5	39.4	23
15	13.7			18.6	23.1	27.7	32.0	36.6	41.0	45.5	12
16	14.6			21.2	26.4	31.6	36.5	41.6	46.5	52.0	15
17	15.5				29.8	35.7	41.2	47.0	52.8	58.8	12
18	16.5				33.3	39.9	46.2	52.7	59.2	65.8	2
19	17.4				37.2	44.6	51.5	59.0	66.0	73.5	2
20	18.3						57.5	65.5	74.5	82.0	
21	19.2						63.5	72.0	81.0	90.0	1
Basis (trees)		46	105	123	185	80	31	53	19		642

See Footnote at end of Table.

TABLE 27-62—*Bark-free cubic volume in entire stems and in merchantable stems of white oak* (Schnur 1937)[1,2,3]—Continued

Dbh (inches)		Total tree height (feet)										Basis:
Outside bark	Inside bark	20	30	40	50	60	70	80	90	100	110	Number of trees
		Cubic feet										
		MERCHANTABLE STEM TO A 4-INCH TOP OUTSIDE BARK										
4			0.15	0.62	1.16							74
5		0.42	1.16	1.76	2.37	3.02	3.68					59
6		1.33	2.09	2.93	3.81	4.72	5.70					45
7		2.14	3.20	4.32	5.52	6.72	8.04	9.40				63
8			4.44	5.92	7.47	9.09	10.60	12.30				82
9			5.84	7.72	9.60	11.50	13.50	15.60				52
10				9.7	11.9	14.3	16.7	19.3	22.0			42
11				11.7	14.5	17.3	20.1	23.3	26.4	30.0		36
12				14.1	17.4	20.6	24.0	27.7	31.4	35.5		33
13				16.5	20.3	24.1	28.0	32.3	36.4	41.2		33
14					23.3	27.8	32.5	37.0	42.0	47.2	52.6	29
15					26.8	31.8	36.8	42.3	47.8	54.0	59.9	15
16					30.5	36.0	41.6	47.8	54.0	61.0	67.0	15
17					34.0	40.0	46.5	53.2	66.0	68.0	75.0	13
18					38.0	45.0	52.0	60.0	67.0	75.0	83.0	5
19					42.0	50.0	58.0	66.0	74.0	83.0	92.0	2
20								72	81	91	101	
21								78	88	100	110	1
22								86	96	108	119	
Basis (trees)		1	73	102	159	143	30	48	40	3	—	599

[1]Volume computed from tree graphs by the planimeter method. Stump height 1.0 foot.
[2]Heavy lines indicate limits of basic data.
[3]Trees measured were in Connecticut, Maryland, New York, Ohio, Pennsylvania, Tennessee, and West Virginia.

TABLE 27-63—*Bark-free cubic volume in entire stems and in merchantable stems of sweetgum* (Schnur 1937)[1,2,3]

Dbh (inches) Outside bark	Dbh (inches) Inside bark	Total tree height (feet) 10	20	30	40	50	60	70	80	90	100	110	120	Basis: Number of trees
		Cubic feet												
		ENTIRE STEM												
2	1.5	0.09	0.16	0.22	0.28	0.34								21
3	2.4	.20	.36	.50	.64	.78								28
4	3.3	.34	.62	.87	1.10	1.30								21
5	4.2		.94	1.28	1.66	2.03	2.37							12
6	5.1		1.29	1.84	2.39	2.91	3.45	4.00						16
7	6.1		1.75	2.50	3.25	4.10	4.90	5.70	6.50					15
8	7.1			3.30	4.40	5.50	6.55	7.70	9.00	10.20	11.4			20
9	8.1			4.33	5.75	7.30	8.70	10.40	12.00	13.80	15.3			14
10	9.1			5.5	7.4	9.4	11.3	13.5	15.6	17.7	19.6	20.8		16
11	10.1				9.2	11.8	14.1	16.7	19.2	21.8	24.0	25.4		21
12	11.1				11.2	14.1	17.0	20.0	23.0	26.0	29.0	31.0		25
13	12.1					16.9	20.4	23.8	27.3	31.0	34.0	36.0		34
14	13.0					19.7	23.5	27.3	32.0	36.0	39.5	42.0	44.0	27
15	14.0						27.0	32.0	37.0	41.5	46.0	48.5	50.0	19
16	14.9						31.3	36.3	42.0	47.5	52.5	55.5	58.0	23
17	15.9						35.5	41.5	48.0	54.0	59.5	63.0	65.0	22
18	16.9						39.5	46.0	54.0	60.0	66.0	70.0	72.5	12
19	17.8						44.5	52.0	60.0	67.0	74.0	78.0	82.0	9
20	18.7							58	66	74	82	87	90	7
21	19.7							63	73	82	90	95	99	9
22	20.6							69	80	90	99	104	109	3
23	21.6							75	87	98	109	114	119	2
24	22.6							82	95	107	118	124	130	5
25	23.6							89	103	115	128	135	140	
Basis (trees)....		3	23	52	27	24	17	24	62	61	71	14	3	381

See Footnote at end of Table.

TABLE 27-63—*Bark-free cubic volume in entire stems and in merchantable stems of sweetgum* (Schnur 1937)[1,2,3]—Continued

Dbh (inches)		Total tree height (feet)												Basis:
Outside bark	Inside bark	10	20	30	40	50	60	70	80	90	100	110	120	Number of trees
MERCHANTABLE STEM TO A 4-INCH TOP OUTSIDE BARK														
5		0.6	1.0	1.3	1.6									12
6		1.1	1.7	2.2	2.7	3.2	3.8							16
7		1.6	2.4	3.1	4.0	4.9	6.0	7						15
8			3.2	4.4	5.7	7.1	8.5	10	12					20
9			4.2	5.9	7.8	9.8	12.0	14	17	19				14
10			5.4	7.6	10.0	13.0	16.0	18	21	23	25			16
11				10	13	17	20	23	25	28	30			21
12				12	16	20	24	27	30	33	36			25
13					19	23	27	31	35	38	42			34
14					23	27	31	36	40	44	48	53		27
15						31	36	41	46	51	56	61		19
16						35	41	47	53	58	64	69	73	23
17						40	46	52	59	65	71	77	83	23
18						44	52	59	66	73	80	87	94	12
19						49	57	65	73	81	89	97	104	9
20						54	63	72	81	90	99	108	115	7
21							70	80	90	99	109	118	126	9
22							77	88	99	110	120	130	140	3
23							85	97	109	120	131	142	152	2
24							93	106	119	131	143	155	167	6
25							100	114	129	142	155	169	180	
Basis (trees)			11	24	24	17	24	62	61	73	14	3		313

[1]Volume computed from tree graphs by the planimeter method. Stump height 1.0 foot.
[2]Heavy lines indicate limits of basic data.
[3]Trees measured were in Indiana, Missouri, and South Carolina.

TABLE 27-64—*Bark-free cubic volume in entire stems and in merchantable stems of yellow-poplar* (Schnur 1937)[1,2,3]

Dbh (inches) Outside bark	Dbh (inches) Inside bark	Total tree height (feet) 10	20	30	40	50	60	70	80	90	100	110	Basis Number of trees
		Cubic feet											
		ENTIRE STEM											
1	0.9	0.04	0.06	0.09									7
2	1.8	.11	.20	.28	0.36								7
3	2.7	.23	.42	.60	.77	0.95							5
4	3.6	.39	.73	1.05	1.39	1.71	2.05	2.36					6
5	4.5		1.11	1.66	2.18	2.68	3.18	3.65					13
6	5.5			2.38	3.14	3.85	4.56	5.30	6.00				10
7	6.4			3.20	4.20	5.20	6.10	7.05	8.00				31
8	7.3			4.20	5.50	6.74	7.95	9.20	10.50				31
9	8.2			5.30	6.90	8.50	10.00	11.70	13.10				25
10	9.2			6.5	8.5	10.5	12.3	14.2	16.2	18.0			28
11	10.1			7.6	10.0	12.4	14.8	17.0	19.2	21.7	24.0		28
12	11.0				12.0	14.7	17.5	20.0	23.0	25.5	28.0	31.0	21
13	12.0					17.0	20.2	23.5	26.7	30.0	33.2	36.0	21
14	12.9					19.5	23.2	27.0	30.8	34.5	38.0	42.0	18
15	13.8					22.4	26.5	31.0	35.4	39.5	44.0	48.0	7
16	14.8						30.0	35.5	40.0	45.0	50.0	55.0	4
17	15.7							39.5	45.0	50.0	56.0	62.0	
18	16.6							44.3	50.0	57.0	63.5	70.0	1
19	17.5							49.0	56.0	63.5	70.0	78.0	
20	18.5							54	63	70	78	86	
21	19.4							60	70	78	87	95	1
22	20.4							66	76	86	95	105	
23	21.3							72	83	94	104	115	
24	22.2							80	90	101	113	125	
Basis (trees)		4	10	7	13	27	82	93	20	3	5		264

See Footnote at end of Table.

TABLE 27-64—*Bark-free cubic volume in entire stems and in merchantable stems of yellow-poplar* (Schnur 1937)[1,2,3]—Continued

Dbh (inches) Outside bark	Dbh (inches) Inside bark	Total tree height (feet) 10	20	30	40	50	60	70	80	90	100	110	Basis Number of trees
		Cubic feet											
		MERCHANTABLE STEM TO A 4-INCH OUTSIDE BARK											
5			0.93	1.26	1.59	1.95	2.33	2.74					13
6			1.57	2.18	2.80	3.50	4.22	5.00	5.95				10
7				3.10	4.08	5.05	6.25	7.45	8.75				30
8				4.15	5.48	6.90	8.50	10.10	11.80				32
9				5.30	7.00	8.90	10.90	12.80	15.00				25
10				6.5	8.6	10.9	13.0	15.5	18.1	20.6			29
11					10.5	13.0	15.8	18.7	21.8	24.8	27.0		29
12					12.2	15.2	18.6	22.0	25.8	29.0	32.0	34.8	20
13					14.1	17.6	21.4	25.4	30.0	34.0	37.8	41.0	21
14						20.2	24.7	29.0	34.7	39.8	44.0	48.0	18
15						23.0	28.1	33.8	40.0	46.0	51.0	55.5	7
16						25.8	31.8	38.0	45.5	52.5	58.0	64.0	4
17							35.5	43.0	51.5	59.5	66.5	72.5	
18										67.5	75.0	82.5	1
19										75.5	85.0	93.0	
20										85	95	106	
21										95	108	118	1
22										109	120	130	
Basis (trees)				1	10	25	82	95	19	3	5		240

[1]Volume computed from tree graphs by the planimeter method. Stump height 1.0 foot.
[2]Heavy lines indicate limits of basic data.
[3]Trees measured were in Indiana, Missouri, and South Carolina.

TABLE 27-65A—*Regression equations for estimating above-stump green cubic-foot volume of the whole tree and its components for northern red oak trees 6 to 24 inches in dbh from natural stands in the Southeast, using dbh and total height as independent variables* (Clark et al. 1980a)

Cubic-foot volume (Y)	Regression equation[1]	Coefficient of determination (R^2)	Standard error[2] ($S_{y,x}$)[3]	Number trees sampled (N)
Whole tree (excluding foliage):				
Wood	$Y = 0.002439 (D^2TH)^{1.00568}$	0.99	0.0382	71
Bark	$Y = 0.000633 (D^2Th)^{0.97091}$	.98	.0571	71
Wood & bark ..	$Y = 0.003052 (D^2Th)^{1.00014}$	.99	.0390	71
Stem from stump to saw-log merchantable top (trees ≥ 11.0 inches d.b.h.):				
Wood	$Y = 0.000633 (D^2Th)^{1.09537}$	.95	.0546	35
Bark	$Y = 0.000119 (D^2Th)^{1.06819}$	.93	.0676	35
Wood & bark ..	$Y = 0.000753 (D^2Th)^{1.09162}$	.95	.0537	35
Stem from stump to 8-inch d.i.b. top (trees ≥11.0 inches d.b.h.):				
Wood	$Y = 0.000745 (D^2Th)^{1.08867}$	.97	.0451	35
Bark	$Y = 0.000140 (D^2Th)^{1.06148}$	.93	.0650	35
Wood & bark ..	$Y = 0.000885 (D^2Th)^{1.08492}$	.97	.0449	35
Stem from stump to 4-inch d.i.b. top:				
Wood	$Y = 0.001763 (D^2Th)^{1.01258}$	.99	.0347	71
Bark	$Y = 0.000460 (D^2Th)^{0.95492}$	.99	.0517	71
Wood & bark ..	$Y = 0.002183 (D^2Th)^{1.00496}$	.99	.0339	71
Crown material (all branches and topwood <4 inches d.i.b. excluding foliage):				
Wood	$Y = 0.000697 (D^2Th)^{0.97993}$	.92	.1295	71
Bark	$Y = 0.000188 (D^2Th)^{0.99205}$	.93	.1200	71
Wood & bark ..	$Y = 0.000889 (D^2Th)^{0.98263}$	.92	.1254	71

See Footnote at end of Table.

TABLE 27-65A—*Regression equations for estimating above-stump green cubic-foot volume of the whole tree and its components for northern red oak trees 6 to 24 inches in dbh from natural stands in the Southeast, using dbh and total height as independent variables* (Clark et al. 1980a)—Continued

Cubic-foot volume (Y)	Regression equation[1]	Coefficient of determination (R^2)	Standard error[2] ($S_{y,x}$)[3]	Number trees sampled (N)
Crown material ≥4.0 inches d.o.b. (trees ≥ 11.0 inches d.b.h.):				
Wood	$Y = 0.000000011 (D^2Th)^{1.96775}$	.76	.2490	35
Bark	$Y = 0.000000002 (D^2Th)^{1.98052}$	.80	.2239	35
Wood & bark ..	$Y = 0.000000013 (D^2Th)^{1.96991}$	.77	.2434	35

[1]$Y = b_0(D^2Th)^{b_1}$
where:
Y = component volume in cubic feet.
D = dbh in inches
Th = total height of tree in feet,
$b_0 b_1$ = regression coefficients.

[2]Standard error in $\log_{10}$ form.

[3]Additional statistics for computation of confidence intervals:
$\Sigma(x-\bar{x})^2 = 13.3864$ and $\bar{x} = 4.0718$ for equations based on 71 trees and
$\Sigma(x-\bar{x})^2 = 1.6835$ and $\bar{x} = 4.4538$ for equations based on 35 trees.

TABLE 27-65B—*Regression equations for estimating above-stump green cubic-foot volume of the whole tree and its components for scarlet oak trees 6 to 20 inches in dbh from natural stands in the Southeast, using dbh and total height as independent variables* (Clark et al. 1980b)

Cubic-foot volume (Y)	Regression equation[1]	Coefficient of determination (R^2)	Standard error[2] ($S_{y,x}$)[3]	Number trees sampled (N)
Whole tree (excluding foliage):				
Wood	$Y = 0.00233 (D^2TH)^{1.01465}$	0.99	0.0353	28
Bark	$Y = 0.00086 (D^2Th)^{0.95266}$	.99	.0439	28
Wood & bark ..	$Y = 0.00311 (D^2Th)^{1.00368}$	.99	.0335	28
Stem from stump to saw-log merchantable top (trees ≥ 11.0 inches d.b.h.):				
Wood	$Y = 0.00054 (D^2Th)^{1.09480}$	.87	.0824	16
Bark	$Y = 0.00027 (D^2Th)^{0.97983}$	.80	.0966	16
Wood & bark ..	$Y = 0.00074 (D^2Th)^{1.07831}$	.87	.0834	16

See Footnote at end of Table.

TABLE 27-65B—*Regression equations for estimating above-stump green cubic-foot volume of the whole tree and its components for scarlet oak trees 6 to 20 inches in dbh from natural stands in the Southeast, using dbh and total height as independent variables* (Clark et al. 1980b)—Continued

Cubic-foot volume (Y)	Regression equation[1]	Coefficient of determination (R^2)	Standard error[2] ($S_{y,x}$)[3]	Number trees sampled (N)
Stem from stump to 8-inch d.i.b. top (trees ≥11.0 inches d.b.h.):				
Wood	$Y = 0.00087 (D^2Th)^{1.07477}$	.98	.0336	16
Bark	$Y = 0.00043 (D^2Th)^{0.95980}$	.95	.0414	16
Wood & bark ..	$Y = 0.00119 (D^2Th)^{1.05828}$	.98	.0317	16
Stem from stump to 4-inch d.i.b. top:				
Wood	$Y = 0.00104 (D^2Th)^{1.06736}$	.99	.0419	28
Bark	$Y = 0.00040 (D^2Th)^{0.97815}$	.98	.0569	28
Wood & bark ..	$Y = 0.00137 (D^2Th)^{1.05401}$	.99	.0413	28
Crown material (all branches and topwood <4 inches d.i.b. excluding foliage):				
Wood	$Y = 0.00153 (D^2Th)^{0.91833}$	.94	.0972	28
Bark	$Y = 0.00040 (D^2Th)^{0.93593}$	.94	.1004	28
Wood & bark ..	$Y = 0.00194 (D^2Th)^{0.92165}$	.94	.0941	28
Crown material ≥2.0 inches d.o.b.:				
Wood	$Y = 0.00033 (D^2Th)^{1.02852}$	.86	.1720	28
Bark	$Y = 0.00005 (D^2Th)^{1.08727}$	.88	.1672	28
Wood & bark ..	$Y = 0.00037 (D^2Th)^{1.03921}$	.86	.1699	28
Dead branch material:				
Wood & bark ..	$Y = 0.00014 (D^2Th)^{1.01008}$	.84	.1817	28

[1] $Y = b_0(D^2Th)^{b_1}$
where:
Y = component volume in cubic feet.
D = dbh in inches
Th = total height of tree in feet,
$b_0 b_1$ = regression coefficients.

[2] Standard error in $\log_{10}$ form.

[3] Additional statistics for computation of confidence intervals:
$\Sigma(x-\bar{x})^2 = 4.3559$ and $\bar{x} = 3.9631$ for equations based on 28 trees and
$\Sigma(x-\bar{x})^2 = 0.5386$ and $\bar{x} = 4.4520$ for equations based on 16 trees.

TABLE 27-65C—*Regression equations for estimating above-stump green cubic-foot volume of the whole tree and its components for southern red oak trees 5 to 22 inches in dbh from natural stands in the Southeast, using dbh and total height as independent variables* (Clark et al. 1980c)

Cubic-foot volume (Y)	Regression equation[1]	Coefficient of determination (R^2)	Standard error[2] ($S_{y,x}$)[3]	Number trees sampled (N)
Whole tree (excluding foliage):				
Wood	$Y = 0.000913\ (D^2TH)^{1.10025}$.	0.98	0.0559	29
Bark	$Y = 0.000318\ (D^2Th)^{1.07124}$	.98	.0524	29
Wood & bark ..	$Y = 0.001220\ (D^2Th)^{1.09436}$	.99	.0524	29
Stem from stump to saw-log merchantable top (trees ⩾ 11.0 inches d.b.h.):				
Wood	$Y = 0.002805\ (D^2Th)^{0.91079}$	.74	.0998	17
Bark	$Y = 0.001801\ (D^2Th)^{0.79487}$	.68	.1015	17
Wood & bark ..	$Y = 0.004113\ (D^2Th)^{0.89093}$	.74	.0985	17
Stem from stump to 8-inch d.i.b. top (trees ⩾11.0 inches d.b.h.):				
Wood	$Y = 0.001072\ (D^2Th)^{1.04378}$	.96	.0422	17
Bark	$Y = 0.000688\ (D^2Th)^{0.92787}$	.93	.0461	17
Wood & bark ..	$Y = 0.001570\ (D^2Th)^{1.02392}$	.96	.0393	17
Stem from stump to 4-inch d.i.b. top				
Wood	$Y = 0.000389\ (D^2Th)^{1.15821}$	.98	.0606	29
Bark	$Y = 0.000221\ (D^2Th)^{1.05965}$	.97	.0775	29
Wood & bark ..	$Y = 0.000567\ (D^2Th)^{1.13994}$	.98	.0611	29

See Footnote at end of Table.

TABLE 27-65C—*Regression equations for estimating above-stump green cubic-foot volume of the whole tree and its components for southern red oak trees 5 to 22 inches in dbh from natural stands in the Southeast, using dbh and total height as independent variables* (Clark et al. 1980c)—Continued

Cubic-foot volume (Y)	Regression equation[1]	Coefficient of determination (R^2)	Standard error[2] $(S_{y,x})^3$	Number trees sampled (N)
Crown material (all branches and topwood <4 inches d.i.b. excluding foliage):				
Wood	$Y = 0.000415\ (D^2Th)^{1.03977}$	.79	.2051	29
Bark	$Y = 0.000068\ (D^2Th)^{1.12860}$	.89	.1580	29
Wood & bark	$Y = 0.000465\ (D^2Th)^{1.06191}$	.82	.1905	29
Crown material ⩾2.0 inches d.o.b.:				
Wood	$Y = 0.000074\ (D^2Th)^{1.17306}$	.75	.2657	29
Bark	$Y = 0.000004\ (D^2Th)^{1.35751}$	.83	.2396	29
Wood & bark	$Y = 0.000068\ (D^2Th)^{1.21332}$	.77	.2575	29

[1] $Y = b_0(D^2Th)^{b_1}$
where:
Y = component volume in cubic feet.
D = dbh in inches
Th = total height of tree in feet,
b_0b_1 = regression coefficients.

[2] Standard error in $\log_{10}$ form.

[3] Additional statistics for computation of confidence intervals:
$\Sigma(x-\bar{x})^2 = 4.1055$ and $\bar{x} = 3.9785$ for equations based on 29 trees and
$\Sigma(x-\bar{x})^2 = 0.5235$ and $\bar{x} = 4.2471$ for equations based on 17 trees.

TABLE 27-66A—*Predicted volumes of wood and bark in above-stump portions of northern red oak trees based on equations in table 27-65A*

Dbh (inches) and tree height (feet)[1]	Wood and bark	Wood
	----------Cubic feet ----------	
ABOVE-STUMP WHOLE-TREE		
6 (60)	6.6	5.5
8 (70)	13.7	11.5
10 (80)	24.4	20.5
12 (80)	35.2	29.6
14 (90)	53.9	45.5
16 (100)	78.2	66.1
STEM TO 8-INCH DIB OR SAWLOG MERCHANTABLE TOP		
12 (80)	20.4	17.8
14 (90)	32.5	28.4
16 (100)	48.9	42.7
STEM TO 4-INCH DIB TOP		
6 (60)	4.9	4.2
8 (70)	10.2	8.8
10 (80)	18.3	15.8
12 (80)	26.3	22.8
14 (90)	40.4	35.2
16 (100)	58.8	51.3
CROWN INCLUDING ALL BRANCHES		
6 (60)	1.7	1.3
8 (70)	3.4	2.6
10 (80)	6.1	4.7
12 (80)	8.7	6.7
14 (90)	13.2	10.1
16 (100)	19.1	14.6

[1]Height tabulated is intermediate for the diameter and includes a 1-ft stump allowance.

TABLE 27-66B—*Predicted volumes of wood and bark in above-stump portions of scarlet oak trees based on equations in table 27-65B*

Dbh (inches) and tree height (feet)[1]	Wood and bark	Wood
	----------Cubic feet ----------	
ABOVE-STUMP WHOLE-TREE		
6 (60)	6.9	5.6
8 (60)	12.3	10.1
10 (70)	22.5	18.6
12 (70)	32.4	26.9
14 (80)	50.5	42.1
16 (80)	66.1	55.2

See Footnote at end of Table.

TABLE 27-66B—*Predicted volumes of wood and bark in above-stump portions of scarlet oak trees based on equations in table 27-65B*—Continued

Dbh (inches) and tree height (feet)[1]	Wood and bark	Wood
	Cubic feet	
STEM TO 8-INCH DIB OR SAWLOG MERCHANTABLE TOP		
12 (70)	15.4	13.0
14 (80)	24.7	21.2
16 (80)	33.0	28.3
STEM TO 4-INCH DIB TOP		
6 (60)	4.5	3.8
8 (60)	8.2	7.0
10 (70)	15.5	13.2
12 (70)	22.7	19.5
14 (80)	36.2	31.3
16 (80)	48.0	41.6
CROWN INCLUDING ALL BRANCHES		
6 (60)	2.3	1.8
8 (60)	3.9	3.0
10 (70)	6.8	5.2
12 (70)	9.5	7.3
14 (80)	14.3	10.9
16 (80)	18.3	13.9

[1]Height tabulated is intermediate for the diameter and includes a 1-ft stump allowance.

TABLE 27-66C—*Predicted volumes of wood and bark in above-stump portions of southern red oak trees based on equations in table 27-65C*

Dbh (inches) and tree height (feet)[1]	Wood and bark	Wood
	Cubic feet	
ABOVE-STUMP WHOLE-TREE		
6 (60)	5.4	4.3
8 (60)	10.2	8.0
10 (70)	19.7	15.5
12 (70)	29.3	23.2
14 (80)	47.6	37.7
16 (80)	63.8	50.6
STEM TO 8-INCH DIB OR SAWLOG MERCHANTABLE TOP		
12 (70)	15.2	12.4
14 (80)	22.5	18.6
16 (80)	28.5	23.7

See Footnote at end of Table.

TABLE 27-66C—*Predicted volumes of wood and bark in above-stump portions of southern red oak trees based on equations in table 27-65C*—Continued

Dbh (inches) and tree height (feet)[1]	Wood and bark	Wood
	Cubic feet	
STEM TO 4-INCH DIB TOP		
6 (60)	3.6	2.8
8 (60)	6.9	5.5
10 (70)	13.7	11.1
12 (70)	20.8	16.9
14 (80)	34.4	28.1
16 (80)	46.6	38.3
CROWN INCLUDING ALL BRANCHES		
6 (60)	1.6	1.2
8 (60)	3.0	2.2
10 (70)	5.6	4.1
12 (70)	8.3	6.0
14 (80)	13.3	9.6
16 (80)	17.6	12.6

[1]Height tabulated is intermediate for the diameter and includes a 1-ft stump allowance.

TABLE 27-66D—*Predicted volumes of wood and bark in above-stump portion of yellow-poplar trees based on equations in table 16-30*

Dbh (inches) and tree height (feet)[1]	Wood and bark	Wood
	Cubic feet	
ABOVE-STUMP WHOLE-TREE		
6 (60)	5.9	4.8
8 (70)	12.2	9.9
10 (90)	24.4	19.8
12 (100)	38.9	31.5
14 (100)	52.9	42.6
16 (110)	75.7	61.0
STEM TO 8-INCH DIB OR SAWLOG MERCHANTABLE TOP		
12 (100)	27.3	21.8
14 (100)	38.5	30.9
16 (110)	57.6	46.6
STEM TO 2-INCH DIB TOP		
6 (60)	5.1	4.3
8 (70)	10.7	8.9
10 (90)	21.7	17.9
12 (100)	35.0	28.7
14 (100)	47.7	39.1
16 (110)	68.9	56.2

See Footnote at end of Table.

TABLE 27-66D—*Predicted volumes of wood and bark in above-stump portion of yellow-poplar trees based on equations in table 16-30*—Continued

Dbh (inches) and tree height (feet)[1]	Wood and bark	Wood
	----------Cubic feet----------	
CROWN INCLUDING ALL BRANCHES		
6 (60)	0.8	0.5
8 (70)	1.4	1.0
10 (90)	2.5	1.8
12 (100)	3.8	2.6
14 (100)	4.9	3.4
16 (110)	6.6	4.6

[1]Height tabulated is intermediate for the diameter and includes a 1-ft stump allowance.

TABLE 27-67—*Total cubic foot yield of wood and bark for unthinned yellow-poplar stands of various stand densities, site indices,*[1] *and ages*[2,3] (Beck and Della-Bianca 1979)

Trees per acre (number)	Age (years) 20	30	40	50	60	70
	----------Cubic feet per acre----------					
SITE INDEX 90						
50	—	—	1,560	2,170	2,850	3,590
100	730	1,510	2,330	3,180	4,080	5,020
150	860	1,810	2,760	3,710	4,660	5,580
200	980	2,020	3,050	4,030	4,950	5,780
250	1,110	2,210	3,280	4,260	5,130	5,870
300	1,250	2,400	3,490	4,450	—	—
350	1,410	2,600	3,710	—	—	—
SITE INDEX 110						
50	—	—	2,340	3,380	4,600	5,990
100	960	2,150	3,500	5,020	6,720	8,600
150	1,130	2,600	4,210	5,960	7,840	9,830
200	1,280	2,940	4,740	6,610	8,550	10,540
250	1,450	3,270	5,200	7,160	9,130	11,060
300	1,650	3,610	5,650	7,670	—	—
350	1,870	3,980	6,120	—	—	—
SITE INDEX 130						
50	—	—	3,360	5,040	7,080	9,530
100	1,240	2,970	5,080	7,600	10,590	14,130
150	1,460	3,630	6,210	9,220	12,700	—
200	1,680	4,190	7,140	10,490	—	—
250	1,920	4,760	8,020	11,560	—	—
300	2,220	5,370	8,920	12,830	—	—
350	2,560	6,030	9,850	—	—	—

[1]Site index = height at age 50.

[2]Only trees 4.5 inches dbh and larger are included.

[3]Volumes shown are for entire stems from 1-foot stump height to apical tip, not including branches.

TABLE 27-68—*Cubic-foot yield of wood only to a 4-inch top, outside bark, for unthinned yellow-poplar stands of various stand densities, site indices*[1] *and ages*[2] (Beck and Della-Bianca 1970)

Trees per acre (number)	Age (years)					
	20	30	40	50	60	70
	Cubic feet per acre					
SITE INDEX 90						
50	—	—	1,220	1,700	2,240	2,840
100	520	1,140	1,790	2,480	3,200	3,950
150	590	1,340	2,110	2,870	3,620	4,360
200	650	1,480	2,300	3,090	3,820	4,490
250	720	1,600	2,460	3,240	3,930	4,520
300	800	1,710	2,590	3,360	—	—
350	890	1,840	2,730	—	—	—
SITE INDEX 110						
50	—	—	1,840	2,670	3,640	4,760
100	700	1,650	2,730	3,950	5,300	6,810
150	800	1,970	3,270	4,660	6,170	7,760
200	890	2,220	3,650	5,150	6,710	8,290
250	990	2,450	3,990	5,560	7,130	8,680
300	1,110	2,690	4,320	5,930	—	—
350	1,260	2,940	4,650	—	—	—
SITE INDEX 130						
50	—	—	2,650	4,000	5,630	7,590
100	920	2,300	3,990	6,010	8,410	11,230
150	1,070	2,800	4,870	7,280	10,060	—
200	1,200	3,200	5,580	8,260	—	—
250	1,370	3,640	6,250	9,160	—	—
300	1,570	4,090	6,940	—	—	—
350	1,800	4,580	7,640	—	—	—

[1]Site index = height at age 50.

[2]Only trees 4.5 inches dbh and larger are included.

TABLE 27-69—*Average yield of hickory per acre* (Boisen and Newlin 1910)

Age (years)	Average dbh	Average height	Trees	Total[1] volume	Merchantable[2] volume
	Inches	*Feet*	*Number*	*Cubic feet*	
30	4.0	33	700	800	100
40	5.0	41	480	1,100	300
50	6.2	49	320	1,400	500
60	7.2	57	230	1,700	700
70	8.1	64	180	2,000	850
80	9.0	69	155	2,300	1,000
90	9.8	74	135	2,600	1,150
100	10.5	78	120	2,900	1,300
120	11.8	85	100	3,500	1,650
150	13.4	92	75	4,400	2,000
200	19.0	100	65	5,700	2,700

[1]The source document does not clearly define "total volume", but it is believed to be total above-stump volume including bark and limbs.

[2]The source document does not define the limit of merchantability nor indicate whether merchantable volume includes bark as well as wood.

TABLE 27-70—*Estimated weight of white ash logs with bark by length and diameter inside bark, small end* (Timson 1972)[1,2,3]

Scaling diameter (inches)	Log length (feet) 8	10	12	14	16	18	Half-width of 95% confidence interval[4]
	Sawlog weight, pounds						*Pounds*
8	186	230	274	318	362	406	148
9	226	282	337	393	449	504	164
10	271	340	409	477	546	615	182
11	322	405	488	571	655	738	199
12	378	477	576	675	774	873	217
13	440	556	672	788	904	1,020	235
14	508	642	777	911	1,046	1,180	254
15	580	735	889	1,044	1,198	1,353	272
16	659	834	1,010	1,186	1,362	1,537	290
17	742	941	1,139	1,338	1,536	1,735	309
18	832	1,054	1,277	1,499	1,721	1,944	328
19	926	1,174	1,422	1,670	1,918	2,166	346
20	1,027	1,301	1,576	1,851	2,125	2,400	365
21	1,132	1,435	1,738	2,041	2,344	2,646	384
22	1,244	1,576	1,908	2,241	2,573	2,905	403
23	1,360	1,723	2,087	2,450	2,813	3,176	423
24	1,482	1,878	2,273	2,669	3,064	3,460	442
25	1,610	2,039	2,468	2,898	3,327	3,756	462
26	1,743	2,208	2,672	3,136	3,600	4,064	482
27	1,882	2,383	2,883	3,384	3,884	4,385	502
28	2,026	2,565	3,103	3,641	4,180	4,718	522
29	2,176	2,753	3,331	3,908	4,486	5,063	543
30	2,331	2,949	3,567	4,185	4,803	5,421	564

[1]$W = 66.0433 - 6.8790D + 0.3433D^2L$.

[2]Line encompasses weight based on 90 percent of the logs measured; values outside the dark line are based on the remaining 10 percent of the field samples.

[3]Study was conducted at six mills in Maryland, West Virginia, and Virginia and included a total of 4,800 woods-run logs representing 15 commercially important Appalachian hardwood species.

[4]Add to or subtract from weight to obtain range interval.

TABLE 27-71—*Estimated weight of hickory logs with bark by length and diameter inside bark, small end* (Timson 1972)[1,2,3]

Scaling diameter (inches)	Log length (feet) 8	10	12	14	16	18	Half-width of 95% confidence interval[4]
	Sawlog weight, pounds						*Pounds*
8	269	327	384	441	499	556	147
9	311	384	457	529	602	674	163
10	361	450	540	630	719	809	181
11	417	526	634	743	851	960	198
12	481	610	739	868	997	1,127	216
13	552	704	855	1,007	1,158	1,310	234
14	630	806	982	1,157	1,333	1,509	252
15	715	917	1,119	1,320	1,522	1,724	270
16	808	1,037	1,267	1,496	1,726	1,955	289
17	907	1,166	1,426	1,685	1,944	2,203	307
18	1,014	1,305	1,595	1,885	2,176	2,466	325
19	1,128	1,452	1,775	2,099	2,422	2,746	344
20	1,249	1,608	1,966	2,325	2,683	3,042	362
21	1,377	1,773	2,168	2,563	2,959	3,354	380
22	1,513	1,947	2,381	2,815	3,248	3,682	399
23	1,656	2,130	2,604	3,078	3,552	4,027	417
24	1,805	2,322	2,838	3,354	3,871	4,387	435
25	1,962	2,523	3,083	3,643	4,203	4,764	454
26	2,126	2,732	3,338	3,944	4,550	5,156	472
27	2,298	2,951	3,605	4,258	4,912	5,565	491
28	2,476	3,179	3,882	4,585	5,287	5,990	510
29	2,662	3,416	4,170	4,923	5,677	6,431	592
30	2,855	3,661	4,468	5,275	6,082	6,889	547

[1] $W = 190.1192 - 18.7348D + 0.4482D^2L$.

[2] Line encompasses weight based on 90 percent of the logs measured; values outside the dark line are based on the remaining 10 percent of the field samples.

[3] Study was conducted at six mills in Maryland, West Virginia, and Virginia and included a total of 4,800 woods-run logs representing 15 commercially important Appalachian hardwood species.

[4] Add to or subtract from weight to obtain range interval.

TABLE 27-72—*Estimated weight of red maple logs with bark by length and diameter inside bark, small end* (Timson 1972)[1,2,3]

Scaling diameter (inches)	Log length (feet) 8	10	12	14	16	18	Half-width of 95% confidence interval[4]
	Sawlog weight, pounds						*Pounds*
8	260	311	363	415	467	519	150
9	285	351	416	482	547	613	163
10	317	398	479	560	641	722	179
11	356	454	551	649	747	845	195
12	401	517	634	750	867	983	212
13	452	589	725	862	999	1,136	229
14	510	668	827	986	1,144	1,303	247
15	574	756	938	1,120	1,302	1,484	265
16	645	852	1,059	1,266	1,473	1,681	283
17	722	956	1,190	1,424	1,658	1,891	302
18	806	1,068	1,330	1,592	1,855	2,117	320
19	896	1,188	1,480	1,772	2,065	2,357	338
20	993	1,317	1,640	1,964	2,287	2,611	356
21	1,096	1,453	1,810	2,167	2,523	2,880	375
22	1,206	1,597	1,989	2,381	2,772	3,164	393
23	1,322	1,750	2,178	2,606	3,034	3,462	412
24	1,445	1,911	2,377	2,843	3,308	3,774	431

[1]$W = 289.0249 - 29.4911D + 0.4045D^2$.

[2]Line encompasses weight based on 90 percent of the logs measured; values outside the dark line are based on the remaining 10 percent of the field samples.

[3]Study was conducted at six mills in Maryland, West Virginia, and Virginia and included a total of 4,800 woods-run logs representing 15 commercially important Appalachian hardwood species.

[4]Add to or subtract from weight to obtain range interval.

TABLE 27-73—*Estimated weight of chestnut oak logs with bark by length and diameter inside bark, small end* (Timson 1972)[1,2,3]

Scaling diameter (inches)	Log length (feet) 8	10	12	14	16	18	Half-width of 95% confidence interval[4]
	Sawlog weight, pounds						*Pounds*
8	286	344	402	460	517	575	143
9	332	405	478	551	624	697	160
10	384	474	565	655	745	836	177
11	444	553	663	772	881	990	194
12	511	641	771	901	1,031	1,161	211
13	585	738	891	1,043	1,196	1,349	229
14	667	844	1,021	1,198	1,375	1,552	246
15	756	959	1,162	1,365	1,569	1,772	264
16	852	1,083	1,314	1,545	1,777	2,008	282
17	955	1,216	1,477	1,738	1,999	2,260	299
18	1,065	1,358	1,651	1,943	2,236	2,529	317

See Footnote at end of Table.

TABLE 27-73—*Estimated weight of chestnut oak logs with bark by length and diameter inside bark, small end* (Timson 1972)[1,2,3]—Continued

Scaling diameter (inches)	Log length (feet) 8	10	12	14	16	18	Half-width of 95% confidence interval[4]
	Sawlog weight, pounds						*Pounds*
19	1,183	1,509	1,835	2,161	2,487	2,813	335
20	1,308	1,669	2,031	2,392	2,753	3,114	353
21	1,440	1,838	2,237	2,635	3,033	3,432	371
22	1,579	2,017	2,454	2,891	3,328	3,765	389
23	1,726	2,204	2,682	3,159	3,637	4,115	408
24	1,880	2,400	2,920	3,441	3,961	4,481	426

[1]$W = 183.3447 - 15.9959D + 0.4516D^2L$.

[2]Line encompasses weight based on 90 percent of the logs measured; values outside the dark line are based on the remaining 10 percent of the field samples.

[3]Study was conducted at six mills in Maryland, West Virginia, and Virginia and included a total of 4,800 woods-run logs representing 15 commercially important Appalachian hardwood species.

[4]Add to or subtract from weight to obtain range interval.

TABLE 27-74—*Estimated weight of red oak sp. logs with bark by length and diameter inside bark, small end* (Timson 1972)[1,2,3]

Scaling diameter (inches)	Log length (feet) 8	10	12	14	16	18	Half-width of 95% confidence interval[4]
	Sawlog weight, pounds						*Pounds*
8	261	321	382	443	503	564	159
9	306	383	460	537	613	690	178
10	360	454	549	644	739	833	198
11	420	535	650	764	879	994	218
12	489	625	762	898	1,034	1,171	237
13	565	725	885	1,045	1,205	1,365	257
14	648	834	1,020	1,205	1,391	1,577	277
15	739	952	1,166	1,379	1,592	1,805	297
16	838	1,081	1,323	1,565	1,808	2,050	316
17	944	1,218	1,492	1,766	2,039	2,313	336
18	1,058	1,365	1,672	1,979	2,286	2,593	356
19	1,180	1,521	1,863	2,205	2,547	2,889	376
20	1,309	1,687	2,066	2,445	2,824	3,203	396
21	1,445	1,863	2,280	2,698	3,116	3,534	416
22	1,589	2,048	2,506	2,965	3,423	3,881	436
23	1,741	2,242	2,743	3,244	3,745	4,246	456
24	1,900	2,446	2,991	3,537	4,083	4,628	475

[1]$W = 169.0737 - 18.7765D + 0.4736D^2L$.

[2]Line encompasses weight based on 90 percent of the logs measured; values outside the dark line are based on the remaining 10 percent of the field samples.

[3]Study was conducted at six mills in Maryland, West Virginia, and Virginia and included a total of 4,800 woods-run logs representing 15 commercially important Appalachian hardwood species.

[4]Add to or subtract from weight to obtain range interval.

TABLE 27-75—*Estimated weight of white oak sp. logs with bark by length and diameter inside bark, small end* (Timson 1972)[1,2,3]

Scaling diameter (inches)	Log length (feet) 8	10	12	14	16	18	Half-width of 95% confidence interval[4]
	Sawlog weight, pounds						*Pounds*
8	264	324	384	444	504	564	170
9	303	379	455	530	606	682	187
10	349	443	536	630	723	817	206
11	403	516	629	743	856	969	225
12	464	599	734	868	1,003	1,138	245
13	533	691	849	1,007	1,165	1,323	265
14	609	792	976	1,159	1,342	1,526	286
15	692	903	1,113	1,324	1,534	1,745	306
16	784	1,023	1,262	1,502	1,741	1,981	327
17	882	1,152	1,423	1,693	1,963	2,234	348
18	988	1,291	1,594	1,897	2,200	2,504	368
19	1,102	1,439	1,777	2,115	2,452	2,790	389
20	1,223	1,597	1,971	2,345	2,719	3,094	410
21	1,351	1,764	2,176	2,589	3,001	3,414	431
22	1,487	1,940	2,393	2,845	3,298	3,751	452
23	1,631	2,125	2,620	3,115	3,610	4,105	473
24	1,782	2,320	2,859	3,398	3,937	4,476	494

[1] $W = 224.7721 - 24.9150D + 0.4677D^2L$.

[2] Line encompasses weight based on 90 percent of the logs measured; values outside the dark line are based on the remaining 10 percent of the field samples.

[3] Study was conducted at six mills in Maryland, West Virginia, and Virginia and included a total of 4,800 woods-run logs representing 15 commercially important Appalachian hardwood species.

[4] Add to or subtract from weight to obtain range interval.

TABLE 27-76—*Estimated weight of black tupelo logs with bark by length and diameter inside bark, small end* (Timson 1972)[1,2,3]

Scaling diameter (inches)	Log length (feet) 8	10	12	14	16	18	Half-width of 95% confidence interval[4]
	Sawlog weight, pounds						*Pounds*
8	328	377	426	475	524	573	197
9	373	435	497	558	620	682	211
10	423	499	576	652	729	805	227
11	479	572	665	757	850	942	247
12	542	652	762	872	983	1,093	268
13	611	740	869	999	1,128	1,257	290
14	685	835	985	1,135	1,285	1,435	313
15	766	939	1,111	1,283	1,455	1,627	337
16	853	1,049	1,245	1,441	1,637	1,833	361
17	947	1,168	1,389	1,610	1,831	2,052	385
18	1,046	1,294	1,542	1,790	2,038	2,286	409
19	1,151	1,428	1,704	1,980	2,256	2,533	433
20	1,263	1,569	1,875	2,181	2,487	2,793	457
21	1,381	1,718	2,055	2,393	2,730	3,068	481
22	1,504	1,875	2,245	2,615	2,986	3,356	505
23	1,634	2,039	2,444	2,849	3,253	3,658	529
24	1,770	2,211	2,652	3,093	3,533	3,974	554

[1]$W = 195.5815 - 7.8292D + 0.3826D^2L$.

[2]Line encompasses weight based on 90 percent of the logs measured; values outside the dark line are based on the remaining 10 percent of the field samples.

[3]Study was conducted at six mills in Maryland, West Virginia, and Virginia and included a total of 4,800 woods-run logs representing 15 commercially important Appalachian hardwood species.

[4]Add to or subtract from weight to obtain range interval.

TABLE 27-77—*Estimated weight of yellow-poplar logs with bark by length and diameter inside bark, small end* (Timson 1972)[1,2,3]

Scaling diameter (inches)	Log length (feet) 8	10	12	14	16	18	Half-width of 95% confidence interval[4]
	Sawlog weight, pounds						*Pounds*
8	236	282	327	373	418	464	131
9	273	331	389	446	504	561	147
10	316	387	458	529	601	672	163
11	365	451	537	623	709	795	179
12	419	521	624	726	828	931	195
13	479	599	719	839	959	1,079	211
14	545	684	823	962	1,102	1,241	228
15	616	776	936	1,096	1,255	1,415	244
16	693	875	1,057	1,239	1,421	1,602	261
17	775	981	1,186	1,392	1,597	1,802	277
18	864	1,094	1,324	1,555	1,785	2,015	294
19	958	1,214	1,471	1,727	1,984	2,241	310
20	1,058	1,342	1,626	1,910	2,195	2,479	327
21	1,163	1,476	1,790	2,103	2,417	2,730	343
22	1,274	1,618	1,962	2,306	2,650	2,994	360
23	1,391	1,767	2,143	2,519	2,895	3,270	376
24	1,513	1,923	2,332	2,741	3,151	3,560	393

[1] $W = 144.0939 - 11.1559D + 0.3553\ D^2L$.

[2] Line encompasses weight based on 90 percent of the logs measured; values outside the dark line are based on the remaining 10 percent of the field samples.

[3] Study was conducted at six mills in Maryland, West Virginia, and Virginia and included a total of 4,800 woods-run logs representing 15 commercially important Appalachian hardwood species.

[4] Add to or subtract from weight to obtain range interval.

TABLE 27-78—*Yellow-poplar saw log weights with and without bark* (Clark 1976)[1,2]

Scaling diameter (inches)	Saw log length in feet				
	8	10	12	14	16
	Pounds				
	WITH BARK[3]				
8	200	245	289	334	379
9	247	304	361	417	474
10	301	370	440	510	580
11	359	444	528	613	697
12	423	524	625	725	826
13	493	611	729	847	965
14	569	705	842	979	1,116
15	650	807	964	1,121	1,278
16	736	915	1,094	1,272	1,451
17	828	1,030	1,232	1,434	1,635
18	926	1,152	1,379	1,605	1,831
19	1,029	1,281	1,534	1,786	2,038
20	1,138	1,418	1,697	1,976	2,255
21	1,253	1,561	1,869	2,177	2,484
22	1,373	1,711	2,049	2,387	2,725
23	1,499	1,868	2,237	2,607	2,976
24	1,630	2,032	2,434	2,836	3,238
	WITHOUT BARK[4]				
8	152	192	231	270	309
9	194	243	293	342	392
10	240	301	363	424	485
11	292	366	439	513	587
12	348	436	524	612	700
13	409	512	615	719	822
14	475	595	714	834	954
15	546	683	821	958	1,095
16	621	778	934	1,091	1,247
17	702	879	1,055	1,232	1,408
18	788	985	1,183	1,381	1,579
19	878	1,098	1,319	1,539	1,760
20	973	1,218	1,462	1,706	1,950
21	1,073	1,343	1,612	1,881	2,151
22	1,178	1,474	1,770	2,065	2,361
23	1,288	1,612	1,935	2,258	2,581
24	1,403	1,755	2,107	2,459	2,810

[1]Based on a sample of 230 saw logs selected in western North Carolina. Blocked-in areas indicate limits of sample.

[2]Saw log wood specific gravity averaged 0.415, and wood moisture content averaged 94 percent.

[3]$Y = 21.28306 + 0.34909\ D^2L$.

[4]$Y = -3.93998 + 0.30538\ D^2L$.

TABLE 27-79—*Black oak saw log weights with and without bark* (Phillips 1975)[1,2]

Scaling diameter (inches)	Saw-log length in feet					
	8	10	12	14	16	18
	Pounds					
	SAW-LOG WEIGHT WITH BARK[3]					
8	263	320	377	435	492	549
9	324	396	469	541	613	686
10	392	481	570	660	749	838
11	467	575	683	791	899	1,007
12	549	678	806	935	1,063	1,192
13	638	789	940	1,091	1,242	1,393
14	735	910	1,085	1,260	1,435	1,610
15	838	1,039	1,240	1,441	1,642	1,843
16	949	1,178	1,406	1,635	1,864	2,092
17	1,067	1,325	1,583	1,841	2,099	2,357
18	1,192	1,481	1,771	2,060	2,349	2,639
19	1,324	1,647	1,969	2,291	2,614	2,936
20	1,463	1,821	2,178	2,535	2,892	3,250
21	1,610	2,004	2,398	2,791	3,185	3,579
22	1,764	2,196	2,628	3,060	3,493	3,925
23	1,924	2,397	2,869	3,342	3,814	4,286
24	2,092	2,607	3,121	3,635	4,150	4,664
	SAW-LOG WEIGHT WITHOUT BARK[4]					
8	192	242	293	343	393	443
9	246	309	372	436	499	562
10	305	383	462	540	618	696
11	371	465	560	655	750	844
12	443	555	668	781	893	1,006
13	521	653	786	918	1,050	1,182
14	606	759	912	1,066	1,219	1,372
15	696	872	1,048	1,225	1,401	1,577
16	793	994	1,194	1,394	1,595	1,795
17	897	1,123	1,349	1,575	1,801	2,027
18	1,006	1,260	1,513	1,767	2,020	2,274
19	1,122	1,404	1,687	1,969	2,252	2,534
20	1,244	1,557	1,870	2,183	2,496	2,809
21	1,372	1,718	2,063	2,408	2,753	3,098
22	1,507	1,886	2,265	2,643	3,022	3,401
23	1,648	2,062	2,476	2,890	3,304	3,718
24	1,795	2,246	2,696	3,147	3,598	4,049

[1]Based on a sample of 130 saw logs cut in western North Carolina.

[2]Wood moisture content averaged 91.8 percent of ovendry weight; wood specific gravity averaged 0.544, ovendry weight and green volume basis.

[3]$Y = 34.52022 + 0.44653\ D^2L$

[4]$Y = -7.98753 + 0.39127\ D^2L$.

TABLE 27-80—*Average weight of 8-foot-long mixed oak logs from the Missouri Ozarks and average weight of lumber and residues they produce* (Massengale 1971)[1,2,3,4]

Log diameter (inches)	Average weight per log of:					
	Log with bark	Debarked log	Bark	Lumber	Slabs and edgings	Sawdust
	Pounds					
8	254	210	44	112	42	57
9	333	283	50	144	66	73
10	370	311	59	165	67	79
11	473	413	60	240	70	103
12	540	461	79	274	82	105
13	635	556	79	308	117	131
14	770	664	106	389	118	157
15	880	756	124	478	109	169
16	967	837	131	541	128	168
17	1,122	973	149	591	187	195
18	1,309	1,133	176	663	229	241

[1]Average log weights were determined from a 20-log sample for each diamter class.
[2]Average moisture content of the bark was 48.7 percent (ovendry basis).
[3]Average moisture content of the sawdust was 69.9 percent (ovendry basis).
[4]Values are rounded.

TABLE 27-81—*Black oak biomass regression equations* (Tennessee Valley Authority 1972)

Component(s)	Equation[1]	Coeff. Det. R^2
Complete Tree		
Fresh wood	Log Y = 1.12282 + 2.12073 Log dbh	0.98
Fresh bark	Log Y = 0.53961 + 2.01311 Log dbh	0.95
Fresh total	Log Y = 1.22080 + 2.10416 Log dbh	0.98
Dry wood	Log Y = 0.90951 + 2.11178 Log dbh	0.97
Dry bark	Log Y = 0.27002 + 2.08383 Log dbh	0.96
Dry total	Log Y = 1.00005 + 2.10621 Log dbh	0.97
Tree Crown		
Fresh wood	Log Y = 0.58868 + 2.09742 Log dbh	0.88
Fresh bark	Log Y = 0.08437 + 2.08487 Log dbh	0.86
Fresh total	Log Y = 0.70890 + 2.09360 Log dbh	0.88
Dry wood	Log Y = 0.42075 + 2.06105 Log dbh	0.87
Dry bark	Log Y = −0.22974 + 2.19873 Log dbh	0.88
Dry total	Log Y = 0.50580 + 2.09357 Log dbh	0.88
Merch. Bole		
Fresh wood	Log Y = 0.79041 + 2.13126 Log dbh	0.96
Fresh bark	Log Y = 0.22951 + 1.77026 Log dbh	0.84
Fresh total	Log Y = 0.86878 + 2.10122 Log dbh	0.95
Dry wood	Log Y = 0.55932 + 2.12847 Log dbh	0.95
Dry bark	Log Y = −0.02290 + 1.84814 Log dbh	0.84
Dry total	Log Y = 0.63832 + 2.10813 Log dbh	0.93
Stump and roots		
Fresh wood	Log Y = 0.51989 + 2.10556 Log dbh	0.99
Fresh bark	Log Y = −0.07786 + 2.10255 Log dbh	0.99
Fresh total	Log Y = 0.61783 + 2.10475 Log dbh	0.99
Dry wood	Log Y = 0.28238 + 2.12145 Log dbh	0.99
Dry bark	Log Y = −0.31613 + 2.11888 Log dbh	0.99
Dry total	Log Y = 0.38000 + 2.12094 Log dbh	0.99
Limbs, Up to 4 inches dob		
Fresh wood	Log Y = 1.10606 + 1.32800 Log dbh	0.61
Fresh bark	Log Y = 0.48070 + 1.48380 Log dbh	0.63
Fresh total	Log Y = 1.19125 + 1.37055 Log dbh	0.63
Dry wood	Log Y = 0.92513 + 1.31021 Log dbh	0.61
Dry bark	Log Y = 0.16728 + 1.58130 Log dbh	0.66
Dry total	Log Y = 0.97158 + 1.38644 Log dbh	0.64
Limbs, 4 inches dob and larger		
Fresh wood	Log Y = −0.17751 + 2.51058 Log dbh	0.85
Fresh bark	Log Y = −0.86033 + 2.58256 Log dbh	0.87
Fresh total	Log Y = −0.09636 + 2.52525 Log dbh	0.86
Dry wood	Log Y = −0.37233 + 2.48400 Log dbh	0.84
Dry bark	Log Y = −0.11328 + 2.67315 Log dbh	0.88
Dry total	Log Y = −0.31213 + 2.52763 Log dbh	0.86

[1] $Y = aX^b$ or $Log_{10}Y = Log_{10}a + b\ Log_{10}X$
Where:
Y = weight in pounds
X = dbh in inches

[2] Note: First number of equation is the log_{10} of a. Example: To calculate fresh weight wood for complete tree 20 inches = 1.12282 + 2.12073 (1.30103)
= 1.12282 + 2.75913
Log Y= 3.88195; Y = 7619 pounds

TABLE 27-82—*Predicted green weights of northern red oak trees and stem portions* (Clark et al. 1980a)

Dbh (inches) and tree height (feet)[1]	Wood and bark	Wood
	Pounds	
ABOVE-STUMP WHOLE TREE		
6 (60)	422	354
8 (70)	879	741
10 (80)	1,576	1,333
12 (80)	2,275	1,928
14 (90)	3,494	2,970
16 (100)	5,083	4,331
STEM TO 8-INCH DIB OR SAWLOG MERCHANTABLE TOP		
12 (80)	1,338	1,177
14 (90)	2,128	1,872
16 (100)	3,190	2,809
STEM TO 4-INCH DIB TOP		
6 (60)	317	272
8 (70)	662	572
10 (80)	1,188	1,032
12 (80)	1,717	1,496
14 (90)	2,639	2,308
16 (100)	3,842	3,371

[1]Height tabulated is intermediate for the diameter and includes a 1-ft stump allowance.

TABLE 27-83—*Predicted green weights of scarlet oak trees and stem portions* (Clark et al. 1980b)

Dbh (inches) and tree height (feet)[1]	Wood and bark	Wood
	Pounds	
ABOVE-STUMP WHOLE TREE		
6 (60)	449	374
8 (60)	802	671
10 (70)	1,471	1,234
12 (70)	2,126	1,786
14 (80)	3,321	2,797
16 (80)	4,348	3,667
STEM TO 8-INCH DIB OR SAWLOG MERCHANTABLE TOP		
12 (70)	1,029	891
14 (80)	1,642	1,427
16 (80)	2,177	1,896

See Footnote at end of Table.

TABLE 27-83—*Predicted green weights of scarlet oak trees and stem portions* (Clark et al. 1980b)—Continued

Dbh (inches) and tree height (feet)[1]	Wood and bark	Wood
	Pounds	
STEM TO 4-INCH DIB TOP		
6 (60)	297	254
8 (60)	545	467
10 (70)	1,026	884
12 (70)	1,507	1,302
14 (80)	2,402	2,081
16 (80)	3,183	2,763

[1]Height tabulated is intermediate for the diameter and includes a 1-ft stump allowance.

TABLE 27-84—*Predicted green weights of southern red oak trees and stem portions* (Clark et al. 1980c)

Dbh (inches) and tree height (feet)[1]	Wood and bark	Wood
	Pounds	
ABOVE-STUMP WHOLE TREE		
6 (60)	340	273
8 (60)	644	519
10 (70)	1,256	1,012
12 (70)	1,885	1,520
14 (80)	3,081	2,487
16 (80)	4,147	3,348
STEM TO 8-INCH DIB OR SAWLOG MERCHANTABLE TOP		
12 (70)	980	817
14 (80)	1,463	1,228
16 (80)	1,863	1,571
STEM TO 4-INCH DIB TOP		
6 (60)	224	183
8 (60)	436	358
10 (70)	874	722
12 (70)	1,333	1,105
14 (80)	2,225	1,852
16 (80)	3,032	2,531

[1]Height tabulated is intermediate for the diameter and includes a 1-ft stump allowance.

TABLE 27-85—*Predicted green and ovendry weights of yellow-poplar trees and stem portions* (Clark and Schroeder 1977)

Dbh (inches) and tree height (feet)[1]	Wood and bark	Wood
	Pounds	
GREEN ABOVE-STUMP WHOLE TREE		
6 (60)	321	257
8 (70)	648	523
10 (90)	1,266	1,031
12 (100)	1,989	1,628
14 (100)	2,675	2,197
16 (110)	3,789	3,126
GREEN STEM TO 8-INCH DIB OR SAWLOG MERCHANTABLE TOP		
12 (100)	1,362	1,134
14 (100)	1,907	1,595
16 (110)	2,832	2,380
GREEN STEM TO 2-INCH DIB TOP		
6 (60)	277	228
8 (70)	565	468
10 (90)	1,118	931
12 (100)	1,769	1,479
14 (100)	2,391	2,003
16 (110)	3,406	2,863
DRY ABOVE-STUMP WHOLE TREE		
6 (60)	140	117
8 (70)	292	244
10 (90)	590	495
12 (100)	948	798
14 (100)	1,294	1,090
16 (110)	1,866	1,574
DRY STEM TO 8-INCH DIB OR SAWLOG MERCHANTABLE TOP		
12 (100)	653	547
14 (100)	928	782
16 (110)	1,403	1,190
DRY STEM TO 2-INCH DIB TOP		
6 (60)	122	103
8 (70)	258	218
10 (90)	528	447
12 (100)	855	725
14 (100)	1,172	995
16 (110)	1,699	1,445

[1]Height tabulated is intermediate for the diameter and includes a 1-ft stump allowance.

TABLE 27-86.—*Whole-tree green weight* (Wiant et al. 1977)[1/2]

Dbh (inches)	Northern red oak	Black oak	Scarlet oak	White oak	Chestnut oak	Yellow-poplar	Hickory	Black cherry	Red maple
	Pounds								
2	18	22	25	14	20	21	18	26	21
3	54	60	67	42	56	57	53	67	59
4	116	123	136	92	118	113	113	133	122
5	211	215	233	170	208	192	202	227	213
6	343	338	363	281	332	297	326	350	336
7	518	496	529	429	492	430	489	504	494
8	740	691	731	619	693	591	694	693	691
9	1,013	926	974	855	936	784	945	916	927
10	1,342	1,204	1,258	1,142	1,226	1,008	1,246	1,177	1,207
11	1,731	1,526	1,586	1,484	1,564	1,266	1,600	1,476	1,533
12	2,184	1,895	1,960	1,885	1,954	1,559	2,011	1,815	1,906
13	2,704	2,313	2,381	2,348	2,398	1,888	2,481	2,195	2,329
14	3,296	2,781	2,850	2,878	2,898	2,253	3,014	2,617	2,804
15	3,962	3,302	3,371	3,479	3,458	2,658	3,612	3,083	3,333
16	4,707	3,877	3,943	4,154	4,078	3,101	4,278	3,594	3,918

See Equations used and Footnotes at end of Table.

TABLE 27-86.—*Whole-tree green weight* (Wiant et al. 1977)[1/2]—Continued

Species	Equation used	R^2	Standard error	
			Pounds	%of W-mean
Northern red oak	$W = 2.87249D^{2.66958}$	.989	129	10
Black oak	$W = 3.91058D^{2.48832}$	.994	86	7
Scarlet oak	$W = 4.66811D^{2.43058}$	.996	81	6
White oak	$W = 2.04530D^{2.74698}$	.988	127	10
Chestnut oak	$W = 3.39314D^{2.55778}$	.991	109	9
Yellow-poplar	$W = 4.09609D^{2.39108}$	.996	63	6
Hickory	$W = 2.96160D^{2.62410}$	.986	145	13
Black cherry	$W = 4.95555D^{2.37562}$	.995	75	7
Red maple	$W = 3.78003D^{2.50438}$	.986	123	12

[1]Based on a sample of 19 to 22 trees per species cut in West Virginia.

[2]Stumps, approximately 1/2-foot, roots, and leaves not included.

TABLE 27-87.—*Whole-tree ovendry weight* (Wiant et al. 1977)[1/2]

Dbh (inches)	Northern red oak	Black oak	Scarlet oak	White oak	Chestnut oak	Yellow-poplar	Hickory	Black cherry	Red maple
	Pounds								
2	11	12	14	8	12	9	12	14	11
3	31	34	39	25	34	25	34	37	30
4	67	69	78	55	71	52	73	75	63
5	122	121	135	100	125	90	131	128	112
6	198	190	210	163	199	143	212	200	179
7	299	280	306	247	294	211	317	290	265
8	426	391	424	354	412	295	450	401	374
9	583	525	565	487	556	397	613	534	505
10	772	683	731	648	726	517	808	689	662
11	994	867	922	838	924	657	1,037	868	845
12	1,253	1,078	1,141	1,060	1,152	818	1,303	1,072	1,056
13	1,551	1,318	1,386	1,315	1,411	1,000	1,607	1,302	1,296
14	1,888	1,586	1,661	1,607	1,703	1,205	1,951	1,559	1,567
15	2,269	1,885	1,966	1,936	2,028	1,433	2,338	1,842	1,870
16	2,694	2,216	2,301	2,305	2,388	1,686	2,769	2,155	2,206

Species	Equation used	R^2	Standard error: Pounds	Standard error: %of W-mean
Northern red oak	$W = 1.68914D^{2.65978}$	.988	79	11
Black oak	$W = 2.14567D^{2.50304}$	.994	50	7
Scarlet oak	$W = 2.65743D^{2.43948}$	.993	60	8
White oak	$W = 1.28919D^{2.70096}$	.988	72	10
Chestnut oak	$W = 2.12015D^{2.53442}$	.991	65	9
Yellow-poplar	$W = 1.57792D^{2.51532}$	.995	37	7
Hickory	$W = 1.93378D^{2.62090}$	.987	91	12
Black cherry	$W = 2.58831D^{2.42530}$	.994	45	7
Red maple	$W = 1.81301D^{2.56226}$	.981	78	13

[1]Based on a sample of 19 to 22 trees per species cut in West Virginia.

[2]Stumps, approximately 1/2-foot, roots, and leaves not included.

TABLE 27-88.—*Green weight of stem (wood and bark) to a 4-inch dob top* (Wiant et al. 1977)[1/2]

Dbh (inches)	Northern red oak	Black oak	Scarlet oak	White oak	Chestnut oak	Yellow-poplar	Hickory	Black cherry	Red maple
	Pounds								
5	162	222	184	116	144	121	92	165	203
6	273	280	286	236	258	221	168	264	239
7	415	375	417	384	400	349	280	396	326
8	589	507	578	560	571	505	435	561	464
9	794	677	767	765	769	690	641	758	653
10	1,032	885	985	998	996	904	907	988	893
11	1,301	1,130	1,232	1,259	1,252	1,146	1,241	1,251	1,185
12	1,602	1,413	1,508	1,549	1,535	1,416	1,653	1,547	1,528
13	1,935	1,733	1,812	1,866	1,846	1,716	2,152	1,875	1,922
14	2,300	2,091	2,146	2,213	2,186	2,044	2,747	2,236	2,368
15	2,696	2,486	2,509	2,587	2,554	2,400	3,448	2,630	2,864
16	3,124	2,919	2,901	2,990	2,950	2,785	4,226	3,057	3,412

Species	Equation used	R^2	Standard error: Pounds	Standard error: %of W-mean
Northern red oak	$W = 88.21958 + 15.90187D^2 - 64.67165D$	.988	108	9
Black oak	$W = 497.81493 + 18.76768D^2 - 148.94424D$	.985	104	9
Scarlet oak	$W = 108.22596 + 14.48597D^2 - 57.22531D$	.979	136	12
White oak	$W = 14.14272D^2 - 35.74697D - 58.95854$	.983	127	12
Chestnut oak	$W = 14.10156D^2 - 41.01997D - 3.56707$	.992	82	8
Yellow-poplar	$W = 52.83929 + 14.27865D^2 - 57.70586D$	.971	151	14
Hickory	$W = 0.45983D^{3.29484}$	.969	171	17
Black cherry	$W = 162.72473 + 16.39759D^2 - 81.44786D$	.987	105	9
Red maple	$W = 794.01142 + 25.61191D^2 - 246.17225D$	.979	132	13

[1]Based on a sample of 19 to 22 trees per species cut in West Virginia. [2]Stumps, approximately 1/2-foot, roots, and leaves not included.

TABLE 27-89.—*Weight of ovendry stem (wood and bark) to a 4-inch dob top* (Wiant et al. 1977)[1/2]

DBH (inches)	Northern red oak	Black oak	Scarlet oak	White oak	Chestnut oak	Yellow-poplar	Hickory	Black cherry	Red maple
	Pounds								
5	91	124	88	85	99	64	61	93	105
6	156	156	142	138	157	114	110	161	129
7	238	209	212	207	232	180	183	245	180
8	338	284	301	294	325	261	284	346	259
9	455	380	409	400	438	358	417	462	366
10	590	499	539	528	571	471	590	595	500
11	743	639	691	678	726	600	806	744	662
12	913	800	868	852	904	745	1,073	909	851
13	1,101	984	1,070	1,052	1,107	905	1,395	1,091	1,069
14	1,307	1,189	1,299	1,278	1,334	1,082	1,779	1,288	1,314
15	1,530	1,416	1,556	1,532	1,588	1,274	2,231	1,502	1,586
16	1,771	1,665	1,842	1,815	1,869	1,482	2,758	1,732	1,887

Species	Equation used	R^2	Standard error	
			Pounds	%of W-mean
Northern red oak	$W = 33.10060 + 8.81566D^2 - 32.45835D$	.984	70	11
Black oak	$W = 293.09646 + 10.86577D^2 - 88.11460D$	.987	55	9
Scarlet oak	$W = 1.30430D^{2.61602}$	.979	76	11
White oak	$W = 1.24354D^{2.62792}$	.989	55	8
Chestnut oak	$W = 1.71389D^{2.52260}$	.983	69	10
Yellow-poplar	$W = 53.24629 + 7.91561D^2 - 37.34973D$	.964	90	16
Hickory	$W = 0.30832D^{3.28170}$	.972	106	16
Black cherry	$W = 8.09971D^2 - 21.14376D - 3.40207$	.982	70	11
Red maple	$W = 402.37775 + 13.83454D^2 - 128.58822D$	.976	78	14

[1]Based on a sample of 19 to 22 trees per species cut in West Virginia. [2]Stumps, approximately 1/2-foot, roots, and leaves not included.

TABLE 27-90.—*Red maple stem weight inside bark to 4-inch top diameter inside bark* (Oderwald and Yausey 1980)[1/2/3]

Dbh (inches)	Total tree height, feet			
	40	50	60	70
	Pounds			
	OVENDRY WEIGHT			
6	74	88	102	
7	113	136	159	
8		189	221	254
9		247	290	333
10		311	365	420
11		381	448	515
12			538	619
13			635	731
14			740	851
15			852	980
16			972	1,118
	GREEN WEIGHT			
6	127	151	175	
7	194	234	273	
8		325	380	436
9		425	499	573
10		536	629	723
11		656	771	887
12			926	1,065
13			1,094	1,258
14			1,274	1,465
15			1,467	1,687
16			1,673	1,925

[1]Based on a specific gravity of 0.473 for stem wood and 0.547 for stem bark and a moisture content of 0.721 for stem wood and 0.744 for stem bark.

[2]CAUTION: The main stem of trees with larger dbh's may end before the top diameter is reached.

[3]Data based on 11 trees sampled near Blacksburg, Va.

TABLE 27-91.—*Red maple stem weight, bark included, to a 4-inch top diameter outside bark* (Oderwald and Yausey 1980)[1/2/3]

Dbh (inches)	Total tree height, feet			
	40	50	60	70
	----------Pounds----------			
	OVENDRY WEIGHT			
6	89	106	124	
7	133	160	187	
8		220	258	296
9		286	336	386
10		359	422	485
11		439	516	593
12			618	711
13			729	839
14			849	976
15			977	1,124
16			1,114	1,281
	GREEN WEIGHT			
6	153	183	214	
7	229	276	323	
8		379	444	510
9		493	579	665
10		619	727	836
11		757	889	1,022
12			1,066	1,226
13			1,257	1,446
14			1,463	1,683
15			1,684	1,938
16			1,920	2,209

[1]Based on a specific gravity of 0.473 for stem wood and 0.547 for stem bark and a moisture content of 0.721 for stem wood and 0.744 for stem bark.

[2]CAUTION: The main stem of trees with larger dbh's may end before the top diameter is reached.

[3]Data based on 11 trees sampled near Blacksburg, Va.

TABLE 27-92.—*Merchantable stem weights, to an 8-inch top dib, of freshly felled black oak sawtimber trees, with and without bark* (Phillips et al. 1974[1])

Dbh (inches)	Merchantable height (number of 16-foot logs)[2] 1	1-1/2	2	2-1/2	3	3-1/2	4	4-1/2
	Pounds							
	BARK-FREE[3]							
10	596	746	896	1,046				
11	663	844	1,026	1,207	1,388			
12	736	952	1,168	1,384	1,600			
13	816	1,069	1,322	1,576	1,829	2,082		
14	902	1,196	1,489	1,783	2,077	2,371		
15	994	1,331	1,669	2,006	2,343	2,681	3,018	
16	1,093	1,477	1,860	2,244	2,628	3,012	3,396	
17	1,198	1,631	2,064	2,498	2,931	3,364	3,797	
18	1,310	1,795	2,281	2,767	3,252	3,738	4,224	4,710
19	1,427	1,969	2,510	3,051	3,592	4,133	4,674	5,216
20	1,552	2,151	2,751	3,351	3,950	4,550	5,149	5,749
21	1,682	2,343	3,004	3,666	4,327	4,988	5,649	6,310
22	1,819	2,545	3,270	3,996	4,721	5,447	6,173	6,898
23	1,963	2,756	3,549	4,342	5,135	5,928	6,721	7,514
24	2,112	2,976	3,839	4,703	5,566	6,430	7,293	8,157
25		3,205	4,142	5,079	6,016	6,953	7,890	8,827
26		3,444	4,458	5,471	6,484	7,498	8,511	9,525
27			4,785	5,878	6,971	8,064	9,157	10,250
28			5,126	6,301	7,476	8,651	9,827	11,002
29				6,739	8,000	9,260	10,521	11,782
30				7,192	8,541	9,890	11,240	12,589

See Footnote at end of Table.

TABLE 27-92.—*Merchantable stem weights, to an 8-inch top dib, of freshly felled black oak sawtimber trees, with and without bark* (Phillips et al. 1974[1])—Continued

Dbh (inches)	Merchantable height (number of 16-foot logs)[2]							
	1	1-1/2	2	2-1/2	3	3-1/2	4	4-1/2
	Pounds							
	BARK IN PLACE[4]							
10	728	904	1,080	1,255				
11	807	1,019	1,232	1,444	1,657			
12	892	1,145	1,398	1,651	1,905			
13	986	1,283	1,580	1,877	2,174	2,470		
14	1,087	1,431	1,775	2,120	2,464	2,808		
15	1,195	1,590	1,986	2,381	2,776	3,172	3,567	
16	1,311	1,760	2,210	2,660	3,110	3,560	4,009	
17	1,434	1,942	2,449	2,957	3,465	3,973	4,481	
18	1,565	2,134	2,703	3,272	3,842	4,411	4,980	5,549
19	1,703	2,337	2,971	3,606	4,240	4,874	5,508	6,143
20	1,848	2,551	3,254	3,957	4,660	5,362	6,065	6,768
21	2,001	2,776	3,551	4,326	5,101	5,876	6,650	7,425
22	2,162	3,012	3,863	4,713	5,564	6,414	7,264	8,115
23	2,330	3,259	4,189	5,118	6,048	6,977	7,907	8,836
24	2,505	3,517	4,530	5,542	6,554	7,566	8,578	9,590
25		3,787	4,885	5,983	7,081	8,179	9,277	10,375
26		4,067	5,254	6,442	7,630	8,818	10,005	11,193
27			5,638	6,919	8,200	9,481	10,762	12,043
28			6,037	7,415	8,792	10,170	11,547	12,925
29				7,928	9,406	10,883	12,361	13,839
30				8,459	10,040	11,622	13,203	14,784

[1]Blocked-in areas indicate range of data. Data are based on 40 black oak trees from a mature, uneven-aged stand of mixed oaks on an upland slope near Brevard, N.C. Merchantable stemwood specific gravity averaged 0.54 (based on green volume and ovendry weight), and bark specific gravity averaged 0.55. Stemwood moisture content averaged 94.9 percent of ovendry weight; bark moisture content was not determined.

[2]Includes a 1-foot stump allowance.

[3]$Y = 277.36124 + 0.18739\ D^2Mh$; $R^2 = 0.96$
where: D = dbh, inches; and Mh = merchantable height, feet.

[4]$Y = 354.79422 + 0.21963\ D^2Mh$; $R^2 = 0.96$.

TABLE 27-93.—*Red oak sp. stem weight inside bark to 4-inch top diameter inside bark* (Oderwald and Yausey 1980)[1/2/3]

Dbh (inches)	Total tree height, feet				
	40	50	60	70	80
	Pounds				
	DRY WEIGHT				
6	81	96	111		
7	127	152	178		
8	178	214	251	287	
9	233	282	331	380	
10	295	356	418	481	543
11		438	514	591	668
12		526	618	711	804
13		622	731	840	950
14		724	852	980	1,108
15			981	1,129	1,277
16			1,120	1,288	1,457
17			1,267	1,457	1,648
18			1,422	1,636	1,851
19			1,587	1,825	2,065
20			1,760	2,025	2,290
	GREEN WEIGHT				
6	133	158	183		
7	209	251	293		
8	293	353	413	474	
9	385	464	545	626	
10	486	587	689	792	895
11		721	847	974	1,101
12	867	1,019	1,171	1,324	1,324
13		1,024	1,204	1,385	1,566
14		1,194	1,403	1,614	1,825
15			1,617	1,860	2,104
16			1,845	2,122	2,400
17			2,087	2,401	2,715
18			2,343	2,696	3,049
19			2,614	3,008	3,402
20			2,900	3,336	3,773

[1]Based on a specific gravity of 0.593 for stem wood and 0.600 for stem bark and a moisture content of 0.648 for stem wood and 0.551 for stem bark.

[2]CAUTION: The main stem of trees with larger dbh's may end before the top diameter is reached.

[3]Data based on 33 red oak sp. trees sampled near Blacksburg, Va.

TABLE 27-94.—*Red oak sp. stem weight, bark included, to 4-inch top diameter outside bark* (Oderwald and Yausey 1980)[1/2/3]

Dbh (inches)	Total tree height, feet				
	40	50	60	70	80
	Pounds				
	OVENDRY WEIGHT				
6	110	132	153		
7	165	198	232		
8	225	272	319	366	
9	293	354	416	478	
10	367	444	522	600	678
11		543	639	734	630
12		651	765	880	995
13		768	903	1,038	1,174
14		693	1,051	1,209	1,367
15			1,209	1,391	1,573
16			1,379	1,586	1,794
17			1,559	1,793	2,028
18			1,749	2,013	2,276
19			1,951	2,244	2,539
20			2,163	2,489	2,815
	GREEN WEIGHT				
6	179	215	250		
7	268	323	378		
8	367	443	520	597	
9	477	577	677	778	
10	598	724	851	978	1,105
11		885	1,041	1,197	1,353
12		1,061	1,248	1,435	1,622
13		1,251	1,471	1,692	1,914
14		1,456	1,713	1,970	2,228
15			1,971	2,267	2,564
16			2,247	2,585	2,924
17			2,540	2,922	3,306
18			2,851	3,280	3,710
19			3,179	3,658	4,138
20			3,525	4,056	4,588

[1]Based on a specific gravity of 0.593 for stem wood and 0.600 for stem bark and a moisture content of 0.648 for stem wood and 0.551 for stem bark.

[2]CAUTION: The main stem of trees with larger dbh's may end before the top diameter is reached.

[3]Data based on 33 red oak sp. trees sampled near Blacksburg, Va.

TABLE 27-95.—*White oak stem weight inside bark to 4-inch top diameter inside bark* (Oderwald and Yausey 1980)[1/2/3]

Dbh (inches)	Total tree height, feet				
	40	50	60	70	80
	Pounds				
	OVENDRY WEIGHT				
6	88	104	121		
7	136	163	191		
8	190	229	268	307	
9	249	300	352	405	
10	313	379	445	511	578
11		465	547	628	710
12		559	657	755	854
13		660	776	892	1,009
14		769	904	1,040	1,176
15			1,041	1,198	1,355
16			1,188	1,367	1,546
17			1,344	1,546	1,748
18			1,509	1,736	1,963
19			1,683	1,936	2,190
20			1,867	2,147	2,429
	GREEN WEIGHT				
6	137	163	189		
7	213	256	299		
8	297	358	420	481	
9	390	471	552	634	
10	491	594	698	802	906
11		729	857	985	1,113
12		876	1,029	1,183	1,338
13		1,034	1,216	1,398	1,581
14		1,205	1,417	1,630	1,843
15			1,632	1,878	2,123
16			1,862	2,142	2,422
17			2,106	2,423	2,740
18			2,365	2,720	3,077
19			2,638	3,035	3,432
20			2,925	3,366	3,807

[1]Based on a specific gravity of 0.607 for stem wood and 0.600 for stem bark and a moisture content of 0.567 for stem wood and 0.581 for stem bark.

[2]CAUTION: The main stem of trees with larger dbh's may end before the top diameter is reached.

[3]Data based on 37 red oak sp. trees sampled near Blacksburg, Va.

TABLE 27-96.—*White oak stem weight, bark included, to a 4-inch top diameter outside bark* (Oderwald and Yausey 1980)[1/2/3]

Dbh (inches)	Total tree height, feet				
	40	50	60	70	80
	Pounds				
	OVENDRY WEIGHT				
6	112	134	156		
7	168	202	236		
8	230	277	325	373	
9	298	360	423	486	
10	374	452	532	611	691
11		553	650	748	845
12		663	780	897	1,014
13		782	919	1,058	1,196
14		910	1,070	1,231	1,392
15			1,232	1,417	1,602
16			1,404	1,615	1,827
17			1,587	1,826	2,066
18			1,782	2,050	2,318
19			1,987	2,286	2,586
20			2,203	2,535	2,867
	GREEN WEIGHT				
6	176	210	245		
7	263	317	371		
8	360	435	510	586	
9	468	566	664	763	
10	587	710	834	959	1,084
11		868	1,021	1,173	1,327
12		1,041	1,223	1,407	1,591
13		1,227	1,443	1,660	1,877
14		1,428	1,679	1,932	2,185
15			1,933	2,224	2,515
16			2,204	2,535	2,867
17			2,491	2,866	3,242
18			2,796	3,217	3,639
19			3,118	3,587	4,058
20			3,457	3,978	4,499

[1]Based on a specific gravity of 0.607 for stem wood and 0.600 for stem bark and a moisture content of 0.567 for stem wood and 0.581 for stem bark.

[2]CAUTION: The main stem of trees with larger dbh's may end before the top diameter is reached.

[3]Data based on 37 red oak sp. trees sampled near Blacksburg, Va.

TABLE 27-97.—*List by species of chapter 16 and 27 weight tables and prediction equations (data on bark are in chapter 13, roots in chapter 14, and foliage in chapter 15)*

Species and equations	Weight tables: Whole (or complete) tree	Weight tables: Stem
	Table number	
Appalachian hardwoods, mixed		
Equation 16-1 and table 16-6	16-8	16-9
Equation 27-25 through 27-33	16-9	
Ash, green		
Equation 16-4 and table 16-13	16-2, 16-10	16-2, 16-10
Ash, white[1]		
—	16-2, 16-10, 16-11	16-2, 16-10
Elm, American		
Equation 16-4 and table 16-13	16-2, 16-10, 16-11	16-2, 16-10
Elm, winged		
—	16-2, 16-10	16-2, 16-10
Hackberry and sugarberry		
Equation 16-4 and table 16-13	16-2, 16-10	16-2, 16-10
Hickory, sp.[1]		
Equation 16-1 and table 16-6	16-2	16-2
Table 16-5	16-8	16-10
Equation 16-6 (and species discussion in sect. 16-1)	16-10, 27-86	16-12, 27-88
Tables 27-86 through 27-89	27-87	27-89
Maple, red		
Equation 6-1 and table 6-6	16-2	16-2
Equation 16-6 (and species discussion in sect. 16-1)	16-8, 16-10	16-10, 16-12
Equation 27-34	16-11	27-88
Tables 27-86 through 27-89	27-86, 27-87	27-89, 27-90, 27-91
Oak, black		
Table 27-81	16-2	16-2
Tables 27-86 through 27-89	16-10, 16-14, 27-86, 27-87	16-10, 16-12, 16-14, 27-88, 27-89, 27-92
Oak, cherrybark		
—	16-2, 16-10	16-2, 16-10
Oak, chestnut		
Equation 16-1 and table 16-6	16-2	16-2
Equation 16-6 (and species discussion in sect. 16-1)	16-4, 16-8, 16-18	16-12, 16-18, 27-88
Table 27-81	27-86	27-89
Tables 27-86 through 27-89	27-87	
Oak, laurel		
—	16-2, 16-10	16-2, 16-10
Oak, northern red		
Tables 27-86 through 27-89	16-2, 16-10, 16-11, 16-20, 16-21, 27-82, 27-86, 27-87	16-2, 16-10, 16-12, 16-20, 16-21, 27-82, 27-88, 27-89

See Footnote at end of Table.

TABLE 27-97.—*List by species of chapter 16 and 27 weight tables and prediction equations (data on bark are in chapter 13, roots in chapter 14, and foliage in chapter 15)*—Continued

Species and equations	Weight tables: Whole (or complete) tree	Weight tables: Stem
	Table number	
Oak, post		
—	16-2, 16-10	16-2, 16-10
Oak, red sp.		
Equation 16-1 and table 16-6	16-11	27-93, 27-94
Equation 16-6 (and species discussions in sect. 16-1)		
Oak, scarlet		
Tables 27-86 through 27-89	16-2, 16-10, 16-22, 27-83, 27-86, 27-87	16-2, 16-10, 16-12, 16-22, 27-83, 27-88, 27-89
Oak, Shumard		
—	16-2, 16-10	16-2, 16-10
Oak, southern red		
Table 16-5	16-2, 16-10, 16-23, 27-84	16-2, 16-10, 16-23, 27-84
Oak, water		
—	16-2, 16-10	16-2, 16-10
Oak, white		
Equation 16-1 and table 16-6	16-2	16-2
Table 16-5	16-8	16-10
Equation 16-6 (and species discussion sect. 16-1)	16-10, 16-11	16-12, 16-18
Tables 27-86 through 27-89	16-18, 16-24, 27-86, 27-87	16-24, 27-88, 27-89, 27-95, 27-96
Sweetgum		
Equation 16-4 and table 16-13	16-2	16-2
Table 16-5	16-8, 16-10, 16-25, 16-26	16-10, 16-25, 16-26
Tupelo, black		
Equation 16-1 and table 16-6	16-2, 16-8, 16-10	16-2, 16-10
Yellow-poplar		
Equation 16-1 and table 16-6	16-2	16-2
Equation 16-6 (and species discussion sect. 16-1)	16-8, 16-10	16-10, 16-12
Table 16-29	16-27	16-27
Tables 27-86 through 27-89	27-85, 27-86, 27-87	27-85, 27-88, 27-89

[1]See also: Clark, Alexander III, and W. H. McNab. 1982. Total tree weight tables for mockernut hickory and white ash in North Georgia. Ga. For. Res. Pap. 33. Macon, Ga.: Georgia Forestry Commission, Research Division.

TABLE 27-98—*Yield per acre of above-ground wood and bark, ovendry basis, with 6-inch-high stump and foliage excluded, on fully stocked even-aged upland oak forests* (Wiant and Castaneda 1978)

Total age (years)	Site Index				
	40	50	60	70	80
	Pounds				
	ALL TREES				
10	14,572	15,291	19,414	21,051	22,808
20	27,777	36,860	40,111	47,787	62,262
30	45,459	58,966	69,092	82,496	89,481
40	60,633	73,417	86,380	99,125	110,063
50	71,630	85,924	107,011	121,246	140,522
60	83,905	98,829	121,244	138,570	150,953
70	89,455	108,563	129,683	145,242	158,759
80	98,283	124,304	138,181	157,877	165,330
90	110,213	132,616	148,982	166,234	171,976
100	118,649	140,902	154,938	172,748	182,421
	ALL TREES 5 INCHES IN DBH OR MORE				
10	0	0	0	0	0
20	0	3,275	6,519	15,086	33,725
30	13,319	29,980	46,928	67,853	80,425
40	36,881	56,760	76,014	93,229	106,755
50	54,455	75,082	101,200	117,980	138,784
60	72,159	92,252	117,694	136,612	149,919
70	81,153	104,062	127,240	144,115	158,100
80	92,005	121,024	136,436	157,052	164,836
90	105,260	129,955	147,701	165,585	171,575
100	114,656	138,882	153,800	172,254	182,112
	TREES 5 INCHES DBH OR MORE TO A 4-INCH TOP DOB				
10	0	0	0	0	0
20	0	2,527	4,978	11,691	26,089
30	10,395	23,382	36,584	52,898	62,589
40	29,026	44,508	59,540	72,664	82,628
50	42,908	58,985	79,047	91,381	106,086
60	56,950	72,434	91,624	104,857	113,485
70	64,026	81,438	98,464	109,874	118,165
80	72,456	94,268	105,017	118,796	122,717
90	82,755	100,988	113,300	124,627	126,261
100	89,947	107,799	117,224	129,009	133,163

TABLE 27-98A—*Per-acre green weight of above-ground wood and bark (foliage-free) in all live trees 1.0-inch dbh and larger on commercial forest land in five southeastern states by species group* (McClure et al. 1981)

Southeast region, by State and species group	Biomass			Growing stock			Rough and rotten			Saplings[3]
	Total	Bole	Top[2]	Total	Bole	Top	Total	Bole	Top	Total
	Tons									
Florida:										
Softwoods	29.5	20.8	8.7	25.2	20.5	4.7	0.4	0.3	0.1	3.8
Hardwoods.......	25.7	17.1	8.6	14.4	11.5	2.9	7.1	5.6	1.4	4.3
Total..........	55.2	37.9	17.3	39.6	32.0	7.6	7.5	5.9	1.5	8.1
Georgia:										
Softwoods	30.7	22.3	8.4	26.4	22.0	4.4	.4	.3	.1	3.9
Hardwoods.......	31.9	19.8	12.1	20.1	16.1	4.0	5.0	3.7	1.3	6.7
Total..........	62.6	42.1	20.5	46.5	38.1	8.4	5.4	4.0	1.4	10.6
North Carolina:										
Softwoods	26.1	19.7	6.4	23.0	19.4	3.6	.5	.3	.2	2.5
Hardwoods.......	51.6	33.6	18.0	35.2	28.4	6.7	7.0	5.2	1.8	9.4
Total..........	77.7	53.3	24.4	58.2	47.8	10.3	7.5	5.5	2.1	11.9
South Carolina:										
Softwoods	34.6	27.0	7.6	31.2	26.3	4.9	.9	.7	.2	2.5
Hardwoods.......	46.4	31.0	15.5	31.3	25.2	6.1	7.7	5.8	1.9	7.5
Total..........	81.1	58.0	23.1	62.5	51.5	11.0	8.6	6.5	2.1	10.0
Virginia:										
Softwoods	18.0	13.1	4.9	15.1	12.6	2.5	.6	.4	.1	2.3
Hardwoods.......	63.8	43.3	20.5	43.6	35.1	8.4	10.8	8.1	2.7	9.4
Total..........	81.8	56.4	25.5	58.7	47.7	10.9	11.4	8.5	2.8	11.7
Average/acre:										
Softwoods	27.7	20.4	7.3	24.1	20.1	4.0	.5	.4	.2	3.1
Hardwoods.......	43.0	28.2	14.8	28.2	22.7	5.5	7.3	5.4	1.7	7.5
Total Southeast .	70.7	48.6	22.1	52.3	42.8	9.5	7.8	5.8	1.9	10.6

[1]Columns do not add because of rounding

[2]Includes total sapling weight; tops are otherwise defined as portions of stems and forks below 4 inches in diameter plus all limbs over ½-inch in diameter at the base in trees larger than 5 inches dbh.

[3]Saplings are trees 1 to 5 inches in dbh.

TABLE 27-99—*Coefficients for regression[1] of weight of biomass components Y, in pounds per acre, on 50-year site index, X, for fully stocked upland oak and cove hardwood timber stands in West Virginia* (Wiant and Fountain 1980)

Tree component weight	a Intercept	b Slope	Correlation
Total tree, green	31,319	3,032	0.493**
Total tree, dry	28,192	1,582	.456**
Stem to 4-inch top, green.......................	−9,483	2,756	.514**
Stem to 4-inch top, dry.........................	−4,567	1,551	.504**
Branches, green.................................	36,170	245	.493**
Branches, dry...................................	23,928	94	.105NS

[1]$Y = a + bx$
** = Significant at the .01 level of probability
NS = Not significant at the .05 level of probability
Degrees of freedom = 98

TABLE 27-100—*Average yellow-poplar green weight and conversion factors by dbh classes* (Clark et al. 1974)[1,2]

Dbh class (inches)	Merchantable height	Lumber weight	Chippable residue weight	Bark residue weight	Sawdust weight	Saw-log stemwood weight	Chippable residue weight[3]	Lumber recovery factor
	Feet	*Pounds/board foot*				*Pounds/ cu ft*	*Pounds*	*Board feet/ cubic foot*
12	43	4.4	3.0	1.8	1.3	46.0	15.9	5.2
14	60	4.7	2.2	1.6	1.3	49.9	13.6	6.1
16	68	4.5	1.8	1.3	1.1	47.4	11.4	6.4
18	66	4.6	1.7	1.5	1.1	47.1	11.0	6.3
20	70	4.7	1.5	1.3	1.0	49.1	10.0	6.8
22	76	4.6	1.5	1.2	1.1	48.5	10.0	6.8
24	88	4.5	1.4	1.2	1.0	47.7	9.9	6.9
26	77	4.6	1.4	1.2	1.0	48.0	9.8	6.9
28	82	5.0	1.4	1.0	1.1	53.0	10.0	7.0
Study average		4.6	1.6	1.2	1.1	48.5	10.5	6.7

[1]Based on 47 trees from a mountain cove stand of mature, uneven-aged, natural yellow-poplar in western North Carolina.

[2]Wood specific gravity averaged 0.412 in the saw log portion of the stem, 0.428 in the pulpwood portion, and 0.436 in the topwood. Moisture content of the saw log portion of the main stem averaged 98 percent, pulpwood moisture content 94 percent, and topwood 112 percent. Bark specific gravity and moisture content averaged, respectively, 0.308 and 114 percent in the saw log portion, 0.347 and 102 percent in the pulpwood, and 0.343 and 139 percent in the topwood.

[3]Weight of unchipped residue produced per cubic foot of stemwood processed.

TABLE 27-101—*Weight of green wood and bark required in north central Louisiana to obtain a cubic foot of wood and bark, or a cubic foot of bark-free wood; standard deviations follow each value* (Hughes 1978)

Product and stem portion	Green weight of wood and bark: Per cubic foot of wood and bark	Per cubic foot of wood
	Pounds	
Hard hardwood sawtimber		
to a 10-inch top dob	66.73 ± 4.02	76.97 ± 4.33
topwood[1]	70.59 ± 9.13	80.46 ± 12.46
to a 4-inch top dob	67.94 ± 4.60	77.73 ± 6.16
Soft hardwood sawtimber		
to a 10-inch top dob	66.14 ± 4.64	74.95 ± 4.67
topwood[1]	71.59 ± 7.62	83.06 ± 9.87
to a 4-inch top dib	67.40 ± 4.60	76.92 ± 5.28
Hard hardwood pulptimber		
to a 4-inch top dob	65.06 ± 9.32	78.47 ± 11.86
Soft hardwood pulptimber		
to a 4-inch top dob	63.34 ± 10.07	76.14 ± 12.63

[1]Portion of tree from upper saw log merchantability to upper pulpwood merchantability (does not include limbs, tip, and foliage).

TABLE 27-102—*Number of cords per thousand board-feet of standing timber scaled by three log rules* (Worley 1958)

Dbh	International ¼-inch: Short trees[1]	International ¼-inch: Tall trees[2]	Scribner: Short trees	Scribner: Tall trees	Doyle: Short trees	Doyle: Tall trees
			FORM CLASS[3] 75			
8	2.6	2.8	3.4	4.1	7.6	10.5
10	2.4	2.6	3.1	3.7	6.1	8.4
12	2.3	2.4	2.9	3.3	5.0	6.7
14	2.2	2.3	2.7	3.0	4.1	5.2
			FORM CLASS[3] 80			
8	2.4	2.6	3.1	3.5	7.0	9.4
10	2.3	2.5	2.8	3.2	5.6	7.2
12	2.2	2.3	2.6	2.8	4.5	5.5
14	2.1	2.2	2.3	2.5	3.4	4.1

[1]Merchantable length of 8 to 16 feet.
[2]Merchantable length of 24 to 48 feet.
[3]Defined by equation 27-2.

TABLE 27-103—*Board feet, by three log rules, of 8, 12, and 16-foot-long oak sp. logs of various diameters sufficient to yield a 160-cu-ft cord*[1] *of peeled, split sticks 5 feet long* (Barrett et al. 1941)

Small-end log dib (inches)	Log length, feet		
	8	12	16
	Board feet		
	INTERNATIONAL ¼-INCH		
6	482	483	494
8	582	584	599
10	642	649	659
12	680	685	696
14	718	722	728
16	736	744	749
18	756	762	765
20	771	778	780
22	787	788	792
24	795	797	803
26	805	806	809
28	810	814	816
30	817	821	823
	SCRIBNER DECIMAL C		
6	301	372	519
8	342	433	461
10	664	423	608
12	618	596	574
14	684	663	589
16	701	681	663
18	763	721	693
20	788	770	753
22	792	761	738
24	823	769	755
26	836	810	807
28	836	833	810
30	830	809	806
	DOYLE		
6	120	112	104
8	274	250	246
10	398	381	365
12	495	477	459
14	570	552	535
16	630	613	596
18	680	663	647
20	720	704	689
22	755	739	725
24	784	769	755
26	809	795	782
28	831	818	804
30	850	837	825

[1]To obtain board feet per 160 cu ft of rough 5-ft wood multiply values in table by 0.89. To obtain board feet per 128 cu ft of peeled 4-ft wood multiply values in table by 0.80. To obtain board feet per 128 cu ft of rough 4-ft wood multiply values in table by 0.71.

TABLE 27-104—*Comparison of Doyle and Scribner volumes with International ¼-inch scale—values given in percentages of International ¼-inch log scale volume* (Lane and Schnur 1948)

Scaling diameter (inches)	Log length in feet: 8		10		12		14		16	
	Doyle	Scribner	Doyle	Scribner	Doyle	Scribner	Doyle	Scribner	Doyle	Scribner
	Percent									
8	47	88	45	84	44	81	42	79	41	77
10	62	96	60	90	59	88	57	86	55	85
12	73	98	71	96	69	93	67	90	66	89
14	79	98	78	96	77	94	75	92	74	90
16	86	99	83	97	82	95	81	93	80	92
18	90	99	88	97	87	96	86	94	84	93
20	93	99	92	98	91	97	90	95	88	94
22	96	99	95	98	94	97	93	95	92	94
24	99	99	97	98	96	97	95	96	94	95
26	100	99	99	98	99	97	98	96	97	95
28	102	99	101	98	100	97	99	96	99	96
30	104	99	103	98	102	98	101	97	100	96
32	105	99	104	99	104	98	103	97	102	96
34	106	99	105	99	105	98	104	97	103	96
36	107	99	107	99	106	98	105	97	104	97
38	108	99	107	99	107	98	106	97	105	97
40	109	99	108	99	107	98	106	97	106	97

TABLE 27-105—*Tree volume conversions among log scales for sawtimber*[1] (U.S. Department of of Agriculture, Forest Service 1941)

Dbh (inches)	Cubic feet[2] to board feet			Doyle to Int'l	Int'l to Doyle	Scribner to Int'l	Int'l to Scribner	Doyle to Scribner	Scribner to Doyle
	Doyle	Scribner	Int'l						
	Ratios								
10	2.30	4.45	5.90	2.56	0.39	1.325	0.755	1.93	0.52
11	2.70	4.85	6.05	2.24	.45	1.250	.800	1.80	.56
12	3.00	5.10	6.20	2.07	.48	1.210	.825	1.70	.59
13	3.40	5.35	6.35	1.87	.54	1.185	.845	1.57	.64
14	3.70	5.55	6.50	1.76	.57	1.170	.855	1.50	.67
15	4.00	5.70	6.60	1.65	.61	1.155	.865	1.43	.70
16	4.20	5.85	6.70	1.60	.63	1.140	.875	1.39	.72
17	4.40	6.00	6.80	1.54	.65	1.130	.885	1.36	.73
18	4.70	6.15	6.85	1.46	.69	1.115	.895	1.31	.76
19	4.90	6.25	6.90	1.41	.71	1.105	.905	1.28	.78
20	5.10	6.35	6.95	1.36	.73	1.095	.915	1.25	.80
21	5.30	6.45	7.00	1.32	.76	1.085	.920	1.22	.82
22	5.50	6.50	7.00	1.27	.79	1.080	.925	1.18	.85
23	5.70	6.60	7.05	1.24	.81	1.075	.935	1.16	.86
24	5.90	6.65	7.10	1.20	.83	1.070	.940	1.13	.89
25	6.10	6.70	7.15	1.17	.85	1.065	.940	1.10	.91

[1]Log scales are Doyle, Scribner Decimal C, and International ¼-inch.
[2]Cubic feet inside bark to merchantable top (diameter not specified).

TABLE 27-106—*Average overrun per log according to length and diameter inside bark—Doyle rule and International ¼-inch rule* (Lane 1954)[1]

Log length (feet)	Log diameter at small end inside bark, inches				
	5-9	10-14	15-19	20-24	All diameters
	Board Feet				
8	10 (1)	15 (3)	14 (1)	— (—)	13 (2)
10	13 (2)	18 (2)	18 (2)	15 (2)	15 (2)
12	17 (3)	23 (4)	20 (−1)	24 (9)	21 (3)
14	20 (1)	30 (3)	22 (−8)	−29 (−54)	25 (−2)
16	16 (−6)	42 (10)	24 (−12)	— (—)	33 (3)
All lengths	14 (2)	22 (3)	20 (−3)	5 (−12)	19 (2)

[1]Values in parentheses are based on International rule.

TABLE 27-107—*Board feet and percent overrun of second-growth yellow-poplar by log grade from two bandmills* (Campbell 1959)[1]

Mill	Log grade	Lumber tally	Scale: International ¼-inch	Scale: Scribner Decimal C	Scale: International ¼-inch	Scale: Scribner Decimal C
		Board feet			*Percent Overrun*[2]	
A	1	8,173	7,380	6,750	10.7	21.1
	2	12,079	10,436	9.570	15.7	26.2
	3	10,565	9,773	8,550	8.1	23.6
	Total	30,817	27,589	24,870	11.7	23.9
B	1	9,452	9,330	8,730	1.3	8.3
	2	14,828	14,765	13,710	.4	8.2
	3	12,574	11,695	10,640	7.0	18.2
	Total	36,854	35,790	33,080	3.0	11.4
Combined	1	17,625	16,710	15,480	5.5	13.9
	2	26,907	25,201	23,280	6.8	15.6
	3	23,139	21,468	19,190	7.8	20.6
	Total	67,671	63,379	57,950	6.8	16.8

[1]Based on a sample of nearly 500 factory grade logs from 200 trees sawed at two bandmills.

[2]Percent overrun $= \dfrac{\text{Lumber tally} - \text{net log scale}}{\text{net log scale}}$

TABLE 27-108—*Percent overrun from three scale rules for hickory*[1], *Indiana* (Herrick 1958)

Log dib (inches)	Doyle rule	Scribner Decimal C rule	International ¼-inch rule	Basis (logs)
	Percent			
11	82	49	18	1
12	67	40	14	2
13	54	33	12	5
14	44	27	10	7
15	36	22	8	4
16	30	19	6	5
17	25	15	4	2
18	20	12	3	2
19	16	9	1	0
20	12	6	0	2
21	9	3	−1	1
All sizes	31	18	6	31

[1]Original data collected by Purdue Agricultural Experiment Station. Based upon 4,390 board-feet, mill tally, of sound logs only.

TABLE 27-109—*Percent overrun and lumber recovery factor for hard maple logs (*Acer saccharum *Marsh.) sawn at 10 mills in New York* (Burry 1976)

Type of Mill[1]	No. of logs	Average size		Overrun			
		Diameter	Length	Doyle	International ¼-inch	Scribner	LRF[2]
		Inches	*Feet*	*Percent*			
B (R)	104	12.7	10.7	42	8	21	6.69
B (R)	104	13.9	11.8	38	10	20	7.06
C (R)	104	13.6	12.0	40	9	20	6.83
B (R)	103	13.9	10.9	30	3	11	6.37
C	104	11.4	10.5	31	−6	9	5.48
B	102	12.9	10.9	44	10	22	6.74
B	104	14.0	12.9	27	0	9	6.42
C	102	13.4	12.0	41	9	20	6.75
C	100	15.7	13.2	17	−2	5	6.23
C	103	12.2	10.4	48	8	21	6.43
Averages		13.4	11.5	34	5	15	6.52

[1]B—band, C—circle, (R)—mill has a resaw.

[2]Lumber recovery factor $= \frac{\text{Bd ft of lumber}}{\text{Cu ft of logs}}$, i.e., a 6.52 LRF means that for every cubic foot of logs, 6.52 board feet of lumber is produced.

TABLE 27-110—*Overrun from Scribner decimal C scale by live-sawing and grade-sawing of factory grade 3 northern red oak saw logs in West Virginia* (Huyler 1974)

Log diameter (inches)	Overrun	
	Live-sawn	Grade-sawn
	Percent	
8	16.1	14.5
9	13.9	11.4
10	11.7	8.2
11	9.5	5.1
12	7.3	2.0
13	5.1	−1.2
14	2.9	−4.3
15	.7	−7.4
16	−1.4	−10.6
All diameters	7.3	2.0

TABLE 27-111—*Overrun and No. 1 common yield from plain- and quarter-sawing southern white oak sp* (Garver and Miller 1936)[1]

Log diameter inside bark (inches)	Overrun[2]		Yield of No. 1 common and better	
	Plain	Quarter	Plain	Quarter
	Percent			
17	25.5	20.5	76.0	93.0
18	20.5	15.0	76.0	93.0
19	16.0	10.0	76.0	93.0
20	11.5	5.0	76.0	93.0
21	8.0	0.0	76.5	93.0
22	5.0	−5.0	76.5	93.0
23	2.0	−10.0	77.0	93.0
24	0.0	−14.0	77.5	93.0
25	−1.0	−18.0	78.0	93.0
26	−2.0	−21.0	79.0	93.0
27	−3.0	−22.0	80.0	93.0
28	−4.0	−23.0	81.0	93.0
29	−4.0	−23.0	82.0	93.0

[1]Data from seven mills in Arkansas, Louisiana, and Tennessee.
[2]Based on Scribner Decimal C log scale and green lumber tally.

TABLE 27-112—*Cubic feet of peeled wood per Mbf log scale of southern pine saw logs*[1]

Scaling diameter (Inches)	8-foot saw logs[2]		16-foot saw logs[3]		
	Int'l ¼	Doyle	Int'l ¼	Doyle	Scribner
	Cu ft/Mbf log scale				
6.0	246.7	925.0	210.5	1,000.0	333.3
6.5	225.3	690.3	191.3	733.3	275.0
7.0	214.6	553.3	178.6	555.6	238.1
7.5	200.7	457.3	169.7	466.7	224.0
8.0	191.5	395.0	161.5	393.8	203.2
8.5	184.4	350.5	157.8	355.0	197.2
9.0	177.9	315.2	154.9	316.0	188.1
9.5	172.3	288.7	151.7	293.3	183.3
10.0	167.6	267.2	150.8	272.2	178.2
10.5	163.9	250.2	150.0	257.1	174.2
11.0	160.3	235.5	147.5	240.8	168.6
11.5	157.4	223.4	146.6	230.4	165.4
12.0	155.0	213.1	146.4	221.9	165.1
12.5	152.5	204.4	145.3	213.9	163.8
13.0	150.5	196.5	145.2	206.2	160.6
13.5	148.4	189.6	143.2	198.9	158.4
14.0	146.6	183.6	141.2	192.0	156.1
14.5	145.0	178.2	140.4	186.4	154.1
15.0	143.7	173.3	140.1	181.8	152.8
15.5	142.1	168.9	139.0	178.0	151.6
16.0	140.9	165.0	138.5	173.6	150.6
16.5	139.8	161.4	138.3	171.2	150.0
17.0	138.8	158.2	138.1	168.0	149.5
17.5	137.7	155.2	137.9	165.9	148.8
18.0	136.8	152.4	137.9	163.3	148.1
18.5	135.9	149.8	137.8	161.4	148.0
19.0	135.1	147.6	137.7	159.1	147.3
19.5	134.3	145.3	137.4	157.5	147.1
20.0	133.6	143.3	137.2	155.5	146.3
20.5	132.9	141.4	137.0	153.7	145.6
21.0	132.3	139.6	136.4	151.6	145.0
21.5	131.7	137.4	135.9	149.7	144.0
22.0	131.0	136.4	135.0	147.5	143.1
22.5	130.5	134.9			
23.0	129.9	133.5			
23.5	129.5	132.2			
24.0	129.0	130.9			
24.5	128.6	129.5			
25.0	128.4	128.7			
25.5	128.3	127.6			
26.0	127.3	126.6			
26.5	126.9	125.7			
27.0	126.6	124.8			
27.5	126.2	123.9			
28.0	125.9	123.0			
28.5	125.6	122.3			
29.0	125.3	121.5			
29.5	125.0	120.8			
30.0	124.7	120.1			

[1]Valid only for hardwoods with taper similar to southern pine.
[2]After Williams and Hopkins (1969, p. 29).
[3]Adapted from Reynolds (1937) for loblolly pine in Arkansas.

TABLE 27-113—*Ratio of International ¼-inch board-foot volume to cubic-foot volume*[1] *for southern Appalachian yellow-poplar (top diameter 3.0 inches outside bark)* (Beck 1964)

Dbh (inches)	Total tree height (feet)															
	65	70	75	80	85	90	95	100	105	110	115	120	125	130	135	140
	Ratio															
11	3.76	3.94	4.09	4.22	4.33	4.43	4.52	4.60	4.68	4.75	4.81	4.87				
12	3.89	4.06	4.20	4.32	4.43	4.53	4.61	4.69	4.76	4.82	4.88	4.94				
13	4.02	4.18	4.31	4.43	4.53	4.62	4.70	4.77	4.84	4.90	4.96	5.01	5.05	5.10		
14	4.16	4.30	4.42	4.53	4.63	4.71	4.79	4.86	4.92	4.98	5.03	5.08	5.12	5.16		
15		4.42	4.54	4.64	4.73	4.81	4.88	4.94	5.00	5.05	5.10	5.15	5.19	5.23		
16		4.54	4.65	4.74	4.83	4.90	4.97	5.03	5.08	5.13	5.18	5.22	5.26	5.29		
17		4.66	4.76	4.85	4.93	5.00	5.06	5.11	5.16	5.21	5.25	5.29	5.32	5.36		
18				4.96	5.03	5.09	5.15	5.20	5.24	5.29	5.32	5.36	5.39	5.42	5.45	
19				5.06	5.13	5.18	5.24	5.28	5.32	5.36	5.40	5.43	5.46	5.49	5.51	5.54
20					5.23	5.28	5.33	5.37	5.41	5.44	5.47	5.50	5.53	5.55	5.57	
21							5.41	5.45	5.49	5.52	5.55	5.57	5.59	5.62	5.64	
22							5.50	5.54	5.57	5.59	5.62	5.64	5.66	5.68	5.70	
23								5.62	5.65	5.67	5.69	5.71	5.73	5.75	5.76	
24								5.70	5.73	5.75	5.77	5.78	5.80	5.81	5.82	
25								5.79	5.81	5.82	5.84	5.85	5.87	5.88	5.89	
26								5.87	5.89	5.90	5.91	5.92	5.93	5.94	5.95	
27									5.97	5.98	5.99	5.99	6.00	6.01		
28										6.05	6.06	6.06	6.07	6.07		
29											6.13	6.13	6.14	6.14		
30											6.21	6.21	6.21	6.21		

[1]Ratio of board-foot volume to cubic-foot volume, outside bark, in the saw-log portion of the stem.

TABLE 27-114—*Theoretical lineal yield of veneer rotary-cut from bolts of various sizes according to core diameter and veneer thickness*[1] (Borden Chemical Company 1966)

Veneer thickness and core diameter (inches)	Bolt diameter in inches								
	8	9	10	11	12	14	16	18	20
	Feet								
1/10-inch thick									
5	25.2	36.3	48.7	62.4	77.3	111.2	150.1	194.5	244.0
4	31.2	42.2	54.8	68.4	83.3	117.2	156.1	200.4	249.9
3	35.8	47.6	59.2	73.0	87.9	121.8	160.7	205.1	254.4
1/8-inch thick									
5	20.4	29.3	39.2	50.1	62.4	89.8	121.2	157.0	196.9
4	25.1	34.1	44.1	55.2	67.2	94.6	126.0	161.8	201.7
3	28.8	37.4	47.8	58.9	71.0	98.3	129.8	165.5	205.4
3/16-inch thick									
5	13.5	19.4	26.1	33.4	41.4	59.6	80.5	104.2	130.4
4	16.7	22.6	29.4	36.6	44.6	62.8	83.7	107.4	133.9
3	19.2	25.5	31.8	39.1	47.1	65.3	86.6	109.9	136.4

[1]Lineal footage figures on a volumetric basis, assuming each bolt to be a perfect cylinder.

$$\text{Lineal footage} = \frac{\text{Bolt volume-core volume}}{\text{Volume of 1 lineal foot of 1/10-, 1/8-, 3/16-inch veneer}}$$

TABLE 27-115—*Recommended hardwood blank standard sizes of four qualities*[1,2]

Nominal thickness, inches					
5/8	3/4	4/4	5/4	6/4	8/4
Inches					
CLEAR QUALITY, C2F or C1F, in 26-INCH-WIDE PANELS					
13	14	15	15	15	15
15	17	18	18	18	18
17	19	21	21	21	21
18	22	25	25	25	25
22	25	29	29	28	28
26	29	33	33	32	32
31	31	38	38	35	35
36	35	45	45	40	40
42	41	50	50	45	45
	47	60	60	50	50
	58	75	75	60	60
	86	100	100	70	70
				85	90
SOUND QUALITY, FOR UPHOLSTERED FRAMES, IN 20-INCH-WIDE PANELS					
		13	15	14	12
		17	18	18	16
		19	20	21	19
		22	23	24	21
		24	25	28	24
		27	28	31	28
		29	33	34	30
		33	45	40	34
		44	55		
		54	65		
		70	80		
		80	90		
		100	100		
CORE QUALITY, IN 26-INCH-WIDE PANELS[3]					
SOUND QUALITY, FOR CASE GOODS, IN 20-INCH-WIDE PANELS[4]					

[1]Based on research conducted by the Northeastern Forest Experiment Station, USDA Forest Service, Princeton, W.Va.

[2]Quality definitions are as follows:

Clear: C1F and C2F

C1F (clear-one-face): This material is clear on one face, both edges, and both ends, and otherwise complies with the clear-two-faces quality, except that the reverse face may contain defects of sound quality.

C2F (clear-two-faces): This material is clear on both faces, the edges, and the ends, except that sapwood, slight streaks, and small burls or swirls and light stain are permitted.

Sound, for frames: This material may contain any defects that will not materially impair the strength of the individual piece for the use intended.

Core: This material is sound on both faces, admitting tight sound knots, small worm holes, slight surface checks, or their equivalent.

Sound, for case goods: Same as sound, for frames.

[3]Core quality, in 16-inch-wide panels
4/4 (15,18,21,23,26,29,34,40,50,60,70, and 95 inches long)
5/4 (same as 4/4 except 85 inches is longest length)

[4]Sound quality, for case goods, in 20-inch-wide panels
4/4 (15, 18, 21, 25, 29, 34, 40, 50, 60, 70, and 95 inches long)

TABLE 27-116—*Comparison of green lumber tally and furniture cutting yield from logs and from bolts of red maple* (Huffman 1973)

		Sawn as logs			Sawn as bolts			
Log diameter class (inches)	Log grade	Log scale[1]	Lumber or cutting tally	Lumber overrun or cutting yield	Log scale[1]	Lumber or cutting tally	Lumber overrun or cutting yield	Difference in lumber overrun or cutting yield[2]
		Board feet	*Board feet*	*Percent*	*Board feet*	*Board feet*	*Percent*	*Percent*
LUMBER TALLY AND PERCENT OVERRUN								
8-12	2	175	210	20	164	250	52	+ 32
8-12	3	139	165	19	133	234	76	+ 57
8-12	Cull	27	36	33	23	100	335	+302
13-16	2	289	373	29	290	413	42	+ 13
13-16	3	230	277	20	243	278	14	− 6
Totals		860	1,061		853	1,275		
Averages				23			49	+ 26
FURNITURE CUTTING TALLY AND PERCENT YIELD (CLEAR-ONE-FACE)								
8-12	2	175	135	77	164	172	105	+ 28
8-12	3	139	96	69	133	137	103	+ 34
8-12	Cull	27	20	74	23	61	265	+191
13-16	2	289	277	96	290	296	102	+ 6
13-16	3	230	174	76	243	170	70	− 6
Totals		860	702		853	836		
Averages				82			98	+ 16

[1]International ¼-inch rule.
[2]Positive sign (+) indicated bolt sawing overrun (or cutting yield) is greater than log sawing overrun (or cutting yield).

TABLE 27-117—*Yield of No. 3A common and better lumber related to the number of clear faces on 4- to 6-foot red oak sp. bolts* (North Carolina Forest Service n.d.)[1]

Clear faces	Number of bolts	No. 1C	No. 2C	No. 3A	Total
		Board feet			
0	71	33	152	285	470
1	31	60	177	145	382
2	12	125	126	69	320
3	3	20	27	10	57
4	5	101	72	51	224
Total	122	339	554	560	1,453

[1]Including No. 3B common lumber, the 122 bolts yielded a lumber tally of 2,850 bd ft, a 13-percent overrun from log scale by the International ¼-inch rule.

TABLE 27-118—*Maximum volumes (in square feet) of clear-one-side (C1S), flat, nominal 4/4-inch dimension*[1] *obtained from red maple bolts*[2] (Landt 1974)

Bolt dib small end (inches)	Bolt length (inches) 20	24	28	32	36	40	44	48	52	56	60	64	68	72	76	80	Number of bolts
5	0.52	0.65	0.79	0.94	1.09	1.24	1.40	1.56	1.73	1.90	2.07	2.25	2.43	2.61	2.79	2.98	—
6	.84	1.06	1.29	1.52	1.77	2.02	2.28	2.54	2.81	3.09	3.37	3.65	3.94	4.24	4.54	4.84	76
7	1.27	1.60	1.94	2.30	2.66	3.04	3.43	3.83	4.24	4.65	5.07	5.51	5.94	6.39	6.84	7.30	75
8	1.81	2.28	2.77	3.27	3.80	4.34	4.89	5.46	6.04	6.64	7.24	7.85	8.48	9.11	9.76	10.41	57
9	2.47	3.12	3.78	4.48	5.20	5.94	6.70	7.47	8.27	9.08	9.90	10.75	11.60	12.47	13.35	14.24	37
10	3.28	4.12	5.01	5.93	6.88	7.86	8..86	9.89	10.94	12.02	13.11	14.22	15.35	16.50	17.67	18.85	20
11	4.22	5.31	6.46	7.64	8.87	10.13	11.42	12.75	14.10	15.48	16.89	18.33	19.79	21.27	22.77	24.29	16
12	5.32	6.70	8.14	9.63	11.17	12.76	14.40	16.07	17.78	19.52	21.29	23.10	24.94	26.81	28.70	30.62	14
13	6.58	8.29	10.07	11.92	13.83	15.79	17.81	19.88	21.99	24.15	26.35	28.59	30.86	33.17	35.51	37.89	5
14	8.02	10.09	12.26	14.51	16.84	19.24	21.70	24.21	26.79	29.42	32.09	34.82	37.59	40.40	43.25	46.15	2
15	9.64	12.13	14.73	17.44	20.23	23.11	26.07	29.09	32.19	35.34	38.56	41.83	45.16	48.54	51.97	55.44	—
Number of bolts	—	19	19	2	32	11	6	51	32	3	11	3	1	54	58	—	302

[1]Regression equation for C1S square feet = 0.000163 x Diameter$^{2.66086}$ x Length$^{1.262316}$ (based on all bolts). Standard error of estimate = 1.957 square feet. R^2 = 0.94.

[2]Heavy black lines indicate distribution of data.

TABLE 27-119—*Maximum volumes (in square feet) of clear-one-side (C1S), flat, nominal 4/4-inch dimension*[1] *obtained from red maple trees and dimension recovery factors (DRF)*[2,3] (Landt 1974)

Dbh (inches)	Item	Tree height to a 6-inch dib top (feet) 10	15	20	25	30	35	40	45	50	55	60	Number of trees
6	C1S	4.30	6.54	8.80	11.08	13.38	15.68	18.00	20.33	22.67	25.02	27.37	—
	DRF	*2.70*	*2.88*	*3.02*	*3.13*	*3.23*	*3.31*	*3.38*	*3.45*	*3.51*	*3.57*	*3.62*	
7	C1S	5.94	9.03	12.15	15.30	18.48	21.67	24.87	28.09	31.32	34.56	37.80	1
	DRF	*2.82*	*3.01*	*3.15*	*3.27*	*3.37*	*3.46*	*3.53*	*3.60*	*3.66*	*3.72*	*3.78*	
8	C1S	7.86	11.95	16.08	20.25	24.44	28.66	32.90	37.16	41.43	45.72	50.01	3
	DRF	*2.92*	*3.12*	*3.27*	*3.39*	*3.50*	*3.59*	*3.67*	*3.74*	*3.80*	*3.86*	*3.92*	
9	C1S	10.06	15.29	20.58	25.92	31.29	36.69	42.11	47.56	53.03	58.52	64.02	12
	DRF	*3.02*	*3.23*	*3.38*	*3.51*	*3.61*	*3.71*	*3.79*	*3.86*	*3.93*	*3.99*	*4.05*	
10	C1S	12.54	19.07	25.67	32.32	39.02	45.75	52.52	59.31	66.13	72.98	79.84	7
	DRF	*3.11*	*3.32*	*3.48*	*3.61*	*3.72*	*3.82*	*3.90*	*3.98*	*4.05*	*4.11*	*4.17*	
11	C1S	15.32	23.29	31.34	39.47	47.65	55.87	64.13	72.43	80.76	89.11	97.49	3
	DRF	*3.19*	*3.41*	*3.58*	*3.71*	*3.82*	*3.92*	*4.01*	*4.08*	*4.15*	*4.22*	*4.28*	
12	C1S	18.38	27.94	37.61	47.36	57.18	67.05	76.96	86.92	96.91	106.94	116.99	7
	DRF	*3.27*	*3.50*	*3.66*	*3.80*	*3.92*	*4.02*	*4.10*	*4.18*	*4.26*	*4.32*	*4.39*	
13	C1S	21.74	33.05	44.48	56.01	67.62	79.29	91.02	102.79	114.61	126.47	138.36	6
	DRF	*3.34*	*3.57*	*3.75*	*3.89*	*4.00*	*4.11*	*4.20*	*4.28*	*4.35*	*4.42*	*4.48*	
14	C1S	25.39	38.60	51.96	65.43	78.98	92.62	106.31	120.07	133.87	147.72	161.61	2
	DRF	*3.41*	*3.65*	*3.82*	*3.97*	*4.09*	*4.19*	*4.28*	*4.37*	*4.44*	*4.51*	*4.58*	
15	C1S	29.34	44.61	60.04	75.61	91.27	107.03	122.85	138.75	154.70	170.70	186.76	1
	DRF	*3.48*	*3.72*	*3.90*	*4.04*	*4.17*	*4.27*	*4.37*	*4.45*	*4.53*	*4.60*	*4.67*	
Number of trees		*1*	*1*	*2*	*6*	*8*	*7*	*12*	*1*	*4*	—	—	*42*

[1]Regression equation for C1S flat dimension is $0.009326 \times Dbh^{2.09589} \times Height^{1.03289}$. Standard error of estimate is 9.222 square feet. $R^2 = 0.94$.

[2]Dimension recovery factor equals volume of C1S in square feet divided by total cubic feet in tree to a 6-inch d.i.b. top. Prediction equation for cubic feet equals $0.008293 \times Dbh^{1.81788} \times Height^{0.86923}$. Standard error of estimate is 1.627 cubic feet. $R^2 = 0.96$.

[3]Heavy black lines indicate distribution of data.

TABLE 27-120—*Best width in inches for different cutting lengths by grade* (Hallock 1980)

Best width	Cutting length	Best width	Cutting length
FAS		SELECTS	
1.5	96-72	1.0	96-94
2.0	72-60	1.5	94-36
2.5	60-50	5.0	36-10
3.0	50-38		
3.5	38-22		
4.0	22-10		
NO. 1 COMMON		NO. 2 COMMON	
1.0	80-68	1.0	40-38
1.5	68-28	1.5	38-22
2.0	28-26	2.0	22-20
2.5	26-24	2.5	20-18
3.0	24-22	3.0	18-12
3.5	22-18	3.5	12-10
4.5	18-10		
NO. 3A COMMON			
1.5	30-18		
2.0	18-16		
3.0	16-12		
3.5	12-10		

TABLE 27-121—*Observed and calculated values of lumber grade No. 1 Common, rip width 1.5 inches* (Hallock 1980)

1	2	3	4	5	6	7	8	9	10	11
Cutting data				Nomogram data				Surface measure		
Size	No.	SM	Ripped pieces	Yield	Width adjustment value	Adjusted yield	Net yield	Lumber required	Subsequent cutting	Balance
In.		*Fsm*		*Pct.*	*Pct.*	*Pct.*	*Pct.*	*Fsm*	*Fsm*	*Fsm*
FIRST CALCULATION										
60 x 3.5	100	145.8	234	35.7	+0.3	36.0	36.0	405	—	0.0
48 x 4.0	600	800.0	1,600	45.0	+1.3	46.3	10.3	—	41.7	−758.3
26 x 2.0	300	108.3	400	57.4	+4.5	61.9	15.6	—	63.2	−45.1
12 x 6.0	100	50.0	400	61.8	+7.5	69.3	7.4	—	30.0	−20.0
SECOND CALCULATION										
48 x 4.0	—	758.3	1,517	41.6	+1.3	42.9	42.9	1,768	—	0.0
26 x 2.0	—	45.1	167	56.3	+4.5	60.8	17.9	X	316.5	+271.4
12 x 6.0	—	20.0	160	61.5	+7.5	69.0	8.2	X	145.0	+125.0

TABLE 27-122—*Yield of hickory handle bolts (clear of defect), and additional saw logs, by tree dbh, Missouri*[1] (Herrick 1958)

Tree dbh (inches)	Basis: number of trees	Gross volume[2] and number of handles[3] by number of 40-inch bolts[4]: 1 bolt, Volume or handles			2 bolts, Volume or handles			3 bolts, Volume or handles			4 bolts, Volume or handles			5 bolts, Volume or handles			Saw log volume above bolts in tree[4]: 1	2	3	4	5	Cull[5]
		Board-feet		*Number*	*Board-feet*		*Number*	*Board-feet*		*Number*	*Board-feet*		*Number*	*Board-feet*		*Number*	*Board-feet*					*Percent*
12	19	10	or	9	20	or	18	26	or	25	34	or	33	42	or	41	19	12	9	0	0	8
14	11	16	or	10	26	or	20	44	or	30	57	or	39	70	or	49	37	31	19	11	4	11
16	10	23	or	12	39	or	24	54	or	34	70	or	45	86	or	55	59	51	44	37	29	10
18	5	31	or	13	54	or	27	77	or	39	100	or	52	104	or	63	87	74	63	53	62	9
20	5	41	or	16	71	or	31	104	or	45	135	or	59	144	or	72	113	98	82	68	82	9
22	5	46	or	17	91	or	33	135	or	49	154	or	64	166	or	78	145	119	98	109	139	9
24	3	57	or	18	113	or	37	170	or	54	197	or	71	216	or	87	135	157	135	151	184	8
26	1	69	or	20	138	or	40	209	or	60	245	or	78	272	or	95	237	209	174	207	256	8

[1]Adapted from table prepared by the U.S. Forest Service and modified to apply to Reynolds County, Mo., trees.

[2]Saw log and bolt volumes determined by the Scribner scale.

[3]Yield of 10.5 handles per board-foot scale. All bolt dib measurements in inches at the small end.

[4]Bolts from trees of 18 inches dbh and under on a one-foot stump; bolts from trees of 20 inches dbh and over on a two-foot stump. Bolts taken from trees with minimum top dib of 7 inches. Saw logs above bolts cut to a minimum top dib of 10 inches with a minimum length of 8 feet.

[5]Cull based on log-scale measurements at logging operations.

TABLE 27-122A.—*Pallet cant and lumber yields from 4- and 6-foot-long, 6- to 10-inch-diameter, woods-run bolts from hardwood pole-timber thinnings in West Virignia, by bolt diameter and sweep class* (Craft and Emanuel 1981)[1/2]

Bolt diameter class	Sweep class	Bolt volume	Product yield	Product yield	Cant yield		Side lumber yield		Cants only
					4 by 4	4 by 6	1 by 4	1 by 6	
---Inches---		---Cu ft---		---Percent of bolt volume---					
4-FOOT-LONG BOLTS									
6	0-0.5	283.9	160.3	53	53	0	0	0	53
	0.6-1.0	124.0	68.6	48	48	0	0	0	48
	1.1-1.5	29.6	16.0	43	42	0	1	0	42
7	0-0.5	200.1	103.1	52	31	16	5	0	47
	0.6-1.0	101.6	47.8	47	40	2	5	0	42
	1.1-1.5	32.1	14.7	45	39	2	4	0	41
8	0-0.5	127.4	72.7	57	3	44	7	3	47
	0.6-1.0	88.2	47.6	54	7	37	7	3	43
	1.1-1.5	12.6	5.8	46	13	26	6	1	40
9	0-0.5	88.5	50.5	57	4	36	7	10	40
	0.6-1.0	44.2	24.9	56	0	39	7	10	39
	1.1-1.5	12.4	6.6	53	0	38	7	8	38
10	0-0.5	58.9	36.2	61	2	41	5	13	43
	0.6-1.0	28.3	16.9	60	5	38	8	9	42
	1.1-1.5	10.9	5.1	47	4	25	7	11	28

See Footnote at end of Table.

TABLE 27-122A.—*Pallet cant and lumber yields from 4- and 6-foot-long, 6- to 10-inch-diameter, woods-run bolts from hardwood pole-timber thinnings in West Virignia, by bolt diameter and sweep class* (Craft and Emanuel 1981)[1/2]—Continued

Bolt diameter class	Sweep class	Bolt volume	Product yield	Product yield	Cant yield		Side lumber yield		Cants only
					4 by 4	4 by 6	1 by 4	1 by 6	
Inches		*Cu ft*		*Percent of bolt volume*					
				6-FOOT-LONG BOLTS					
6	0-0.5	188.8	110.4	54	50	1	3	0	51
	0.6-1.0	107.4	59.2	46	45	0	1	0	45
	1.1-1.5	22.4	11.7	39	39	0	0	0	39
7	0-0.5	211.2	116.0	55	36	9	10	0	45
	0.6-1.0	163.2	86.2	50	34	7	9	0	41
	1.1-1.5	28.8	11.2	39	31	3	5	0	34
8	0-0.5	53.2	31.2	60	1	46	11	2	47
	0.6-1.0	46.0	26.2	57	8	37	10	2	45
	1.1-1.5	14.6	7.8	53	14	27	9	3	41
9	0-0.5	45.1	27.5	61	6	35	13	10	35
	0.6-1.0	21.2	11.7	55	3	33	8	11	36
	1.1-1.5	8.0	4.1	51	0	37	8	6	37
10	0-0.5	36.0	22.2	62	2	43	10	7	45
	0.6-1.0	19.6	11.7	60	0	40	9	11	40
	1.1-1.5	3.3	1.2	36	21	0	15	0	21

[1]Mixed species, including oaks, yellow-poplar, cherry, beech, birch, and maple.

[2]In this study only 4- by 4 and 4- by 6-inch cants plus side lumber was produced. Only 4-inch and wider lumber was tallied as usable; all 5-inch lumber was tallied as 4-inch widths, and all side lumber over 6 inches as 6-inch widths.

TABLE 27-123.—*Merchantable volume of white oak stave bolt trees* (Smith 1952)

Dbh (inches)	Number of 39-inch cuts 1	2	3	4	5	6	7	8
	Bolt feet[1]							
12	2.8							
14	3.3	6.4						
16	3.7	7.4	10.9					
18	4.2	8.3	12.3	16.2				
20	4.7	9.2	13.7	18.0	22.2	26.3		
22	5.2	10.2	15.1	19.9	24.6	29.1	33.6	
24	5.6	11.1	16.5	21.8	26.9	31.9	36.9	41.6
26	6.1	12.0	17.9	23.6	29.2	34.8	40.1	45.4
28	6.6	13.0	19.3	25.3	31.3	37.2	43.0	48.7
30	7.0	13.9	20.7	27.4	33.9	40.4	46.7	52.9
32	7.5	14.9	22.1	29.2	36.3	43.2	50.0	56.6
34	8.0	15.8	23.5	31.1	38.6	46.0	53.2	60.4
36	8.4	16.7	24.9	33.0	41.0	48.8	56.5	64.1

[1]Assumes 1-foot stump, ½-inch taper per cut.

TABLE 27-124.—*Board foot/bolt foot ratios for white oak logs when cut for stave and head stock* (Goebel 1956)

Scaling diameter of log (inches)	Length of log, feet 6	8	10	12
	Number of board feet per bolt foot[1]			
	STAVE STOCK[2]			
14	4.93	6.58	8.22	9.87
16	5.69	7.59	9.49	11.38
18	6.41	8.55	10.68	12.82
20	7.13	9.50	11.88	14.26
22	7.84	10.46	13.07	15.69
24	8.56	11.42	14.27	17.13
26	9.28	12.38	15.47	18.57
	HEAD STOCK[3]			
14	2.98	3.98	4.97	5.96
16	3.43	4.58	5.72	6.87
18	3.89	5.19	6.49	7.79
20	4.36	5.81	7.27	8.72
22	4.83	6.44	8.06	9.66
24	5.31	7.08	8.86	10.62
26	5.80	7.73	9.67	11.60

[1]Board foot volumes by the Doyle rule.
[2]Values computed from the regression equation:

$$\text{Volume ratios} = (0.059D + 0.00002D^2) \times \text{length.}$$

[3]Values computed from the regression equation:

$$\text{Volume ratios} = (0.03354D + 0.00014D^2) \times \text{length.}$$

TABLE 27-125.—*Comparison of sawing logs of three classes for lumber and railroad stock and for standard lumber only* (Putnam 1959)[1/2]

Sawed for—	Doyle scale	Green lumber scale	No. 1 Common and better	No. 3 B Common	Dry lumber value per Mbf	Gross tie and timber yield	Net total product: Volume	Net total product: Value per Mbf	Equivalent value [3]	Value per Mbf log scale [4]
	Board feet	*Board feet*	*Percent*	*Percent*	*Dollars*	*Board feet*	*Board feet*	*Dollars*	*Dollars*	*Dollars*
NO. 3 OAK, 2 LOGS										
Lumber only	215	278	19.8	10.0	66.92	None	256	66.92	76.84	79.67
Lumber and ties	Same	172	32.0	None	79.75	141	285	69.02		91.49
NO. 3 SWEETGUM, 2 LOGS										
Lumber only	144	171	19.3	None	52.10	None	157	52.10	62.80	56.80
Lumber and ties	Same	108	30.6	None	57.44	84	175	56.34		68.47
SOUND OAK, 2 LOGS										
Lumber only	162	252	5.5	12.0	58.19	None	232	58.19	66.47	83.33
Lumber and ties	Same	118	12.0	6.0	65.05	168	260	59.33		95.19

[1]Based on actual sawing and tally of the product of five small logs selected as typical of the classes and grades shown.

[2]Lumber grade prices are essentially those of the current (1959) Hardwood Market Report on standard, well-manufactured lumber, rough, airdry, fob mills at shipping points in the deep South. Adjustments were made for degrade and shrinkage in curing. For ties and structural material, an average price of $55/M ft was assumed. Gross outturn was reduced 10 percent for cutbacks and rejects.

[3]This is the price per M ft that would have to be realized on straight lumber production to realize as much from the logs as from combined lumber and tie production. Then there is the additional advantage of materially cheaper costs for tie production.

[4]The greater product value for Sound logs, due to greatest overrun, may be deceiving. If each log's actual cost were assigned to it, this extra value might be more than offset by higher production costs for the smaller logs.

TABLE 27-126.—*Potential yields from the sample area for various harvesting options* (Martin 1977)[1]

Harvesting option	Gross volume yield of roundwood		Fresh weight yield of all products[2]			
	Sawtimber	Pulpwood	Sawtimber	Pulpwood	Chips	Total
	Bd ft/acre[3]	*Cords/acre*	*Tons/acre*			
"Near-complete" removal	12,451	1.5	54.9	3.7	63.2	121.8
Sawlogs only from trees ⩾ 10.5″ dbh	13,522	—	59.6	—	—	59.6
Sawlogs from trees ⩾ 10.5″ dbh and pulpwood from trees 4.5″-10.4″ dbh	13,522	4.9	59.6	11.6	—	71.2
Sawlogs plus pulpwood (topwood) from trees ⩾ 10.5″ dbh and pulpwood from trees 4.5″-10.4″ dbh	13,522	13.1	59.6	30.5	—	90.1
Pulpwood only from trees ⩾ 4.5″ dbh	—	41.3	—	95.8	—	95.8

[1]Stand was predominantly yellow-poplar and red maple and was in southwest Virginia.
[2]Average moisture content = 75 percent (dry basis).
[3]International 1/4-inch scale.

TABLE 27-127.—*Proportion of total-tree (above ground portions) wood and bark in crown material of yellow-poplar and northern red oak* (Clark 1978)

Dbh class (inches)	Proportion of tree wood in crown		Proportion of tree bark in crown	
	Yellow-poplar	Northern red oak	Yellow-poplar	Northern red oak
	Percent			
6	35	30	39	38
8	23	23	27	35
10	16	21	20	31
12	11	20	16	32
14	8	23	13	35
16	8	24	13	37
18	8	25	13	38
20	9	25	14	39
22	10	26	14	40
24	11	26	15	40
All classes	14	24	18	33

TABLE 27-128.—*Percent of yield per acre of dry weight of wood in material 4 inches dob or less, upland oaks* (Wiant and Castaneda 1978)

Total age (years)	Site Index[1]				
	40	50	60	70	80
	Percent				
10	100	100	100	100	100
20	100	93	87	76	58
30	77	60	47	35	30
40	52	39	31	26	25
50	40	31	26	25	25
60	32	27	25	25	26
70	28	25	25	26	27
80	27	25	25	26	27
90	25	25	25	27	29
100	25	25	26	28	29

[1]Tree height at 50 years, feet.

TABLE 27-129.—*Yield per acre of branches (ovendry-weight basis) of trees 5 inches in dbh or larger, upland oaks*[1] (Wiant and Castaneda 1978)

Total age (years)	Site Index[2]				
	40	50	60	70	80
	Pounds				
10	0	0	0	0	0
20	0	1,359	2,644	5,822	11,744
30	4,903	10,031	15,240	20,459	22,927
40	11,734	16,899	21,119	24,243	26,383
50	15,844	20,460	25,510	28,186	32,245
60	19,424	23,307	27,689	31,412	34,057
70	20,681	24,739	29,064	32,499	35,490
80	22,459	27,705	30,678	34,933	36,627
90	24,660	29,276	32,655	36,553	38,001
100	26,169	30,720	33,864	37,771	39,954

[1]Wood and bark.
[2]Tree height at 50 years, feet.

TABLE 27-130.—*Regression statistics for equations[1] developed to predict weights of tops of Appalachian hardwoods[2]* (Wartluft 1978)

w (pounds) for class and portion of tree	b_0	b_1	S.E.	r^2
Soft hardwoods				
Total treetop green weight	5.122	0.1090	0.400	0.51
Total treetop oven-dry weight	4.530	.1092	.379	.53
>3 inch treetop green weight	4.320	.1300	.458	.53
>3 inch treetop oven-dry weight	3.746	.1301	.432	.56
Hard hardwoods				
Total treetop green weight	5.506	.1129	.345	.70
Total treetop oven-dry weight	4.951	.1174	.348	.71
>3 inch treetop green weight	4.700	.1326	.402	.70
>3 inch treetop oven-dry weight	4.166	.1358	.403	.71
Mixed hardwoods				
Total treetop green weight	5.392	.1132	.404	.60
Total treetop oven-dry weight	4.818	.1173	.428	.59
>3 inch treetop green weight	4.590	.1331	.450	.63
>3 inch treetop oven-dry weight	4.038	.1360	.463	.62

[1]All equations are of the form: $^{l}n\ w = b_0 + b_1 dbh$, where dbh is diameter at breast height in inches and ^{l}n is the natural logarithm function.

[2]Data collected in three oak-hickory stands in southern West Virginia and southwestern Virginia.

TABLE 27-131.—*Green weight of branches, bark included, per tree of six diameters and eight species sampled in West Virginia* (Wiant et al. 1977)[1]

Species	Tree dbh, inches: 6	8	10	12	14	16
	Pounds					
Hickory, sp.	87	153	281	472	726	1,043
Maple, red	120	186	267	365	478	608
Oak, black	97	181	294	437	612	818
Oak, chestnut	91	148	249	396	588	825
Oak, northern red	133	212	328	481	670	896
Oak, scarlet	107	173	289	456	673	940
Oak, white	77	122	208	335	503	712
Yellow-poplar	52	46	87	176	311	493

[1]Branches include topwood and limbs smaller than 4 inches in diameter outside bark. Data are based on 19 to 22 trees of each species.

[2]See table 13-11 for dry weight of branchbark and stembark of these trees; table 16-12 gives dry weight of their branchwood and stemwood.

TABLE 27-132.—*Ovendry weight of branches, bark included, per tree of six diameters and eight species sampled in West Virginia* (Wiant et al. 1977)[1]

Species	Tree dbh, inches					
	6	8	10	12	14	16
	Pounds					
Hickory, sp.	54	95	178	304	473	685
Maple, red	64	101	145	197	256	323
Oak, black	58	99	166	262	385	535
Oak, chestnut	51	85	145	232	345	486
Oak, northern red	78	126	196	287	401	537
Oak, scarlet	64	101	172	276	413	584
Oak, white	45	64	110	184	285	413
Yellow-poplar	26	25	45	85	144	224

[1]Branches include topwood and limbs smaller than 4 inches in diameter outside bark. Data are based on 19 to 22 trees of each species.

[2]See table 13-11 for dry weight of branchbark and stembark of these trees; table 16-12 gives dry weight of their branchwood and stemwood.

TABLE 27-133.—*Predicted ovendry weight of wood and bark in branches of yellow-poplar trees* (Clark and Schroeder 1977)[1/2]

Dbh (inches)	Total tree height (feet)[3]										
	40	50	60	70	80	90	100	110	120	130	140
	Pounds										
6	12	14	17	19	21						
7	15	19	22	25	28	31					
8	19	24	28	32	36	40	43				
9		29	34	39	44	49	53	58			
10			41	47	53	59	64	70	76		
11			49	56	63	69	76	83	89		
12			57	65	73	81	89	97	104	112	
13			65	75	84	93	102	111	120	129	
14				85	96	106	116	127	137	147	157
15				96	108	120	132	143	155	166	177
16				108	121	134	147	160	173	186	198
17				120	135	150	164	178	193	207	221
18				132	149	165	181	197	213	229	244
19					164	182	200	217	234	252	269
20					179	199	219	238	257	275	294
21					196	217	238	259	280	300	320
22					212	236	258	281	304	326	348
23						255	280	304	328	352	376
24						275	301	328	354	380	405
25						295	324	352	380	408	436
26							347	377	408	437	467
27							371	403	436	467	499
28							395	430	464	498	532

[1]Blocked-in area indicates range of data.

[2]$\mathrm{Log}_{10}\ Y = -1.71827 + 0.88172\ \mathrm{Log}_{10}\ (D^2Th)$.

[3]Includes 1-foot stump allowance.

TABLE 27-134.—*Predicted ovendry weight of wood, excluding bark, in branches of yellow-poplar trees* (Clark and Schroeder 1977)[1/2]

Dbh (inches)	Total tree height (feet)[3]										
	40	50	60	70	80	90	100	110	120	130	140
	Pounds										
6	9	11	13	15	17						
7	12	15	17	20	22	25					
8	15	19	22	25	28	31	34				
9		23	27	31	35	38	42	46			
10			32	37	41	46	50	55	59		
11			38	44	49	54	59	64	69		
12			44	51	57	63	69	75	81	87	
13			51	58	65	72	79	86	93	99	
14				66	74	82	90	98	105	113	121
15				75	84	93	102	110	119	127	136
16				83	94	104	114	123	133	142	152
17				93	104	115	126	137	148	158	169
18				102	115	127	139	151	163	175	186
19					126	140	153	166	179	192	205
20					138	153	167	181	196	210	224
21					150	166	182	197	213	228	243
22					162	180	197	214	231	247	264
23						194	213	231	249	267	285
24						209	229	249	268	288	307
25						225	246	267	288	309	329
26							263	286	308	330	352
27							281	305	329	353	376
28							299	325	351	376	401

[1]Blocked-in area indicates range of data.
[2]$\text{Log}_{10} Y = -1.76294 + 0.86612 \text{ Log}_{10} (D^2Th)$.
[3]Includes 1-foot stump allowance.

TABLE 27-135.—*Weights, green and dry, of black oak stump-root systems* (Tennessee Valley Authority 1972)[1]

Dbh (inches)	Green basis			Ovendry basis		
	Wood	Bark	Wood and bark	Wood	Bark	Wood and bark
	Pounds					
12	619	155	775	373	93	466
14	857	214	1,072	517	129	646
16	1,135	284	1,420	686	171	858
18	1,455	364	1,819	881	220	1,102
20	1,816	454	2,271	1,102	275	1,378
22	2,220	555	2,775	1,349	337	1,687
24	2,667	666	3,333	1,623	405	2,029
26	3,156	789	3,945	1,923	480	2,404
28	3,689	922	4,611	2,251	562	2,814
30	4,266	1,066	5,332	2,606	651	3,257
32	4,887	1,221	6,108	2,988	746	3,735
34	5,553	1,387	6,939	3,399	848	4,247
36	6,263	1,564	7,826	3,837	958	4,795

[1]See table 27-81 for the equations from which these weights were derived. The values are not based on experimental data from excavated stump-root systems, but from assumptions derived from the literature on tree biomass proportions.

TABLE 27-136.—*Mean stump heights and stump volumes observed at a total of 200 logging operations in Alabama and Louisiana.* (Data from Beltz 1976)

Product	Height		Volume	
	Alabama	Louisiana	Alabama	Louisiana
	Feet		*Cubic feet*	
Softwood saw logs	0.59	0.85	0.97	1.39
Softwood veneer	.55	.83	.85	1.46
Softwood pulpwood	.37	.50	.22	.39
Hardwood saw logs	.96	1.15	2.33	2.51
Hardwood pulpwood	.68	.91	.96	1.17

TABLE 27-137.—*Volume loss, cubic feet and board feet, caused by cutting stumps above height specified in a logging contract* (Patterson 1977)[1]

Stump dib (inches)	Excessive stump height, inches[2]				
	2	4	6	8	10
	CUBIC FEET				
4	0.014	0.029	0.043	0.058	0.072
6	.033	.065	.098	.131	.163
8	.058	.116	.174	.233	.291
10	.091	.182	.273	.363	.454
12	.131	.262	.393	.523	.654
14	.178	.356	.534	.713	.891
16	.233	.465	.698	.931	1.163
	BOARD FEET INTERNATIONAL 1/4-INCH SCALE				
6	.14	.28	.41	.55	.69
8	.32	.63	.95	1.26	1.58
10	.56	1.12	1.68	2.24	2.81
12	.87	1.74	2.62	3.49	4.36
14	1.25	2.50	3.75	5.00	6.25
16	1.69	3.39	5.08	6.77	8.47

[1]These volumes were computed by considering the excess stump height as cylindrical with no taper; volume losses in most pine-site hardwoods, which have considerable butt swell near stump height, would be greater than the tabulated values.

[2]Excessive stump height = total stump height minus target height specified in the logging contract.

TABLE 27-138—*Equations coefficients for estimating tree dbh from stump diameter and stump height for 18 hardwoods in the Southeast* (McClure 1968)[1,2]

Species	Equation coefficients			Total sample		Coefficient of determination (r^2)
	b_1	b_2	b_3	Trees	Stump measurements	
				---------*Number*---------		
Ash sp	0.22695885	−0.21811418	0.00070449	185	760	90.05
Elm sp	0.28530990	−0.18180841	0.00031110	165	637	90.52
Hackberry	0.24284538	−0.13803191	0.00062145	27	101	90.61
Hickory sp	0.34931036	−0.14637565	0.00019429	594	2,544	92.81
Maple, red	0.22824892	−0.23961963	0.00055440	704	2,369	89.86
Oak, black	0.33322093	−0.17790514	0.00058950	302	1,322	93.72
Oak, cherrybark	0.48419049	0.08821150	0.00062965	47	162	95.29
Oak, chestnut	0.26951995	−0.21508193	0.00003391	660	2,811	90.94
Oak, laurel	0.46336496	−0.02465862	0.00041241	37	120	95.65
Oak, northern red	0.35981095	−0.13575169	0.00033791	368	1,554	92.44
Oak, post	0.49462800	−0.10925176	−0.00023411	192	862	95.31
Oak, scarlet	0.32904682	−0.22413832	0.00057593	438	1,891	93.47
Oak, southern red	0.52472287	−0.06674082	−0.00027248	234	992	95.89
Oak, water	0.40473979	−0.14296394	−0.00000277	111	445	95.41
Oak, white	0.52078283	−0.06551398	−0.00001348	1,027	4,112	94.87
Sweetgum	0.24365854	−0.16720758	0.00083024	858	3,337	94.57
Tupelo, black (upland)	0.33929033	−0.07138280	0.00023595	157	676	92.05
Yellow-poplar	0.18226822	−0.25121994	0.00044866	806	3,314	91.43

[1]The equation is $dbh = D\{ b_0 + b_1 [\text{Log}(H + 1.0) - (\text{Log } 5.5)] + b_2 [\text{Log}(H + 1.0) - (\text{Log } 5.5)]^2 + b_3 [D(H - 4.5)]\}$

where: dbh = diameter at 4.5 feet above the ground, inches
D = stump diameter at point of measurement, inches
H = stump height to point of measurement, feet
$b_0 = 1.000$

[2]Based on measurement of over 14,000 standing trees in the Carolinas and Virginia.

TABLE 27-139—*Tree diameter outside bark at 4.5 feet above ground in relation to stump diameter at various heights for southern hardwoods* (McCormack 1953)[1]

Stump diameter outside bark (inches)	Stump height (inches)			
	6	12	18	30
	Dbh (inches)			
6	4	5	5	5
7	5	5	6	6
8	5	6	7	7
9	6	7	7	8
10	7	8	8	9
11	7	8	9	10
12	8	9	10	11
13	9	10	11	12
14	9	11	11	13
15	10	11	12	14
16	11	12	13	14
17	11	13	14	15
18	12	14	15	16
19	13	14	15	17
20	13	15	16	18
21	14	16	17	19
22	15	17	18	20
23	15	17	19	21
24	16	18	20	22
25	17	19	20	23
26	17	20	21	23
27	18	20	22	24
28	19	21	23	25
29	19	22	24	26
30	20	23	24	27
Basis: number of trees	557	620	259	421

[1]Data were obtained on Forest Survey sample plots in central and south Georgia and in eastern North Carolina as part of a study of tree form. Trees having abnormal butt swell, such as tupelo gum, are not included in the table.

TABLE 27-140—*Diameter at breast height estimated from stump diameter of southern Appalachian species* (Vimmerstedt 1957)[1,2]

Stump diameter (inches)	When stump diameter is measured inside bark			When stump diameter is measured outside bark			Curve 7: When stump diameter is measured inside bark for mixed oaks[4] and outside bark for red maple and shrubs
	Curve 1: Yellow-poplar red maple, chestnut oak, miscellaneous species & shrubs[3]	Curve 2: Black locust and Yellow pine	Curve 3: White oak	Curve 4: Yellow pine, chestnut oak, white oak, and miscellaneous species[3]	Curve 5: Yellow-poplar and black locust	Curve 6: Mixed oaks[4]	
	Dbh, inches						
1	0.9	1.1	0.2	0.2	0.8	0	0.5
2	1.9	2.0	1.1	1.0	1.6	0.7	1.4
3	2.8	3.0	2.1	1.9	2.5	1.6	2.2
4	3.7	4.0	3.0	2.8	3.3	2.4	3.1
5	4.6	5.0	3.9	3.7	4.2	3.3	4.0
6	5.5	5.9	4.8	4.5	5.1	4.1	4.9
7	6.5	6.9	5.8	5.4	5.9	5.0	5.8
8	7.4	7.9	6.7	6.3	6.8	5.8	6.7
9	8.3	8.8	7.6	7.1	7.7	6.7	7.6
10	9.2	9.8	8.6	8.0	8.5	7.5	8.5
11	10.2	10.8	9.5	8.9	9.4	8.4	9.4
12	11.1	11.7	10.4	9.7	10.2	9.2	10.3
13	12.0	12.7	11.3	10.6	11.1	10.1	11.2
14	12.9	13.7	12.3	11.5	12.0	10.9	12.0
15	13.8	14.7	13.2	12.3	12.8	11.8	12.9
16	14.8	15.6	14.1	13.2	13.7	12.6	13.8
17	15.7	16.6	15.0	14.1	14.6	13.5	14.7
18	16.6	17.6	16.0	14.9	15.4	14.3	15.6
19	17.5	18.5	16.9	15.8	16.3	15.2	16.5
20	18.4	19.5	17.8	16.7	17.1	16.0	17.4

See Footnote at end of Table.

TABLE 27-140—*Diameter at breast height estimated from stump diameter of southern Appalachian species* (Vimmerstedt 1957)[1,2]—Continued

Stump diameter (inches)	When stump diameter is measured inside bark			When stump diameter is measured outside bark			Curve 7: When stump diameter is measured inside bark for mixed oaks[4] and outside bark for red maple and shrubs
	Curve 1: Yellow-poplar red maple, chestnut oak, miscellaneous species & shrubs[3]	Curve 2: Black locust and Yellow pine	Curve 3: White oak	Curve 4: Yellow pine, chestnut oak, white oak, and miscellaneous species[3]	Curve 5: Yellow-poplar and black locust	Curve 6: Mixed oaks[4]	
	Dbh, inches						
21	19.4	20.5	18.8	17.5	18.0	16.9	18.3
22	20.3	21.4	19.7	18.4	18.9	17.7	19.2
23	21.2	22.4	20.6	19.3	19.7	18.6	20.1
24	22.1	23.4	21.5	20.1	20.6	19.4	21.0
25	23.1	24.4	22.5	21.0	21.5	20.3	21.8
26	24.0	25.3	23.4	21.9	22.3	21.1	22.7
27	24.9	26.3	24.3	22.7	23.2	22.0	23.6
28	25.8	27.3	25.2	23.6	24.0	22.8	24.5
29	26.7	28.2	26.2	24.5	24.9	23.7	25.4
30	27.7	29.2	27.1	25.4	25.8	24.5	26.3

[1]Stump height is 6 inches above ground.

[2]Based on the following equations:

curve number	1	Dbh = .922 stump diameter + .01
	2	Dbh = .970 stump diameter + .11
	3	Dbh = .928 stump diameter − .72
	4	Dbh = .868 stump diameter − .69
	5	Dbh = .862 stump diameter − .10
	6	Dbh = .850 stump diameter − .96
	7	Dbh = .890 stump diameter − .42

[3]Includes all other native tree species and shrubs, especially laurel and rhododendron.

[4]Includes scarlet, northern red, blackjack, black, and southern red oaks.

TABLE 27-141—*Growth factor*[1] *for southeastern hardwoods* (McCormack 1955)

Species	Growth factor	Trees sampled
		Number
Ash sp.	2.10	249
Elm sp.	2.10	139
Hackberry	2.08	33
Hickory sp.	2.11	461
Maple, red	2.10	485
Oak, black	2.13	221
Oak, chestnut	2.18	160
Oak, laurel	2.11	317
Oak, northern red	2.15	169
Oak, post	2.19	120
Oak, scarlet	2.11	572
Oak, southern red	2.14	152
Oak, water	2.10	305
Oak, white	2.16	873
Sweetbay	2.16	257
Sweetgum	2.07	950
Tupelo, black	2.12	105
Yellow-poplar	2.18	599

[1]See related text for definition.

TABLE 27-142—*Volumes of lumber, kerf, shrinkage, and slabs and edging for various log lengths as determined by the International 1/4-inch Log Rule* (Bennett and Lloyd 1974)[1]

Diameter (inches)	Lumber			Kerf		Shrinkage		Slab-edging		Slab-edging/ 1,000 board feet
	Bd ft	*Cu ft*	*Pct*	*Cu ft*	*Pct*	*Cu ft*	*Pct*	*Cu ft*[2]	*Pct*	*Cu ft*
					8-FOOT LOG					
6	8	0.63	33.0	0.29	15.2	0.09	4.8	0.87	45.6	115.11
8	17	1.38	42.3	.53	16.1	.16	4.8	1.15	35.2	69.35
10	29	2.40	48.1	.83	16.6	.24	4.8	1.43	28.7	49.61
12	44	3.68	52.2	1.20	17.0	.34	4.8	1.70	24.2	38.61
14	63	5.23	55.1	1.64	17.3	.45	4.8	1.98	20.9	31.60
16	84	7.04	57.3	2.15	17.5	.58	4.8	2.26	18.4	26.74
18	109	9.12	59.1	2.73	17.7	.73	4.8	2.54	16.4	23.18
20	138	11.47	60.5	3.37	17.8	.90	4.8	2.81	14.9	20.45
22	169	14.08	61.7	4.09	17.9	1.09	4.8	3.09	13.5	18.30
24	203	16.96	62.7	4.87	18.0	1.29	4.8	3.37	12.5	16.56
					12-FOOT LOG					
6	13	1.07	34.9	0.47	15.4	0.15	4.8	1.35	43.9	104.85
8	27	2.25	43.6	.83	16.2	.25	4.8	1.76	34.2	65.31
10	46	3.82	49.2	1.30	16.7	.37	4.8	2.17	28.0	47.40
12	70	5.79	53.1	1.86	17.1	.52	4.8	2.58	23.7	37.19
14	98	8.16	56.0	2.53	17.3	.69	4.8	3.00	20.6	30.59
16	131	10.93	58.2	3.29	17.5	.89	4.8	3.41	18.1	25.98
18	169	14.10	59.9	4.16	17.7	1.12	4.8	3.82	16.2	22.58
20	212	17.76	61.3	5.14	17.8	1.37	4.8	4.23	14.7	19.97
22	260	21.64	62.5	6.21	17.9	1.65	4.8	4.65	13.4	17.89
24	312	26.01	63.4	7.38	18.0	1.95	4.8	5.06	12.3	16.21
					16-FOOT LOG					
6	19	1.60	36.5	0.68	15.5	0.21	4.8	1.86	42.3	96.44
8	39	3.24	44.8	1.18	16.3	.34	4.8	2.40	33.2	61.89
10	65	5.40	50.1	1.81	16.8	.51	4.8	2.95	27.4	45.53
12	97	8.10	53.8	2.57	17.1	.72	4.8	3.50	23.3	36.00
14	136	11.33	56.6	3.47	17.4	.95	4.8	4.05	20.2	29.77
16	181	15.09	58.7	4.51	17.6	1.22	4.8	4.59	17.9	25.37
18	233	19.38	60.4	5.68	17.7	1.53	4.8	5.14	16.0	22.11
20	290	24.21	61.8	6.99	17.8	1.87	4.8	5.69	14.5	19.58
22	355	29.56	62.9	8.43	17.9	2.24	4.8	6.24	13.3	17.58
24	425	35.45	63.9	10.00	18.0	2.64	4.8	6.78	12.2	15.94

Note: The percentages of total volume for the various components at each diameter do not total 100 because a 3-inch trim allowance was included on all log lengths when calculating slab-edging and kerf volumes but omitted when calculating board foot volumes. The latter also deviate slightly, in some instances, from published values because some coefficients were not rounded at the same points as in the original rule.

[1]The component values can be calculated for any desired diameter and log length.

[2]When the slab volume is converted to chips by chipping head-rigs, these estimates should be increased by 19 percent and the kerf estimates reduced by the calculated amount.

TABLE 27-143—*Volume of lumber, kerf, and slabs and edging for various log lengths determined by the Scribner ¼-inch Log Rule* (Bennett and Lloyd 1974)[1]

Diameter (inches)	Lumber			Kerf		Slab-edging		Slab edging/ 1,000 bd ft log scale
	Bd ft	*Cu ft*	*Pct*	*Cu ft*	*Pct*	*Cu ft*[2]	*Pct*	*Cu ft*
				8-FOOT LOG				
6	6	0.51	26.7	0.49	25.4	0.90	47.1	147.16
8	15	1.27	38.8	.81	24.9	1.15	35.1	75.46
10	27	2.29	45.9	1.21	24.2	1.41	28.4	51.54
12	43	3.57	50.6	1.67	23.7	1.70	24.1	39.68
14	61	5.12	54.0	2.20	23.2	2.00	21.1	32.62
16	83	6.93	56.4	2.81	22.9	2.32	18.9	27.94
18	108	9.00	58.3	3.49	22.6	2.66	17.2	24.63
20	136	11.34	59.9	4.24	22.4	3.01	15.9	22.15
22	167	13.94	61.1	5.06	22.2	3.38	14.8	20.23
24	202	16.80	62.1	5.95	22.0	3.77	13.9	18.70
				12-FOOT LOG				
6	9	0.77	24.9	0.77	25.0	1.52	49.6	165.60
8	23	1.90	36.9	1.27	24.6	1.94	37.7	85.07
10	41	3.43	44.2	1.86	24.0	2.39	30.8	58.06
12	64	5.36	49.1	2.57	23.5	2.87	26.3	44.62
14	92	7.68	52.6	3.37	23.1	3.37	23.1	36.60
16	125	10.39	55.3	4.29	22.8	3.90	20.8	31.27
18	162	13.50	57.4	5.31	22.5	4.45	18.9	27.49
20	204	17.01	59.0	6.43	22.3	5.03	17.5	24.66
22	251	20.91	60.4	7.66	22.1	5.63	16.3	22.46
24	302	25.20	61.5	9.00	22.0	6.26	15.3	20.71
				16-FOOT LOG				
6	12	1.02	23.3	1.08	24.6	2.27	51.8	185.54
8	30	2.53	35.0	1.76	24.3	2.90	40.1	95.34
10	55	4.57	42.4	2.57	23.8	3.57	33.1	64.99
12	86	7.14	47.5	3.52	23.4	4.27	28.4	49.85
14	123	10.23	51.1	4.61	23.0	5.01	25.0	40.80
16	166	13.85	53.9	5.84	22.7	5.78	22.5	34.78
18	216	18.00	56.1	7.21	22.5	6.59	20.5	30.50
20	272	22.67	57.9	8.72	22.3	7.43	19.0	27.29
22	334	27.87	59.3	10.37	22.1	8.30	17.7	24.80
24	403	33.60	60.6	12.17	21.9	9.20	16.6	22.82

Note: The percentages of total volume for the various components at each diameter do not total 100 because a 3-inch trim allowance was included on all log lengths when calculating slab-edging and kerf volumes but omitted when calculating board foot volumes. The latter also deviate slightly, in some instances, from published values because some coefficients were not rounded at the same points as in the original rule.

[1]The component values can be calculated for any desired diameter and log length. However, as log length increases, the percentage of log volumes going to slabs increases.

[2]When the slab volume is converted to chips by chipping head-rigs, these estimates should be increased by 20 percent and the kerf estimates reduced by the calculated amounts.

TABLE 27-144—*Weight/volume relationships for 8-foot mixed oak logs from the Missouri Ozarks, per 1,000 board feet, Doyle log scale* (Massengale 1971)[1]

Log diameter (inches)	Log scale on yard	Number of logs per Mbf	Green weight of		
			Bark	Slabs and edgings	Sawdust
	Board feet		*Pounds*		
8	16	63	2,780	2,620	3,590
9	16	63	3,150	4,155	4,600
10	18	56	3,300	3,750	4,425
11	24	42	2,520	2,920	4,325
12	32	32	2,530	2,610	3,360
13	40	25	1,975	2,915	3,280
14	50	20	2,120	2,360	2,860
15	60	17	2,110	1,855	2,880
16	72	14	1,835	1,790	2,350
17	84	12	1,790	2,240	2,320
18	98	11	1,940	2,520	2,650

[1]Doyle Log Scale adjusted for 8- and 9-inch logs on the yard. All logs were sawn for maximum yield of 4/4 lumber; kerf was 3/16-inch. The average moisture content of the bark was 48.7 percent, ovendry-weight basis. The average moisture content of the sawdust was 69.9 percent, ovendry-weight basis. Values are rounded.

TABLE 27-145—*Weight/volume relationships for 8-foot mixed oak logs from the Missouri Ozarks, per 1,000 board feet lumber scale* (Massengale 1971)[1]

Log diameter (inches)	Lumber yield	Number of logs per Mbf	Green weight of		
			Bark	Slabs and edgings	Sawdust
	Board feet		*Pounds*		
8	18	56	2,460	2,350	3,190
9	20	50	2,500	3,300	3,650
10	24	42	2,480	2,820	3,320
11	36	28	1,680	1,960	2,880
12	38	26	2,060	2,140	2,730
13	43	24	1,900	2,810	3,150
14	52	20	2,220	2,360	3,140
15	73	14	1,740	1,530	2,370
16	82	13	1,700	1,660	2,180
17	90	12	1,790	2,240	2,340
18	97	11	1,930	2,520	2,650

[1]All logs were sawn for maximum yield of 4/4 lumber; kerf was 3/16-inch. Average moisture content of the bark was 48.7 percent, ovendry-weight basis. Average moisture content of the sawdust was 69.9 percent, ovendry-weight basis. Values are rounded.

TABLE 27-146—*Projected average green-weight yields of bark, slabs and edgings, sawdust, and lumber from mixed oak logs of four lengths from the Missouri Ozarks* (Massengale 1971)[1,2,3]

Log diameter (inches)	Bark	Slabs and edgings	Sawdust	Lumber
	Pounds/log			
		8-FOOT LOGS		
8	30	34	50	112
10	57	65	84	165
12	83	96	118	389
14	109	127	152	270
16	35	158	186	541
		10-FOOT LOGS		
8	44	50	71	153
10	78	89	114	233
12	110	128	156	362
14	143	167	199	524
16	175	205	241	707
		12-FOOT LOGS		
8	58	66	92	194
10	99	113	143	300
12	137	160	194	465
14	176	206	245	660
16	215	252	296	872
		14-FOOT LOGS		
8	73	83	113	236
10	119	137	165	368
12	165	191	232	562
14	210	246	291	795
16	256	300	351	1,038
		16-FOOT LOGS		
8	87	99	134	270
10	140	161	202	430
12	192	223	270	650
14	244	285	338	930
16	296	347	406	1,100

[1]Average weights determined from graphs with lumber yield being average for the log sample. All logs sawn into 4/4 lumber.

[2]Average moisture content of bark was 48.7 percent and of sawdust 69.9 percent, ovendry-weight basis.

[3]Kerf was 3/16-inch.

TABLE 27-147—*Average lumber, chippable residue, bark residue, and sawdust recovery percentages, green-weight basis, black oak saw logs* (Phillips 1975)[1]

Log scaling diameter (inches)	Sample size	Average log length	Green log weight w/bark	Lumber	Chippable residue[2]	Bark residue[3]	Sawdust
	Number	*Feet*	*Pounds*	*Percent*			
9	11	14.2	581	48.9	23.4	16.8	10.9
10	9	13.5	672	46.3	25.6	16.9	11.2
11	15	14.2	787	51.0	20.7	17.1	11.2
12	17	14.2	1,004	50.7	21.8	17.0	10.5
13	11	13.9	1,169	51.4	22.2	15.4	11.0
14	8	12.5	1,085	50.4	23.4	16.5	9.7
15	14	13.6	1,381	54.6	19.7	15.2	10.5
16	15	13.0	1,516	56.6	18.1	15.2	10.1
17	12	13.1	1,729	56.3	18.6	14.7	10.4
18	6	13.7	1,979	58.8	16.9	14.3	10.0
19	6	14.8	2,375	59.9	16.4	13.9	9.8
20	2	14.3	2,360	59.1	16.8	14.1	10.0
21	4	16.0	3,246	61.0	16.6	12.8	9.6
Weighted study average							
14.0	–	13.8	1,305	54.8	19.6	15.3	10.3

[1]Based on a sample of 130 logs processed in North Carolina with a rosserhead debarker and thin-kerf band headsaw.

[2]Includes slabs, edgings, and end trim.

[3]Includes wood fiber removed during debarking.

TABLE 27-148—*Predicted green residue weights for black oak saw logs* (Phillips 1975)[1]

Scaling diameter (inches)	Saw log length in feet					
	8	10	12	14	16	18
	Pounds					
	CHIPPABLE RESIDUE[2]					
8	103	112	120	128	137	145
10	122	135	148	161	174	187
12	145	164	183	201	220	239
14	172	198	223	249	274	300
16	203	237	270	304	337	370
18	239	281	323	366	408	450
20	279	331	383	435	487	539
22	322	385	448	512	575	638
24	370	445	520	595	671	746
	SAWDUST[3]					
8	36	41	47	52	58	63
10	48	57	65	74	82	91
12	63	75	88	100	112	124
14	81	97	114	131	147	164
16	101	123	144	166	188	210
18	124	152	179	207	234	261
20	150	184	218	252	286	319
22	178	219	260	302	343	384
24	210	258	307	356	405	454

[1]Based on a sample of 130 logs processed in North Carolina with a rosserhead debarker and thin-kerf band headsaw. Blocked-in area indicates limits of basis data.

[2]$Y = 70.03178 + 0.06516\ D^2L$ $R^2 = 0.71$ $Sy \cdot x = 61.3$.

[3]$Y = 14.27388 + 0.04239\ D^2L$ $R^2 = 0.89$ $Sy \cdot x = 22.1$.

TABLE 27-149—*Green weight of chippable residue and sawdust from black oak saw log merchantable stems to 8-inch dib top* (Phillips et al. 1974)[1,2]

Dbh (inches)	Merchantable height (number of 16-foot logs)[3]			
	1	2	3	4
	Pounds			
	CHIPPABLE RESIDUE[4]			
10	261	317		
12	287	369	451	
14	319	430	541	
16	355	500	645	790
18	396	580	763	947
20	442	668	895	1,122
22	492	767	1,041	1,316
24	548	874	1,201	1,528
	SAWDUST[5]			
10	99	133		
12	115	164	213	
14	134	200	267	
16	156	242	329	416
18	180	290	400	510
20	207	343	479	614
22	238	402	566	730
24	271	466	661	857

[1]Based on a sample of 40 trees cut in North Carolina and processed with a rosserhead debarker and thin-kerf band headrig.

[2]Blocked-in area indicates the range of basic data.

[3]Includes a 1-foot stump allowance.

[4]$Y = 200.51412 + 0.03545\ D^2Mh$ where D = dbh, inches, and Mh = merchantable height, feet. $R^2 = 0.89$ $Sy \cdot x = 127.7$.

[5]$Y = 63.40778 + 0.02119\ D^2Mh$ $R^2 = 0.95$ $Sy \cdot x = 49.1$.

TABLE 27-150—*Average lumber tally, saw log green weight, and proportion of lumber, chippable residue, bark residue, and sawdust for yellow-poplar saw logs by diameter classes* (Clark 1976)[1]

Log-Scaling diameter	Average log length	Sample size	Lumber tally	Saw log weight	Component recovery			
					Lumber	Chippable residue	Bark residue	Sawdust
Inches	*Feet*	*Number*	*Fbm*	*Pounds*	*Percent*			
7	10.7	4	19	210	36	33	18	13
8	12.4	19	26	303	39	30	18	13
9	13.0	23	39	380	44	25	18	13
10	13.4	27	53	505	47	23	18	12
11	13.2	20	66	606	49	23	16	12
12	14.7	22	90	806	51	21	16	12
13	14.8	18	105	889	52	19	16	13
14	15.0	15	124	1,044	54	18	16	12
15	15.0	14	145	1,200	55	18	15	12
16	15.6	12	170	1,345	55	17	16	12
17	14.9	11	185	1,556	57	18	13	12
18	15.4	14	217	1,762	57	17	13	13
19	15.7	7	237	1,953	57	16	14	13
20	16.1	10	279	2,152	59	14	14	13
21	15.4	7	298	2,451	59	16	12	13
22	16.2	4	332	2,874	59	17	12	12
23	16.4	3	395	3,523	60	17	10	13
Average	—	—	122	1,042	54	18	15	13

[1]Based on a sample of 230 logs processed into 4/4 lumber in North Carolina with a rosserhead debarker and band headsaw with 3/16-inch kerf.

TABLE 27-151—*Weight of chippable residue and sawdust from yellow-poplar saw logs* (Clark 1976)[1,2]

Scaling diameter (inches)	Saw log length in feet				
	8	10	12	14	16
	Pounds				
	CHIPPABLE RESIDUE[3]				
8	72	78	85	91	97
9	79	87	95	103	111
10	86	96	106	116	126
11	95	107	119	131	143
12	104	118	133	147	161
13	114	131	148	164	181
14	125	144	164	183	203
15	136	159	181	204	226
16	149	174	200	225	251
17	162	191	219	248	277
18	176	208	240	273	305
19	190	227	263	299	335
20	206	246	286	326	366
21	222	266	311	355	399
22	240	288	336	385	433
23	258	310	363	416	469
24	276	334	391	449	506
	SAWDUST[4]				
8	25	31	37	42	48
9	31	38	45	53	60
10	38	47	55	64	73
11	45	56	67	77	88
12	53	66	79	91	104
13	62	77	92	107	121
14	72	89	106	123	140
15	82	102	121	141	161
16	93	115	138	160	182
17	104	130	155	180	206
18	117	145	173	202	230
19	130	161	193	225	256
20	143	178	213	248	284
21	158	196	235	274	312
22	173	215	258	300	342
23	188	235	281	328	374
24	205	255	306	357	407

[1]Blocked-in areas indicate limits of sample.

[2]Based on a sample of 230 logs cut from 47 yellow-poplar trees in western North Carolina. Debarked logs were sawn into 4/4 lumber in a mill with a 3/16-inch-kerf headsaw and in-line edger and trim saws.

[3]$Y = 46.28545 + 0.04993\ D^2L$ $R^2 = 0.95$ $Sy \cdot x = 0.95$

[4]$Y = 2.84170 + 0.04386\ D^2L$ $R^2 = 0.97$ $Sy \cdot x = 0.54$.

TABLE 27-152—*Weight of chippable residue and sawdust from yellow-poplar saw log merchantable stem to 8-inch dib top* (Clark et al. 1974)[1,2]

Dbh (inches)	Merchantable tree height (number of 16-foot logs)[3]				
	2	3	4	5	6
	Pounds				
	CHIPPABLE RESIDUE[4]				
12	308	367	426		
14	352	432	513	594	
16	403	508	613	718	824
18	460	594	727	860	993
20		689	854	1,018	1,183
22		795	994	1,193	1,392
24		911	1,148	1,385	1,621
26			1,315	1,593	1,871
28			1,495	1,818	2,140
30			1,689	2,059	2,429
	SAWDUST[5]				
12	131	178	226		
14	166	231	296	361	
16	207	292	377	462	546
18	254	361	468	576	683
20		438	571	703	836
22		523	684	844	1,004
24		617	808	998	1,189
26			942	1,166	1,390
28			1,088	1,347	1,607
30			1,244	1,542	1,840

[1]Based on a sample of 47 trees processed into 4/4 lumber in North Carolina with a 3/16-inch-kerf band headsaw.

[2]Blocked-in area indicates the range of basic data.

[3]Includes a 1-foot stump allowance.

[4]$Y = 85.79319 + 0.02255\ D^2Mh$, where D = dbh, inches, and Mh = saw log merchantable height, feet $R^2 = 0.98$ $Sy \cdot x = 1.60$.

[5]$Y = 32.15269 + 0.02071\ D^2Mh$ $R^2 = 0.98$ $Sy \cdot x = 1.35$.

TABLE 27-153—*Predicted yield of dry wood and bark from one ton of green whole-tree chips from small, understory hardwoods in the Georgia Piedmont and North Carolina mountains* (Derived from Phillips and McClure 1976)[1]

Species	Wood and bark	
	Piedmont	Mountains
	Ovendry pounds/green ton of chips	
Dogwood	1,074	1,132
Hickory	1,242	1,266
Maple, red	1,113	1,052
Oak, chestnut	—	1,185
Oak, southern red	1,178	—
Oak, white	1,159	1,188
Yellow-poplar	839	860

[1]For a description of the study trees, see tables 7-3 and 16-6.

TABLE 27-154—*Metric conversion factors*

English units to metric			Metric units to English		
			LENGTH		
1 in	=	25.4 mm (exactly)	1 mm	=	0.0393701 in
1 in	=	2.54 cm (exactly)	1 cm	=	0.393701 in
1 ft	=	0.3048 m (exactly)	1 m	=	3.28084 ft
1 yd	=	0.9144 m (exactly)	1 m	=	1.09361 yd
1 chain (22 yd)	=	20.1168 m (exactly)	1 m	=	0.0497097 chain
1 mi	=	1.60934 km	1 km	=	0.621371 mi
			AREA		
1 sq in	=	645.16 mm^2 (exactly)	1 mm^2	=	0.0015500 sq in
1 sq in	=	6.4516 cm^2 (exactly)	1 cm^2	=	0.15500 sq in
1 sq ft	=	0.0929030 m^2	1 m^2	=	10.7639 sq in
1 sq yd	=	0.836127 m^2	1 m^2	=	1.19599 sq yd
1 mil-acre	=	4.04686 m^2	1 m^2	=	0.247105 mil-acre
1 acre	=	0.404686 ha	1 ha	=	2.47105 acres
1 sq mi	=	2.58999 km^2	1 km^2	=	0.386102 sq mi
			VOLUME OR CAPACITY		
1 cu in	=	16,387.064 mm^3	1 mm^3	=	0.000061024 cu in
1 cu in	=	16.38706 cm^3	1 cm^3	=	0.061024 cu in
1 cu ft	=	0.0283168 m^3	1 m^3	=	35.3147 cu ft
1 cu yd	=	0.764555 m^3	1 m^3	=	1.30795 cu yd
1 cunit (100 cu ft of solid wood)	=	2.83168 m^3	1 m^3	=	0.353147 cunit
1 cord (128 stacked cu ft)	=	3.62456 m^3 (stacked)	1 m^3 (stacked)	=	0.275896 cord
1 bd ft²	=	0.002359738 m^3	1 m^3	=	423.7759 bd ft
1 gal (US)	=	3.785412 *l*	1 *l*	=	0.264172 gal (US)
			MASS OR WEIGHT		
1 grain	=	0.064799	1 g	=	15.4324 grains
1 oz	=	28.3495 g	1 g	=	0.0352740 oz
1 lb	=	0.453592 kg	1 kg	=	2.20462 lb
1 ton (short)	=	907.1847 kg	1 kg	=	0.0011023 ton (short)
1 ton (short)	=	0.907185 t	1 t	=	1.10231 tons (short)
1 ton (long)	=	1.01605 t	1 t	=	0.98420 ton (long)
			RATIOS		
1 sq ft/acre	=	0.229568 m^2/ha	1 m^2/ha	=	4.35600 sq ft/acre
1 cu ft/acre	=	0.0699725 m^3/ha	1 m^3/ha	=	14.2913 cu ft/acre
1 cord/acre	=	8.95647 m^3 (stacked)/ha	1 m^3 (stacked)/ha	=	0.111651 cord/acre
1 lb/cu ft	=	16.0185 kg/m^3	1 kg/m^3	=	0.0624280 lb/cu ft
1 ton (short)/acre	=	2.24170 t/ha	1 t/ha	=	0.446090 ton (short)/acre
1 mpg (US)	=	0.425143 km/*l*	1 km/*l*	=	2.35215 mpg (US)

27-4 LITERATURE CITED

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PART VI—PROSPECTIVE

28

Economic feasibility analyses

Data drawn principally from research by:

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B. A. Haataja
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CHAPTER 28

Economic feasibility analyses*

CONTENTS

*Values tabulated are capital investments required (1980 dollars).

CHAPTER 28

Economic feasibility analyses[1]

To utilize significant volumes of the hardwoods that grow where southern pines grow, economically viable enterprises using hardwood feedstocks typical of the region must be conceived, designed, financed, built in large numbers, and successfully operated. Examples of such operations are not easily documented, because there are so few of them. Were they more numerous, preparation of this text would have had lower priority.

To stimulate some imaginative and organized thinking about the design of enterprises capable of profitably operating on the low-grade hardwoods typically found among southern pines, a symposium was organized to synthesize enterprises with promise of economic success[1]. Speakers at the symposium were instructed that their target profit (return on investment) before income taxes should be at least 30 percent of total investment required, assuming no debt. While this target was not achieved by all the synthesized enterprises, most of them met or surpassed the threshhold return.

The enterprises proposed ranged in capital investment from $120,000 to $94,000,000. Those selected for abstracting in this text are assembled in order according to investment required, from small to large. Several of them (see sect. 28-5, 28-6, 28-7, 28-9, 28-10, 28-20, and 28-33) are designed to manufacture energy-related products. The first paper abstracted (sect. 28-1) does not describe an enterprise, but tabulates the costs of operating a $13,000 farm tractor on wood gas.

Stumbo (1981a), in his preface to the 1980 symposium proceedings,[1] noted that one objective was to present the economic analyses in a standard format using similar economic evaluations to allow more direct comparison of results. To a large extent this was accomplished. Return on investments and return on sales were calculated on a typical year basis without incorporating income tax, investment credits, or interest on investment.

The reader is cautioned, however, that exact comparisons of the economic data could be misleading. These data are offered as a guide to economic feasibility and as such should be helpful. But, the individual economic analyses have

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[1]The feasibility analysis in this chapter, with three exceptions, are abstracted from papers contained in the Proceedings of a Symposium held October 6-8, 1980 in Nashville, Tenn. (Stumbo 1981a). The Symposium, "Utilization of Low-Grade Southern Hardwoods—Feasibility Studies of 36 Enterprises", was sponsored by the Mid-South Section of the Forest Products Research Society, the Agricultural Extension Service of the University of Tennessee, and the Southern Forest Experiment Station of the U.S. Forest Service with the cooperation of the Forest Products Research Society, the Southeastern Area State and Private Forestry Branch of the U.S. Forest Service, the Hardwood Research Council, and the Tennessee Division of Forestry. The abstracts are reproduced in somewhat modified form by permission of the authors and the Forest Products Research Society. Readers needing more data about the enterprises described should consult the source documents.

utilized varying prices for raw materials, labor, product prices, and other parameters, so the results are not exactly comparable. The reader is also reminded that economic studies such as these are time and location dependent. Economic conditions change rapidly and while each study is appropriate for its specified time and location, it may not be appropriate for conditions at the time and location in which the reader is interested.

The feasibility studies do, however, present physical parameters and well developed economic analyses that can very readily be adapted to most individual situations. Information needed to convert to other economic evaluation techniques is incorporated in most of the papers, providing individuals with data to adapt the information to their preferred system.

Included in the 33 feasibility analyses abstracted are three not included in the Proceedings of the Nashville symposium[1]. One of these, Koch (1982), abstracted briefly in section 28-31, is readily available at forestry libraries in the journal, *Wood and Fiber*. Another, Koch (1978), is reproduced almost in its entirety in section 28-27 because the source article is less readily available. The third, summarized in section 28-18, carries a footnote identifying its source.

This chapter is not intended to be a text on wood procurement, plant location and operation, or marketing. Its purpose is to record a sample of imaginative, aggressive, and optimistic thinking about some potentially viable ways to use pine-site hardwoods as an industrial raw material.

Conspicuously absent from these abstracts are analyses of operations pulping hardwoods for paper and paperboard. It is likely, however, that pulp mills—presently a major consumer of hardwood—will increase the amount they use (figs. 25-6 through 25-8, 29-5ABC, and 29-10AB.

Also absent are analyses of operations producing split firewood for home use, or pelletized fuel for residential and commercial use; cost and profit data for these operations proved difficult to obtain. Frick's (1978) firewood producer's manual should be useful to entrepreneurs interested in this subject. Monahan and Wartluft (1980) examined commercial aspects of operating a LaFont firewood processor (fig. 16-23) and found that such operation could be profitable if non-productive time does not exceed 15 percent. Swain (1980) reported on trends of firewood use, management, and marketing in Maine; his comments on market testing and establishment of firewood marketing outlets should be useful to southern entrepreneurs as well as those from Maine.

The economics of producing whole-tree chips for fuel or fiber are discussed in sect. 28-9, but chips for export are not. See figure 25-2 for data on world chip prices, K. G. Clemens[2] for comments on advantages of mid-south locations for the international chip trade, and Wood (1977) for a discussion of the reasons why the South should export pulp and paper, but not chips.

For suggestions on making and selling bark products, readers are referred to Mater et al. (1968) and Mater (1972).

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[2]Clemens, K. G., 1977. Why export chips? 5 p. Alabama Coop. Ext. Serv., Auburn Univ., Auburn, Ala.

To aid planning, econometric models of a few industries important to hardwood utilization are available, e.g., the pallet market (Schuler and Wallin 1979) and insulation board market (Schuler 1979). Harpole (1979) described an economic model for structural flakeboard production. Also, W. G. Luppold of the Northeastern Forest Experiment Station, USDA Forest Service, has available an econometric model of the hardwood lumber market.

A nationally available computerized information retrieval system (FORDAT) for forest economic data should simplify business research (Spelter 1981), and EVALUE, a computer program for evaluating investments in forest products industries, should be useful (Ince and Steele 1980). Kallio and Dickerhoof (1979) provided a source book for business data and market information related to the forest products industry. Also, Harpole (1978a) provided a cash flow computer program to analyze investment opportunities in wood products manufacturing. SOLVE II is a computerized technique to improve efficiency and solve problems in hardwood sawmills (Adams and Dunmire 1977).

The scale of operations described in sections 28-1 through 28-33 varies from a two-person enterprise to large manufacturing complexes employing several hundred people. Granskog (1978) concluded that in major southern forest industries, the trend has been toward achieving economies of scale, that is, toward building ever larger production plants to reduce unit costs. It is hoped, however, that the southern timber economy will accommodate small ventures as well as large. Proponents of the idea that "small is beautiful" will find encouragement in Mason's (1979) description of making a good living cutting one tree per acre per year from 130 Idaho acres, and help in locating literature from Wertman's (1979) annotated bibliography on small-scale technology for local forest development. Small-scale paper making is described in Paper (1978).

Plant location is usually critical to the success of new forest enterprises. Wolf and Dempsey (1970) offer some suggestions that should be helpful in deciding where to locate; their article contains a short bibliography on the subject.

Data describing quantities and distribution of the various species of hardwoods growing among southern pines can be found in chapter 2.

28-1 $13,000—COST OF OWNING AND OPERATING A 65-HP (DRAWBAR) DIESEL TRACTOR ON WOOD GAS[3]

The use of wood gas (see sect. 26-4) in internal combustion engines has led to development of portable gasifiers and substantial literature on the subject (e.g., Solar Energy Research Institute 1979). Hundreds of thousands of such units were used during World War II. At present, however, the low heat content of the gas, the extra time required for vehicle start-up and maintenance, the nuisance of fuel handling and drying, and transport problems associated with gasification make wood gas not competitive with gasoline or diesel fuel except in special cases.

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[3]Abstracted from Post and Eoff (1981).

In special situations where diesel fuel is unavailable and where wood is plentiful, wood gas can economically provide the energy necessary to drive vehicles such as tractors. About 2.5 pounds of air-dry wood are required per horsepower-hour compared to about 0.40 pound of diesel fuel. A cord of air-dry hardwood should yield gas with energy equivalent to 125 to 150 gallons of diesel fuel.

A diesel tractor rated at 65 drawbar horsepower costs about $0.26 per horsepower-hour of operation. If this tractor is modified to operate on wood gas, the cost should be about $0.31 per horsepower-hour of operation (table 28-1).

TABLE 28-1.—*Estimated cost of owning and operating a 65-hp (drawbar) diesel farm tractor on diesel oil and wood gas* (Post and Eoff 1981)[1]

	Diesel		Wood gas	
	Per year	Per hour	Per year	Per hour
	Dollars			
Depreciation, tractor	900	1.50	900	1.50
Depreciation, gasifier, and cleanup equipment	0	0	250	.41
Interest, insurance, and taxes	1,190	1.98	1,610	2.68
Filters, oil, and hydraulics associated with engine and drive train	306	.51	306	.51
Filters associated with burning wood gas	0	0	72	.12
Fuel				
Diesel ($1.00/gal)	2,499	4.16	198[2]	.33[2]
Wood ($30/dry ton)	0	0	810	1.35
Labor cost	3,000	5.00	3,450[3]	5.75[3]
Total cost	7,895	13.15	7,596	12.65
Cost per horsepower-hour of operation[4]	0.26		0.31	

[1]Assuming $13,000 initial price, $4,000 salvage value, and 600 operating hours per year with 10-year tractor life.

[2]Some diesel fuel is needed for ignition of wood gas.

[3]Assumes 15 percent increase in labor costs for wood gas operation.

[4]Assumes 50 horsepower output for diesel and 40 horsepower output for wood gas.

28-2 $120,000—AN 80-ACRE SOLUTION[4]

The objectives of *the 80-acre solution* are as follows:

- Provide a rural home and a quality of life for the enterprise owners that is difficult to match in an urban setting.
- Provide a small-scale, low-investment enterprise that will challenge the full range of creative abilities of a hard-working team comprised of wife and husband.
- Provide responsible, careful, and intensive stewardship of their 80-acre forest; provide the enterprise with an assured source of wood.
- Provide the owner-operator couple with an annual combined salary and investment profit, before interest and loan payment and income taxes of $66,000, i.e., $36,000 profit + 2 x $15,000 salary.

Eighty acres of upland forest stocked with small hickories and oaks constitute the sustained-yield land base for this two-person enterprise to make high quality furniture on a very small scale. The proprietors are husband and wife; they execute all aspects of the operation—from woodland management through manufacture and direct-mail marketing to the customer. Key statistics describing the enterprise are as follows:

Capital investment (including land)	$120,000
Operating cost, annual	$158,000
Sales, annual	$194,000
Net profit, annual (before income tax)	$ 36,000
Return on sales	19 percent
Return on investment	30 percent
Employees (i.e., the husband and wife owners)	2
Energy requirement, annual	
Electrical	60,000 kWh
Gasoline	700 gallons
Wood residues (to heat shop and home)	10 cords

Illustrative of the class of furniture to be manufactured are the chair and ottoman shown in figure 28-1 (top). This chair and ottoman are manufactured by Vatne Lenestobfabrikk A/S in Norway, and the design simply serves for illustrative purposes. The structural skeletons of both chair and ottoman are constructed of bent and glue-laminated veneer. Cushions are supported on canvas slings and upholstered with high quality leather over synthetic stuffing formed to contour. Net annual sales are projected at 400 chairs at $400 each and 200 ottomans at $160 each. Forty cords of oak and hickory are harvested annually with raw-material flow as shown in figure 28-1 (bottom). Not depicted here, but described in the source article, are data on fabrication of the metal hardware, canvas slings, and upholstered leather cushions, as well as the manufacture and finishing of the wood parts, which are simply designed for easy purchaser assembly after shipment.

[4]Abstracted from Koch (1981).

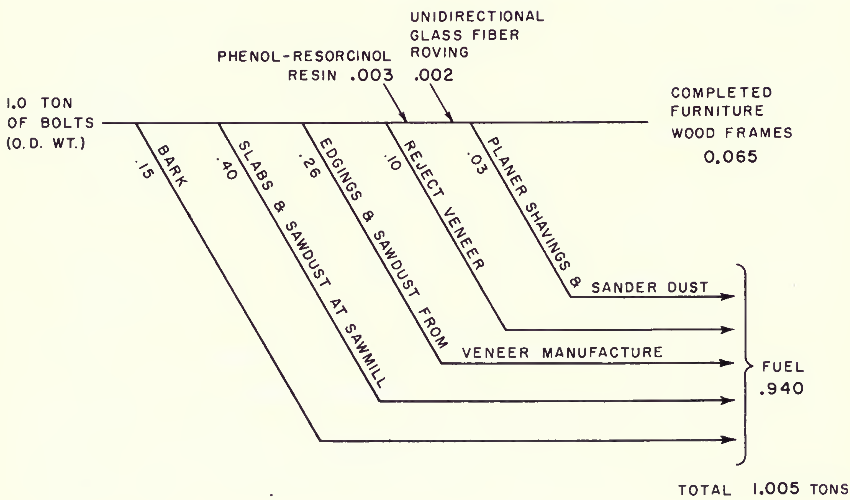


Figure 28-1.—(Top) Simple, elegant, and comfortable laminated-veneer furniture appropriate for construction from white oak, southern red oak, or hickory. The wood portion of the lounge chair weighs about 10 pounds, that of the ottoman about 6½ pounds. (Bottom) Materials balance for the structural skeleton wood frames, based on ovendry (OD) weight. Weight of the 6.7-foot-long oak and hickory bolts includes bark. Annual cordwood requirement, bark included, OD basis, is about 73 tons. (Photo and drawing from Koch 1981.)

28-3 $223,500—SMALL-SCALE MANUFACTURE OF PALLETS[4]

A small independent hardwood pallet plant is a marginal investment if pallets are sold at prices competitive with larger production facilities manufacturing large orders of "standard" pallets. To be viable a small pallet plant, located adjacent to an urban center, may enter a more lucrative market for small-order, quick-delivery, specialized pallets. A key to its success is the versatility to produce small orders of many different pallet or container designs with minimal change-over costs.

To supply a hand-nailed pallet operation, the enterprise purchases green rough pallet lumber of standard stock dimensions and cants for block pallets and produces about 275 pallets per day at an average of 40 to 60 units per order. Besides two radial-arm cutoff saws, its equipment would include a bandsaw or a single-head notcher, a table router, two hydraulic floor trucks, a fork lift, and one or more assembly tables adjustable for a range of pallet sizes. Nailing or stapling requires up to six pneumatic tools and an air compressor.

Key statistics of the enterprise are as follows:

Capital investment	$223,500
Operating cost, annual	$391,140
Sales, annual	$422,812
Net profit, annual (before income taxes)	$ 31,672
Return on sales	7.5 percent
Return on investment	14.2 percent
Employees	10
Energy requirement, annual	
Electrical	30,000 kWh
Diesel fuel and gasoline for fork lift and delivery truck	5,350 gallons
Wood residue, for plant heat	1 billion Btu

With a total staff of 10 employees, the pallet plant should produce about 275 pallets per day for 250 days per year, and consume about 1.6 million board feet of lumber annually. About 0.92 ton of pallets is produced per ton of lumber purchased (fig. 28-2).

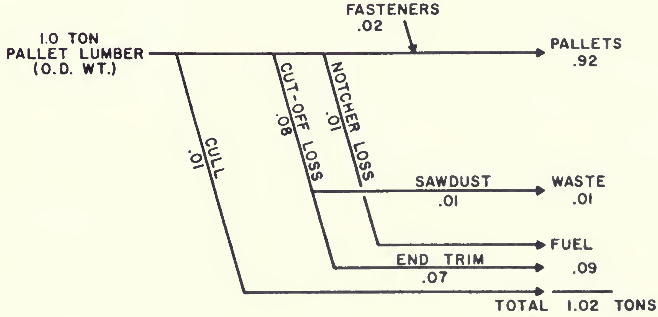


Figure 28-2.—Materials balance (ovendry-weight basis) for the manufacture of pallets. Annual wood requirement is about 1.6 million board feet purchased in standard sizes for pallet fabrication. (Drawing after White et al. 1981.)

[4]Abstracted from White et al. (1981).

28-4 $275,000—BOLTER MILL OPERATION TO PRODUCE SHORT LUMBER FOR UPHOLSTERED FURNITURE[5]

Short lumber has been produced on a bolter mill (fig. 28-3) at Marimont Furniture Co., Marion, N.C. for over 3 years. Seven-foot hardwood bolts are purchased by the cord, processed into lumber, air dried, kiln-dried, and manufactured into sound cuttings for use in upholstered furniture. Production averages 7 Mbf of lumber per 8-hour shift at a cost about 30 percent less than similar lumber purchased on the open market. No real problems have been encountered in processing, handling, drying, and using this lumber in furniture manufacture.

Key statistics describing the enterprise are as follows:

Capital investment	$275,520
Operating cost, annual	287,400
Sales, annual	338,280
Net profit (before taxes)	50,880
Return on sales	15.0 percent
Return on investment	18.5 percent
Employees	5
Energy requirement, annual	
Electrical	192,000 kWh

A cord of bolts, mostly oak and hickory with ovendry weight of about 3,340 pounds, yields about 704 pounds of unsanded furniture cuttings, ovendry-weight basis (fig. 28-4). For this analysis, bolt cost was estimated at $40 per cord. Average lumber sale price was estimated at $175/Mbf. Annual wood consumption was projected at 3,360 cords with lumber production of 1,680 Mbf.

After 2 years on an experimental basis the operation was continued and supplemented with a debarker and improved conveyors and chippers; this is evidence that for this company the bolter saw operation was economically satisfactory.

[5]Abstracted from Smith (1981).

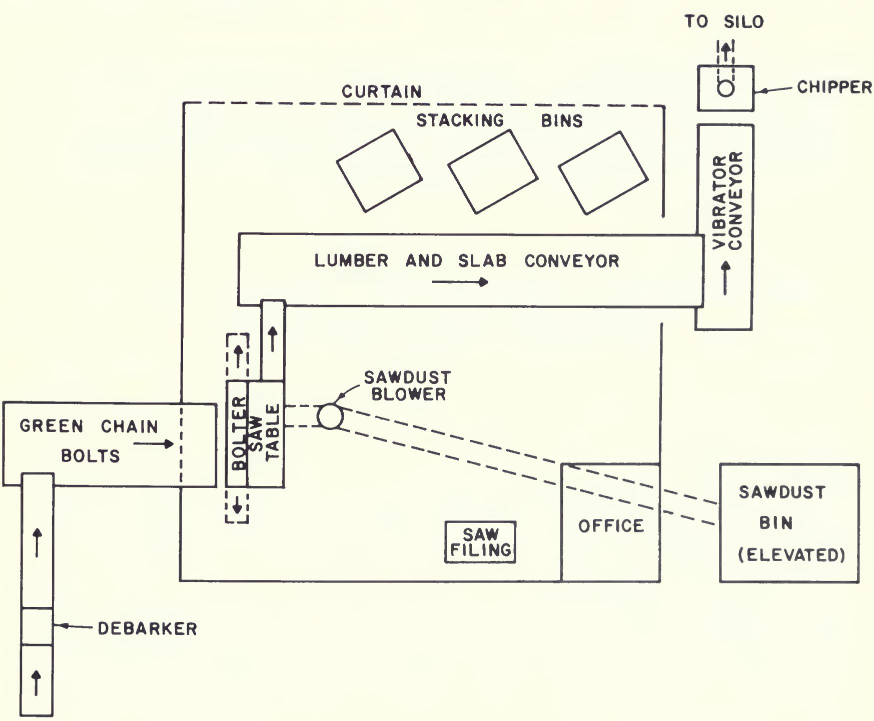


Figure 28-3.—(Top) Bolter with bottom circular saw in cut, and top saw available for use on larger bolts. See figure 18-123 top for a clearer view of a bolter saw. (Bottom) Plan layout of bolter mill at Marimont Furniture Co., Marion, N.C. (Photo and drawing from Smith 1981.)

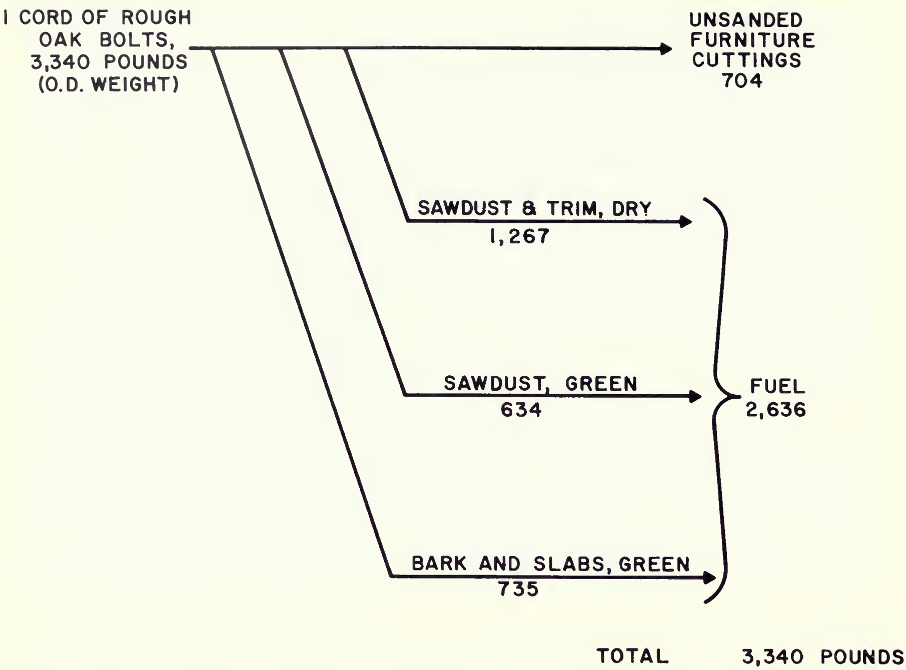


Figure 28-4.—Materials balance, ovendry-weight basis, for Marimont's bolter mill operation. Output averages about 7 Mbf of lumber per 8-hour shift. About 500 board feet of 5/4 lumber can be sawn from a cord of oak and hickory bolts, so daily wood usage is about 14 cords. The lumber is first air dried, then kiln dried, before delivery to the furniture plant for processing into cuttings. (Drawing after Smith 1981.)

28-5 $292,550—SMALL-SCALE PRODUCTION OF ETHANOL AND FURFURAL[6]

This projected enterprise for small-scale production of fuel and alcohol from pine-site hardwoods is owner-operated. The setting contemplated is in north Arkansas where a farmer owns 125 acres of oak, hickory, and sweetgum. He annually can harvest 250 tons of wood (ovendry basis) from his acreage and can also purchase additional tonnage from his neighbors paying a stumpage price of $15 per ton, ovendry basis.

The enterprise is projected to consume about 780 tons of wood (ovendry basis) annually to yield 19,500 gallons of 95-percent ethanol, 27,000 pounds of yeast, and 63,500 pounds of furfural. In the processing system, 64 percent of the wood feed is used to produce wood sugars by dilute acid hydrolysis (fig. 28-5 top). A continuous fermentation scheme is employed to convert hexose sugars to

[6]Abstracted from Karchesy (1981).

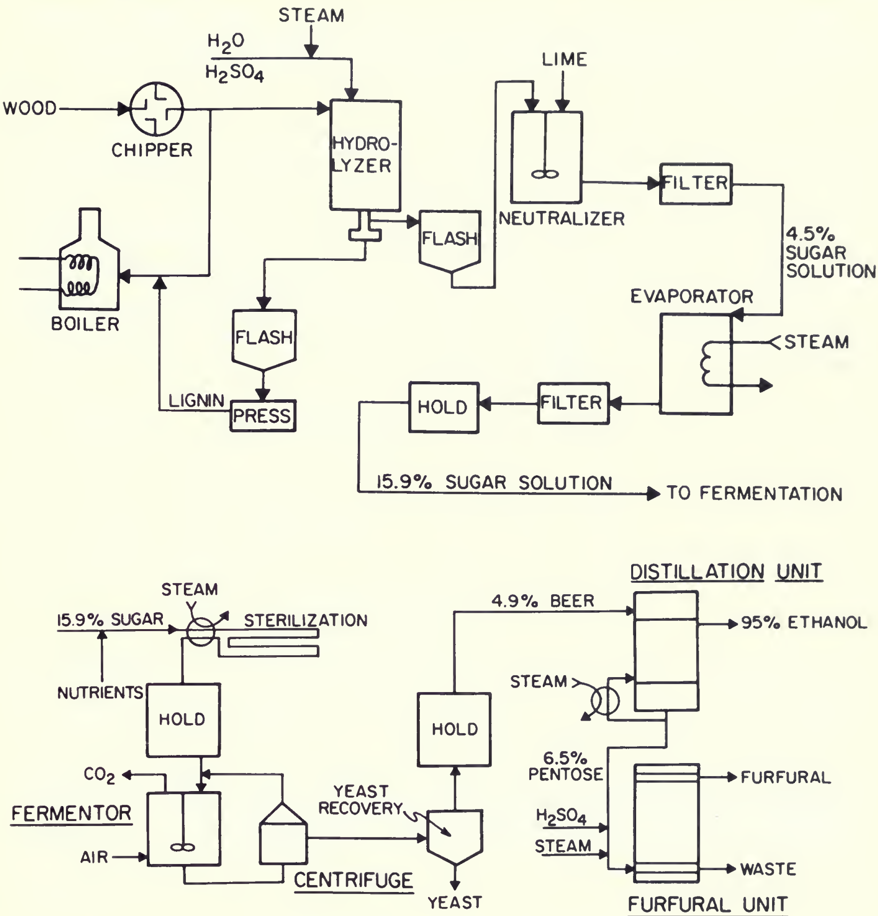


Figure 28-5.—(Top) Wood sugars production using dilute-acid hydrolysis. (Bottom) Processing wood sugars to ethanol, yeast, and furfural. (Drawings after Karchesy 1981.)

ethanol and pentose sugars are converted to furfural by acid catalyzed dehydration after ethanol recovery (fig. 28-5 bottom). Lignin residue from hydrolysis and 36 percent of the wood feed are burned to meet process steam requirements. Product yield per ton of hardwood chips is shown in figure 28-6. In order to obtain a 30 percent pretax return on investment, it is found necessary to sell ethanol produced for \$6.87/gallon. Projected sale price of furfural is \$0.55/pound and that of yeast \$0.25/pound.

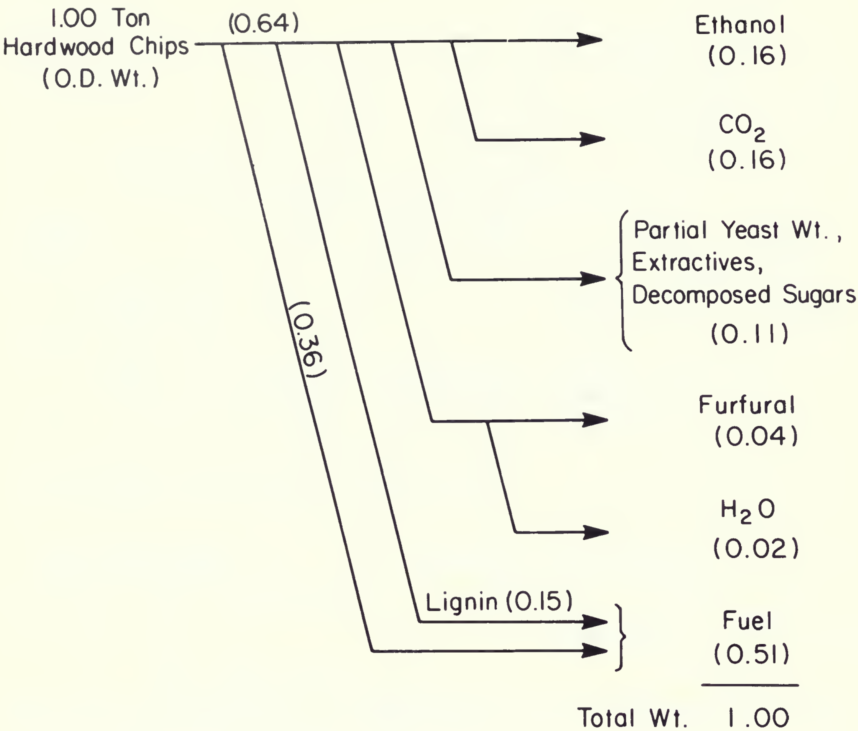


Figure 28-6.—Material balance for small-scale ethanol production based on ovendry weight of wood feed including bark. (Drawing after Karchesy 1981.)

Key statistics describing the enterprise are as follows:

Capital investment	$292,550
Operating cost, annual	$ 87,859
Sales, annual (ethanol at $6.87/gal)	$175,640
Net profit, annual (before income taxes)	$ 87,781
Return on sales	50 percent
Return on investment	30 percent
Employees	2½
Energy requirement, annual	
Electrical	4.90×10^4 kWh
Oil equivalent (of gasoline, oil, and gas)	1.25×10^3 gallons
Wood	2.53×10^9 Btu

Because the mill-gate market price of ethanol is about $1.65/gallon (1981), the small-scale production of ethanol and furfural from pine-site hardwoods appears economically unsound. Economic feasibility might be achieved if free waste steam was available from an existing adjacent industry, and if furfural was not produced so both hexose and pentose sugars could be converted to ethanol.

28-6 $350,000—WOOD GASIFIER RETROFITTED TO EXISTING GAS/OIL-FIRED BOILER[7]

The Georgia Forestry Commission, the Georgia Institute of Technology, and the Applied Engineering Company cooperated to retrofit a 19,000-pound/hour gas/oil burner at the Northwest Georgia Regional Hospital in Rome, Ga., with a 25-million-Btu/hour updraft wood gasification system fired with hardwood chips. The gasifier design (fig. 28-7) is described in section 26-4. Consumption of wood chips is projected to average 22,093 tons (green-weight basis) annually; the wood is converted with 85-percent thermal efficiency to gas having a heating value of 127 Btu/cu ft and constituents about as follows:

Constituent	Percent
Nitrogen	53.0
Oxygen/argon	2.4
Carbon dioxide	9.5
Carbon monoxide	25.0
Hydrogen	8.0
Methane	1.8
Other	.3
	100.0

Overall efficiency of the entire gasification system (fig. 28-7) is estimated at 70 percent. Computations by the authors indicate a yield of 5,500 to 6,500 pounds of gas from one ovendry ton of chips. Capital cost of the retrofit system was $350,000 with expected life of 20 years. With 7,000 operating hours annually, a wood cost of $15/green ton, and a net heat output of 6.02 million Btu/green ton of wood, cost comparisons with operation on No. 6 fuel oil (table 28-2) indicate annual savings of $272,095, indicating payback of the $350,000 investment in 1.3 years.

TABLE 28-2.—*Annual costs of retrofitted wood gasifier compared to existing system fired with No. 6 fuel oil* (Bulpitt et al. 1981)

Item	Retrofit wood gasifier	Existing gas/oil furnace
	Dollars	
Annual cost of capital	59,034[1]	0
Maintenance	10,500	2,250
Operating costs of labor and electricity	48,290	30,107
Fuel	331,395[2]	668,957[3]
Total annual cost	449,219	721,314

[1]Total investment in system, $350,000.
[2]Hardwood chips at $15/ton, green-weight basis.
[3]No. 6 fuel oil at $26/barrel.

[7]Abstracted from Bulpitt et al. (1981).

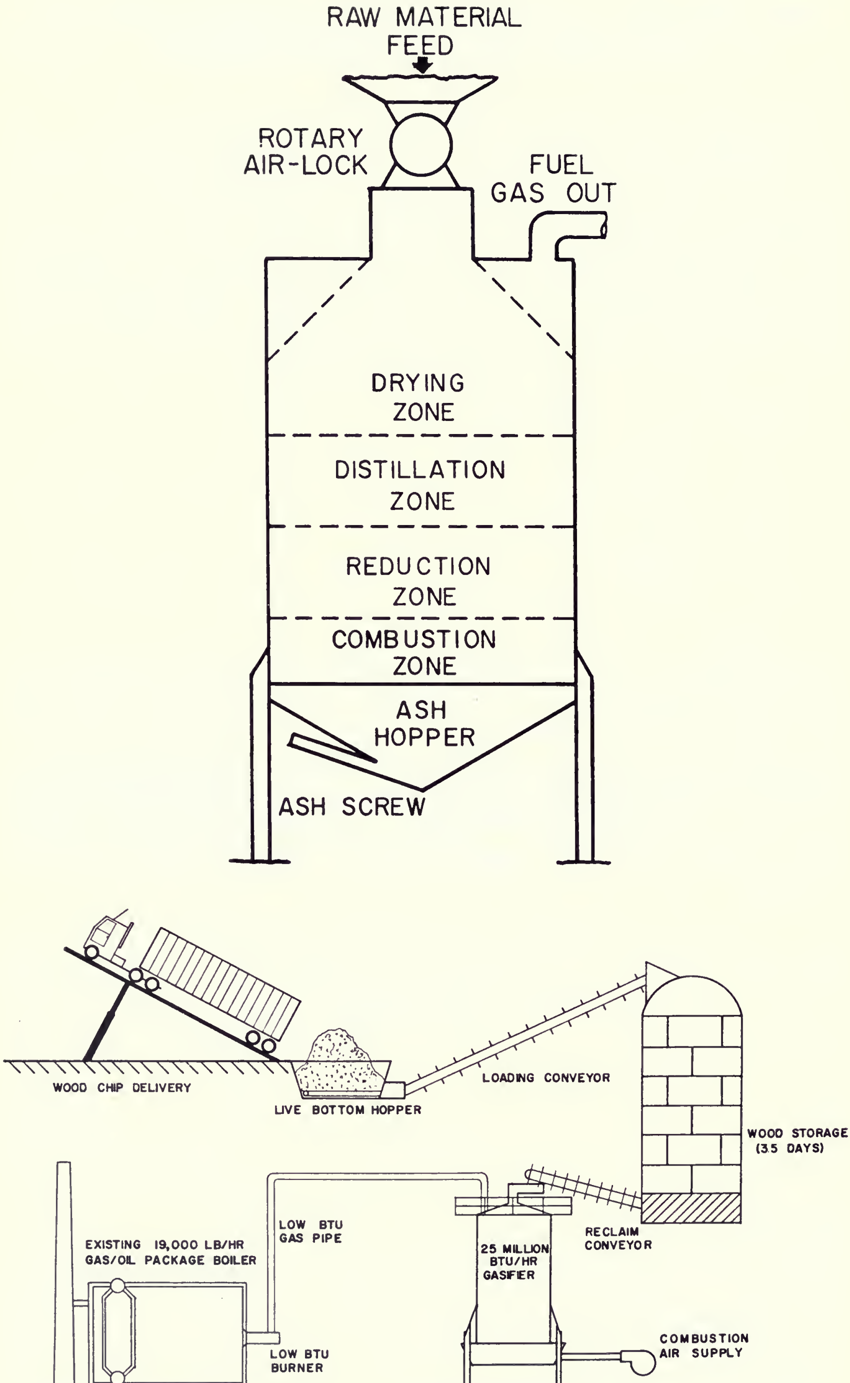


Figure 28-7.—Updraft gasifier (top) and overall system (bottom) retrofitted to an existing boiler at the Northwest Regional Hospital, Rome, Georgia. (Drawings after Bulpitt et al. 1981.)

28-7 $336,838—MODIFICATION OF CONVENTIONAL HARVESTING SYSTEMS TO RECOVER FOREST RESIDUES IN BALES[8]

In southern forest tracts with a significant component of hardwoods among merchantable southern pines, removal of essentially all above-ground biomass at time of harvest eases natural or artificial regeneration of desired species. The most successful systems to accomplish such removal have used in-woods whole-tree chippers. The major disadvantages of these whole-tree chipping systems are the large capital investment required, the logistical problems associated with moving the equipment, and the economic restriction to operation on large tracts only.

Baling of logging residues, in combination with the feller-bunchers and grapple skidders conventionally used by small-scale loggers, is an alternative that requires less capital, is more portable, and can operate on smaller tracts than whole-tree chipping systems. To test the concept a prototype baler was constructed to produce logging-residue bales about 3 by 3 by 3½ feet in size and weighing about 1,500 pounds (figs. 28-8 and 16-61).

To illustrate how the baler might be incorporated into a conventional longwood system, consider the following example.

First, assume that the conventional system without modification is a longwood system commonly found in the Piedmont and Upper Coastal Plain. The operation consists of a feller-buncher with accumulating shear which fells and piles material for chainsaw limbing and topping; the sawyers also fell and limb material too large for the feller-buncher. Movement to the landing is accomplished with two grapple skidders. At the landing the trees are separated by product type or tree size and loaded by a knuckleboom loader. Hauling is accomplished with two truck-tractors and four set-out trailers which allows the trucking function to be independent of the logging system production.

Now, modify this system to include the use of a residue baler. The limbing and topping function will be moved to the landing, but one sawyer will be left at the stump to fell oversize trees. The feller-buncher will fell and pile all remaining stems on the stand. Skidder productivity, measured in terms of conventional products, is expected to drop about 25 percent because of whole-tree skidding. Limbing and topping will take place at the landing and conventional products will be loaded as before. The logging residues left near the baler will be placed into the baler infeed by the loader for processing. As long as the infeed is charged, shearing, compaction, tying, and bale discharge functions will be automatic. As bales are produced, they will be stacked for re-loading when a truck load has been accumulated.

Performance of the conventional system was simulated on a 36-acre mixed pine-hardwood stand in the Upper Coastal Plain of the deep South. The stand

[8]Abstracted from Stuart et al. (1981).

Figure 28-8.—(Top) Inverted grapple designed to feed topwood into the baler. (Bottom) Sheared and baled branches emerging from the baler. (Photo from W. B. Stuart.) See also figure 16-61.

contained 250 merchantable trees per acre, about 28.5 cords of pine pulpwood and slightly over 5 cords of hardwood pulpwood. The projected costs and revenues of this sytem are presented in table 28-3.

TABLE 28-3.—*Costs and revenues of conventional and modified (to incorporate residue baling) harvesting of 36-acre pine-hardwood stand* (Stuart et al. 1981)

Item	Conventional	Modified to incorporate baler
	Dollars	
Costs		
Stumpage costs	15,479	17,290
Harvesing costs	11,965	21,660
Hauling costs	8,269	12,742
Total costs	35,713	51,692
Revenues		
Pulpwood (1,216 cords)	41,538	41,538
Residue	—	17,481[1]
Total revenues	41,538	59,019
Profit	5,825	7,327

[1]1,811 tons, green-weight basis.

Next, yield by the system modified to incorporate the baler was simulated on this same stand. An additional yield of about 50 tons per acre, or about 18 cords, of residues from limbs, tops, and non-merchantable trees could be removed. The projected costs and revenues of the modified system are also presented in table 28-3.

Capitalization for the system modified to incorporate the baler increased investment from $266,838 to $336,838 under the assumption that the baler would cost about $70,000 (table 28-4). With revenue from residue at $9.65/ton (green-weight basis), profit in the system incorporating the bales was $7,327 compared to $5,825 for the conventional system. Based on projected annual production of the baler (11,404 tons) the authors[8] conclude that a residue sales price for the baled wood need be only $6.14 per ton, green-weight basis, to yield a 30-percent pre-tax profit on the additional investment required for the baler. Additionally the land owner benefits from having the tract free of residue and ready for regeneration.

TABLE 28-4.—*Capitalization of conventional and modified (to incorporate residue baling) harvesting system* (Stuart et al. 1981)[1]

Equipment	Conventional	Modified to incorporate baler
	-------------*Dollars*-------------	
Feller-buncher, Bobcat 1075	39,000	39,000
Two grapple skidders, JD 540	90,082	90,082
Loader, Prentice 210	31,500	31,500
Residue baler	—	70,000
Two tractors, Fleetstar 2070A	70,000	70,000
Four longwood trailers, Chancey	36,256	36,256
Total	266,838	336,838

[1]1979 costs.

28-8 $474,000—SMALL-SCALE PRODUCTION OF RECTANGULAR BLANKS (OVERSIZE PARTS) FOR USE BY FURNITURE PLANTS AND INDUSTRY[9]

The proposed enterprise is a small furniture dimension plant using low-grade hardwood lumber to produce solid and glued-up panel stock in unfinished dimension. The economic analysis is based on purchased No. 2 Common lumber sawn from ash, sweetgum, red maple, red oaks, and yellow-poplar. By adding a bolter saw and subsidiary equipment, the operation could be based on short logs and bolts.

The proposed plant uses conventional machinery for a dimension plant, with wood and solar-heat assisted dehumidification dry kilns. Average lumber drying time is calculated at 21 days, allowing purchase of fresh sawn lumber from local sawmills. The product is typical of sizes used for kitchen cabinet stock. The "Optimum Furniture Cutting Computer Program"[10] was used in yield and cost calculations and it is anticipated this system will be used in preparing price quotes.

The plant is designed to consume 8 Mbf of lumber per day (single shift) with minimium of 50-percent yield of parts. Key statistics for the enterprise are as follows:

[9]Abstracted from Huber et al. (1981).
[10]Available from H. A. Huber, Forestry Dept., Michigan State University, East Lansing.

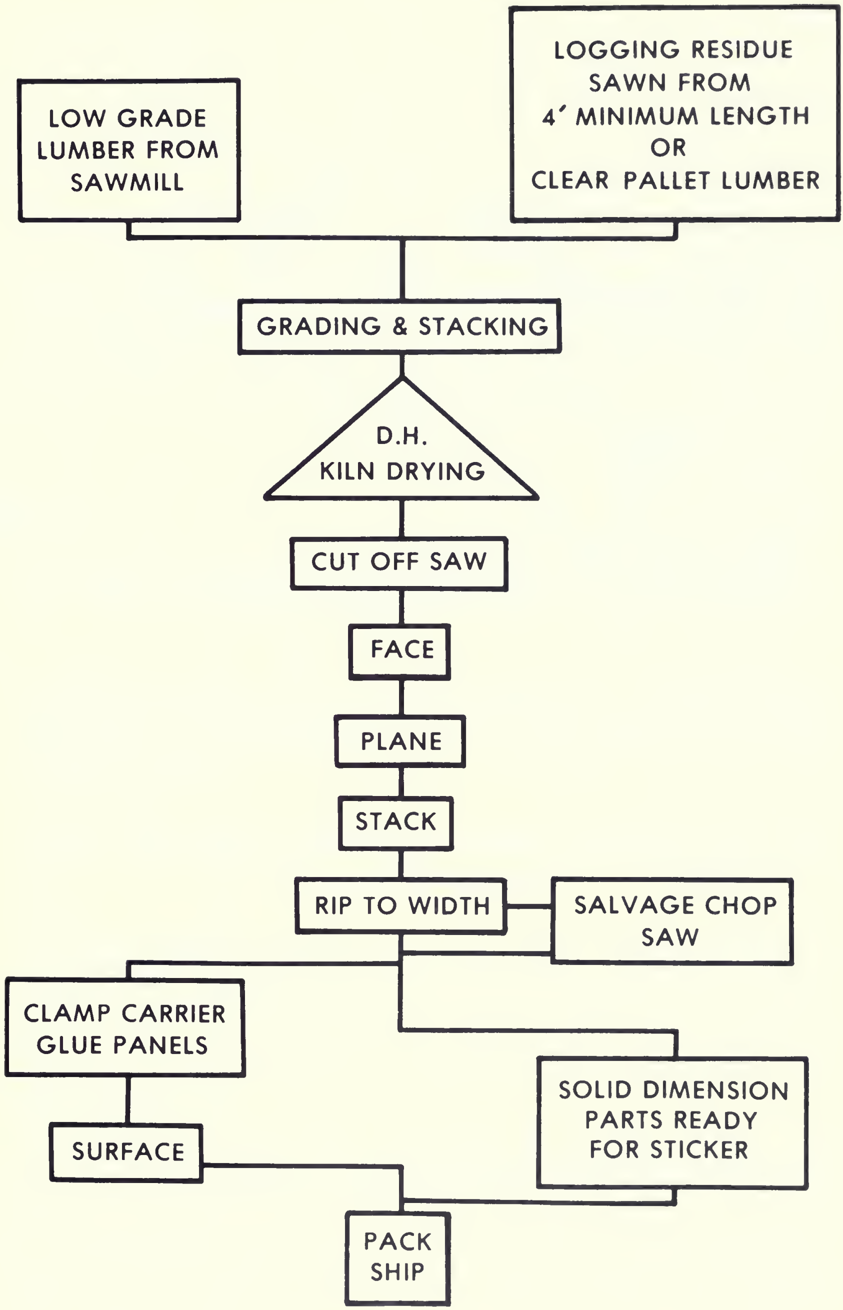


Figure 28-9.—Operation flow chart. (Drawing after Huber et al. 1981.)

Capital investment, not including $26,000 of working capital	$474,000
Operating cost, annual	$710,000
Sales, annual	$976,000
Net profit, annual (before income taxes)	$266,000
Return on sales	27 percent
Return on investment	56 percent
Employees	13
Energy requirement	
Electrical	1,623 kWh/day
Oil equivalent (of gasoline, oil, or gas)	15 gal/day
Wood residue, burned or sold	16 million Btu/hr

Average cost of the 8 Mbf of No. 2 Common lumber consumed daily in the plant is estimated at $200/Mbf and sale price of the 4 Mbf of rectangular blanks marketed daily is estimated at $1,200/Mbf. Material flow is diagrammed in figure 28-9 and plant plan view in figure 28-10.

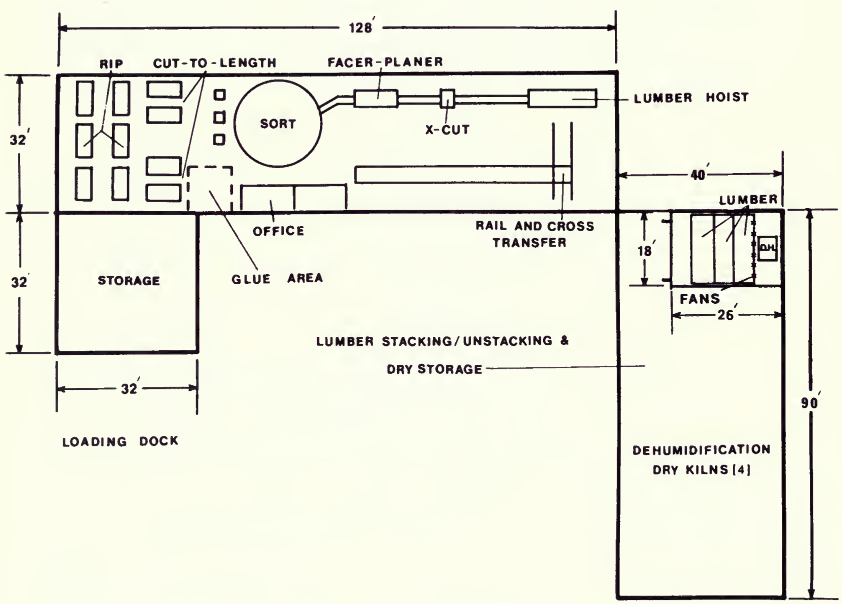


Figure 28-10.—Plant layout. (Drawing after Huber et al. 1981.)

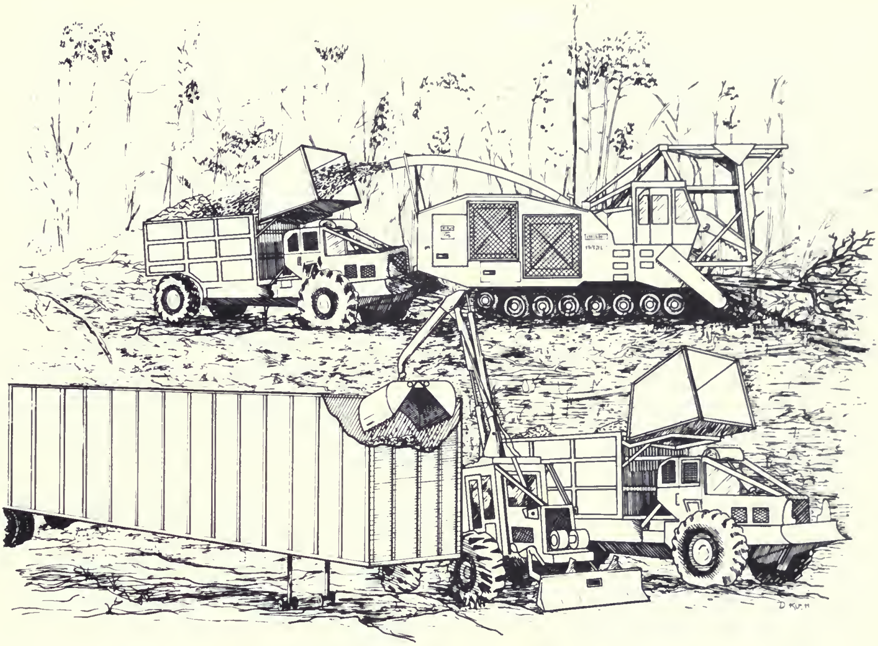


Figure 28-11.—Swathe-felling mobile chipper teamed with two forwarders and equipment to load chips in transport trucks; 1982 configuration for commercial fields trials. See further discussion in text related to figures 16-49 through 16-53. (Drawing from files of D. Sirois.)

28-9 $603,000 to $975,000—CHIP HARVESTING BY THREE SYSTEMS[11]

Three methods of clear-felling and whole-tree chipping pine-site hardwoods include conventional whole-tree chipping with feller buncher and grapple skidder (fig. 16-18), cable yarding with chainsaw felling and whole-tree chipping (fig. 16-45), and harvesting with a swathe-felling mobile chipper (figs. 28-11 and 16-52).

Each method yields whole-tree green chips at roadside; production costs (1980 basis) of such chips are estimated to range from $9.42 to $22.75 per ton with a 15 percent cost of capital. Costs are $12.01 to $29.12 per ton if a 30 percent return on investment is included. Initial equipment costs are $603,000 for a swathe-felling mobile chipper, $663,000 for a conventional whole-tree chipper, and $975,000 for a cable logging-chipper system. Annual operating costs including depreciation, fuel, labor, and interest are $426,499 for the mobile chipper, $474,607 for the conventional system, and $694,529 for the cable system. Costs cannot be compared directly because all harvesting methods would not normally operate on similar types of stands. The cable yarding system

[11]Abstracted from Vasievich and Croll (1981).

is best adapted to steep slopes and yields from 20 to 25 tons per operating hour. The swathe-felling mobile chipper operates best on stone-free level ground and can produce 12.5 to 20 tons per hour. The conventional system averages 25 to 30 tons per hour on flat to moderate slopes. Productivity depends on stand conditions such as tree size, volume per acre, and tract size. Whole-tree chipping, and particularly the swathe-felling mobile chipper, leaves the site very clean and substantial site preparation savings can result. Continuing commercial field trials of the mobile chipper should engender design improvements and increased productivity.

Key comparative statistics for the three systems are as follows (1980 basis):

Statistic	Conventional whole-tree chipper	Cable-yarder chipper	Swathe-felling mobile chipper
Initial capital investment, dollars	663,000	975,000	603,000
Annual production, tons/year (green-weight basis)			
High	50,400	42,000	30,000
Low	42,000	33,600	18,750
Employees number	8.5	15	6.5
Fuel consumption, gallons/year	63,950	110,468	50,423
Total annual costs, dollars/year (with 15 percent cost of capital)	474,607	694,529	426,499
Production cost, dollars/ton			
High	11.30	20.67	22.75
Low	9.42	16.54	14.21
Total annual costs, dollars/year (with 30 percent return on investment)	528,245	777,085	474,608
Production cost, dollars/ton			
High	14.14	26.50	29.12
Low	12.01	21.20	18.20

28-10 $700,000—MANUFACTURE OF CHARCOAL, OIL, AND GAS WITH A PORTABLE PYROLYSIS PLANT[12]

The Enerco™ model 24-D pyrolysis unit (fig. 28-12), in which hot pyrolytic gases are recirculated through the reactor—sometimes termed converter, was mounted on a 35-foot trailer and operated for 200 hours by the Tennessee Valley Authority to obtain data for commercial operations. Air, with its nitrogen, is kept out of the system to diminish nitrous oxides and other nitrogenous material in resulting pyrolysis gas and oil, thereby reducing their corrosiveness. Moisture content of wood chips entering the converter should not exceed 20 percent (wet-weight basis).

[12]Abstracted from Klein (1981).

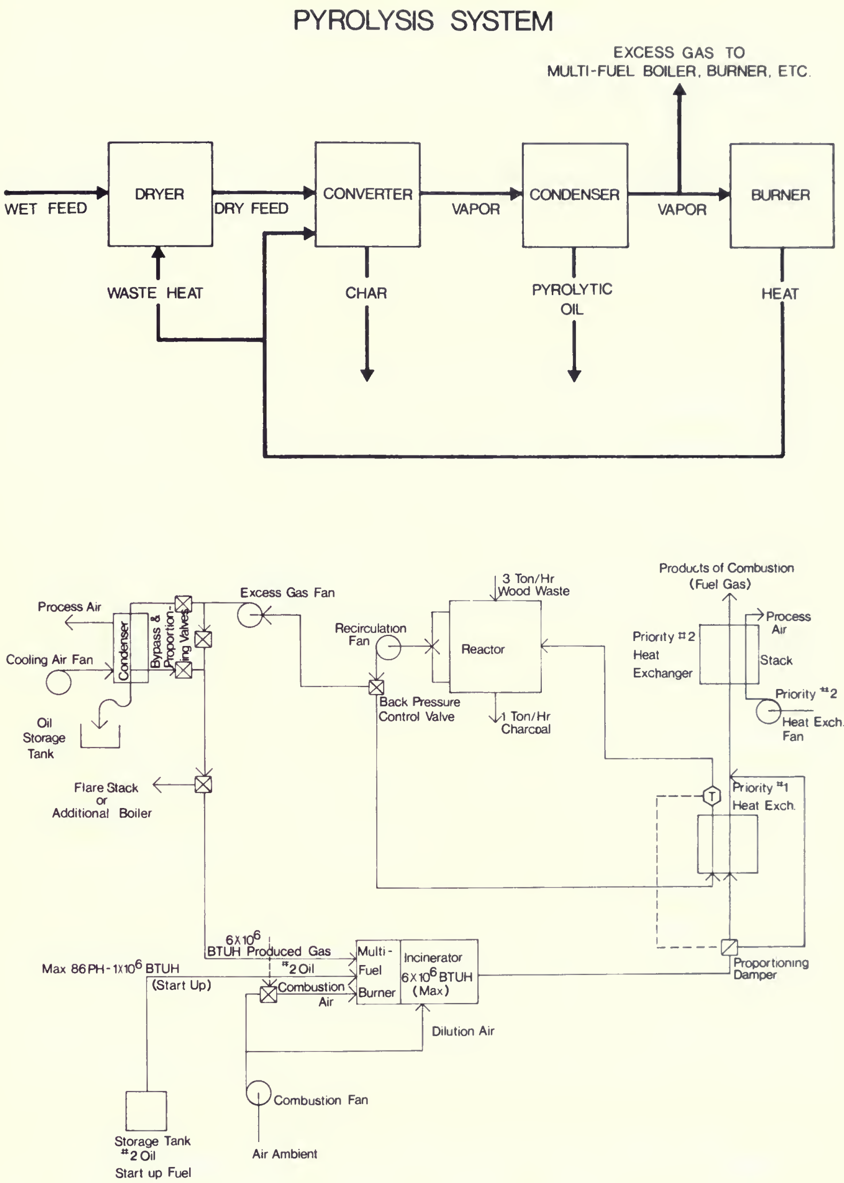


Figure 28-12.—(Top) Simplified flow diagram for the pyrolysis system of Enerco, Inc., Langhorne, Penn. (Bottom) More detailed flow diagram for the Enerco 24-D pyrolyzer. (Drawing after Klein 1981.)

The unit evaluated is designed for a flow-through rate of 3 tons of wood per hour (ovendry basis). This 3 tons of wood contains about 51 million Btu; output is about 43.3 million Btu/hour for an efficiency of about 85 percent, with products as follows:

Pyrolysis product and energy content (Btu/pound)	Weight output	Energy output
	Pounds/hour	*million Btu/hour*
Charcoal (12,834)	2,000	25.7
Oil (9,573)	1,000	9.6
Gas (4,000)	2,000	8.0
Total	5,000	43.3

In analyzing economic feasibility of the operation, cost of delivered hardwood chips was estimated at $12/green ton for wood averaging 40 percent moisture content (wet-weight basis). Annual wood consumption was projected to be 21,000 tons (ovendry basis) or 35,000 tons on a green-weight basis. Charcoal production was estimated at 7,000 tons/year with sales price of $80/ton less $5/ton transport cost for delivery to the user. Annual production of pyrolysis oil and gas was estimated at 100 billion Btu, with sales price of $3.50/million Btu.

Key statistics projected for the enterprise are as follows:

Capital investment	$700,000
Operating cost, annual	$680,000
Sales, annual	$910,000
Net profit, annual (before income tax)	$230,000
Return on sales	25 percent
Return on investment	33 percent
Employees	7
Energy requirement, annual	
Electrical	150,000 kWh
Oil (for system start-up)	3,500 gal
Wood	357 x 10^9 Btu

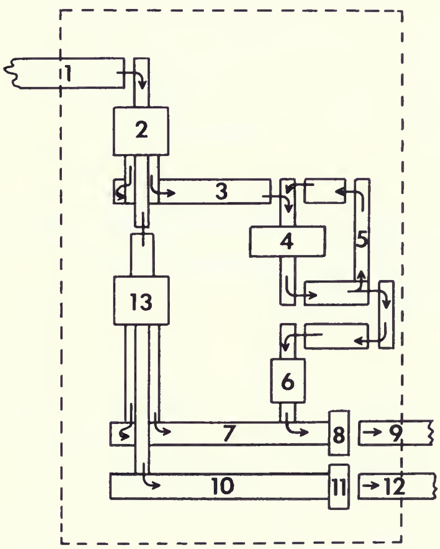
Klein (1981) points to potentially great expansion of demand for charcoal and pyrolytic oil as non-polluting extenders for blending with high-nitrogen and high-sulfur coals to reduce their stack pollutant concentration. Best prospects for use of the low-Btu gas from the process are at heating or energy installations where it can be burned efficiently while still hot from the pyrolyzer.

28-11 $718,038—SHORT-LOG PROCESS FOR PRODUCING PALLET PARTS AND PULP CHIPS[13]

The projected single-shift, 240-day/year operation requires a daily input of 38 cords of hardwood bolts 52 inches long and 5.5 to 11.5 inches in diameter. From each cord, about 525 board feet of pallet parts are produced in a mill equipped with a two-saw skrag mill (figs. 18-119 and 28-13 top) and resaws. The operation, producing 20 Mbf daily of 40-inch-long deckboards cut 3¾ or 5¾ inches

[13]Abstracted from Hansen and Reynolds (1981).

wide and ¾-inch thick, and stringers 48 inches long and 1¾ inches by 3¾ inches, is located immediately adjacent to an existing pallet assembly plant so that pallet parts are transported directly by conveyor from one plant to the other. About 43 percent of the cordwood weight is converted to pallet parts, 38 percent to pulp chips, and 19 percent to sawdust (fig. 28-13 bottom). Cost of wood is estimated at $37.50/cord delivered to the mill. Sales price of the pallet parts is estimated at $170/Mbf and that of pulp chips at $13/ton, green-weight basis. No sales value is assigned the 4,800 tons of sawdust, green-weight basis, produced annually.



1 LOG DECK
2 SCRAGG HEADRIG
3 SLAB CONVEYOR
4 RESAW
5 SLAB RETURN
6 EDGER
7 DECK BOARD CONVEYOR
8 TRIMMER – 40″
9 CHAIN CONVEYOR TO MILL
10 STRINGER CONVEYOR
11 TRIMMER – 48″
12 CHAIN CONVEYOR TO MILL
13 CANT RESAW

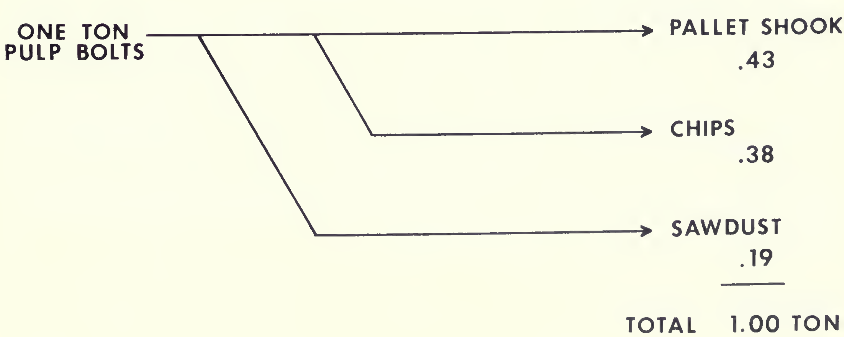


Figure 28-13.—(Top) Plant layout for manufacture of pallet parts. Not shown is a cutoff saw on the input log deck. (Bottom) Material balance for pallet-part manufacture based on ovendry weight of cordwood including bark. Both pulp chips and sawdust include some bark. (Drawings after Hansen and Reynolds 1981.)

Key statistics for the projected enterprise are as follows:

Capital investment	$718,038
Operating cost, annual	$669,792
Sales, annual	$940,800
Net profit, annual (before income tax)	$271,008
Return on sales	28.8 percent
Return on investment	37.7 percent
Employees	8 or 9
Energy requirements, annual	
Electrical	420,000 kWh
Diesel fuel	Sufficient for one front-end loader

Important to the economic efficiency of this enterprise is its location adjacent to an existing pallet assembly plant, allowing both plants to work entirely with green wood, which not only facilitates nailing, but avoids the need for drying in stacks or kilns. It also essentially eliminates costs of sales, inventories of raw materials or product, and degrade of parts during storage or shipment.

28-12 $775,000—SAWMILL, KILN, AND PLANING MILL TO PRODUCE YELLOW-POPLAR LUMBER FOR FRAMING BUILDINGS[14]

In this proposed operation, a small hardwood sawmill is purchased and converted for sawing of yellow-poplar framing lumber, or a mill is built and equipped with used machinery to minmize investment (fig. 28-14 top). Proposed is a circular-headrig mill, with debarker, live deck, log turner, trimmer, and a double-arbor edger. Additional facilities would include a dry kiln, dry ripping, surfacing, and end trimming equipment. Output of such a mill could largely be absorbed by local markets. Raw material for the operation is 8- to 13-inch-diameter grade 3, yellow-poplar logs. The mill cuts about 12 Mbf of logs, Doyle scale, per day, producing 20 Mbf of 2- by 4- and 2- by 6-inch framing lumber. Based on 250 single-shift working days per year, annual log input is 3 million board feet log scale and lumber production is five million board feet. From each ton of logs (ovendry-weight basis), lumber yield is about 0.34 ton, chips and shavings 0.45 ton, and bark and sawdust 0.21 ton (fig. 28-14 bottom).

Log cost at this eastern Tennessee mill is projected to average $88/Mbf Doyle scale. Average sale price of the kiln-dried framing lumber is $204/Mbf fob mill. Chips and shavings are sold at $10/ton fob mill and sawdust at $5/ton fob mill to yield daily revenue from residues of $495.

[14]Abstracted from Stumbo (1981b).

Key statistics for the proposed enterprise are as follows:

Capital investment	$775,000
Operating costs, annual	$750,250
Sales, annual	$1,143,750
Net profit, annual (before income tax)	$393,500
Return on sales	34 percent
Return on investment	51 percent
Employees	20

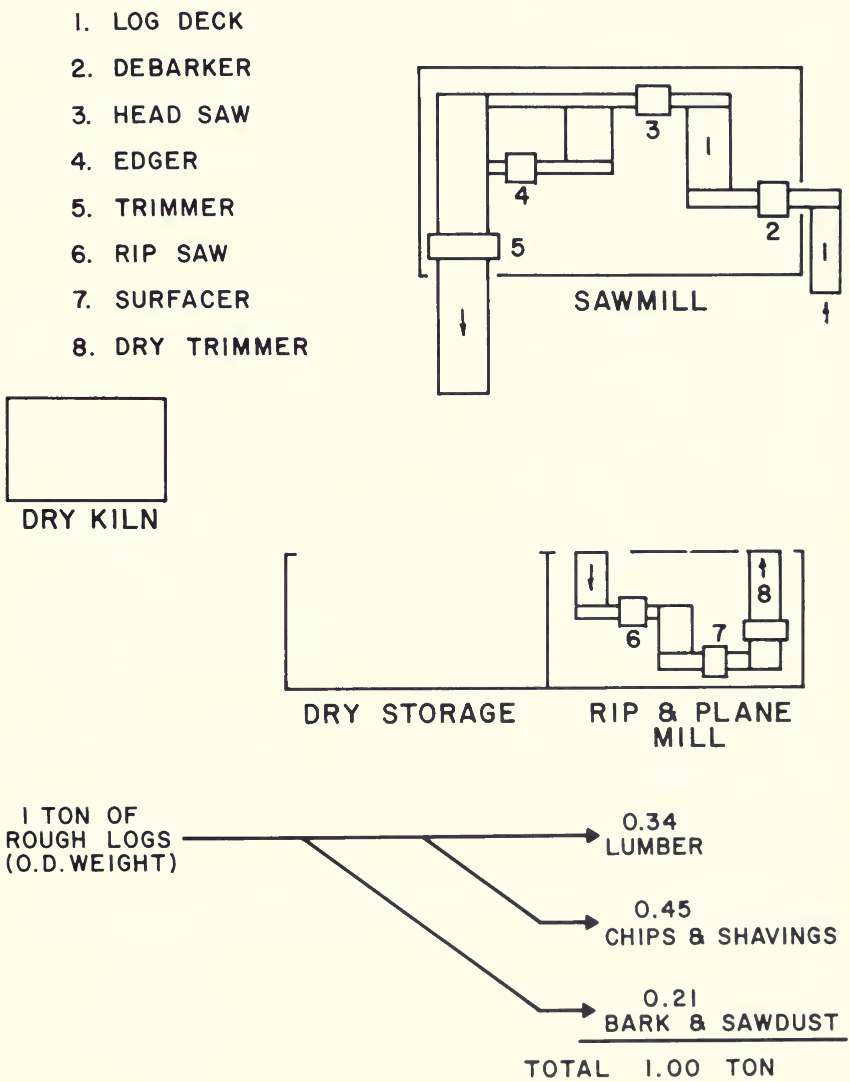


Figure 28-14.—(Top) Layout of mill designed to produce 20,000 board feet of kiln-dry yellow-poplar framing lumber daily. (Bottom) Material balance for manufacture of yellow-poplar framing lumber, based on ovendry weight of logs (including bark), and products. (Drawings after Stumbo 1981b.)

28-13 $937,000—SYSTEM-6 PRODUCTION OF STANDARD-SIZE BLANKS FOR THE FURNITURE INDUSTRY[15]

The raw material feeding this proposed operation is hardwood cants, purchased from sawmills at a price of $200/Mbf lumber scale. Sawmillers produce the cants from bolts 75 inches long selected to have no more than 1½ inches of sweep and with small-end diameters of 7.6 to 12.5 inches. These bolts are sawn at the sawmill into two-sided cants 3 or 4 inches thick by slabbing to at least a 3-inch face, turning the bolt 180°, offsetting by the width of two cants plus one kerf, slabbing again, and finally sawing through the center of the bolt.

The proposed operation converts these cants into standard-size blanks (table 27-115). A standard blank is a piece of solid wood which may be of edge-glued construction and is of specified size and quality. They are 13 to 100 inches long and 20 to 26 inches wide. These are sold to furniture manufacturers at an average price of $1.76/sq ft of blanks, 4/4 basis.

In the proposed operation, cants are processed (fig. 28-15 top) into boards in a single pass through a gang resaw. Boards from the resaw are immediately stacked for air-drying with ½-inch-thick sticks on 24-inch centers separating courses; to prevent twisting of boards in top courses, 4-inch-thick concrete top weights are placed on each stack. After forced-air predrying to 20-percent moisture content, the stacked lumber is moved to an adjacent independent operation where it is kiln-dried to 6-percent moisture content at a contract price and returned for remanufacture.

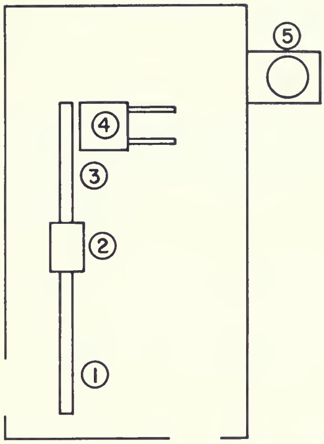
The kiln-dry boards are processed to blanks in five machining steps (fig. 28-15 bottom), i.e., they are rough planed, gang crosscut, gang ripped, cut-to-length, and, if necessary, salvage ripped. Following any desired matching of grain and color, the pieces are edge glued into standard blanks of specified size. (See table 27-115 for standard sizes and page 1960 for additional procedural details.)

Annual requirement for cants totals 1,407 Mbf, lumber scale, for single-shift operation 225 days/year. Annual production of standard blanks is 703,125 square feet. With resaw production per shift of 6.25 Mbf of lumber, about 3,125 square feet of blanks (520 of them) will be made per shift for a yield of about 50 percent from the lumber.

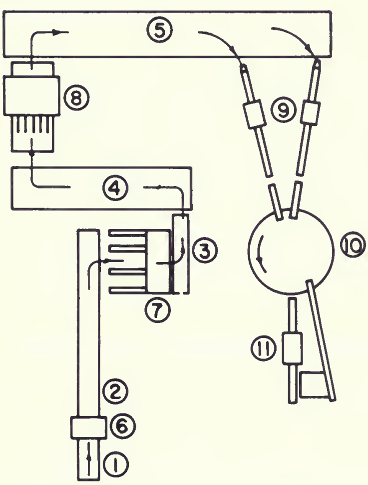
Key statistics for the proposed enterprise are as follows:

Capital investment	$937,000
Operating costs, annual	$929,900
Sales, annual	$1,237,500
Net profit, annual (before income taxes)	$307,600
Return on sales	24.9 percent
Return on investment	32.8 percent
Employees	20
Energy requirement, daily	
Electrical	1,000 kWh/day
Oil equivalent (gasoline, oil, and gas)	20 gallons/day
Wood (ovendry basis)	1.7 tons/day

[15]Abstracted from Gatchell and Reynolds (1981).



MINI-MILL MACHINERY		COST
1	CANT CONVEYOR	$ 14,000
2	CANT RESAW (150 HP)	18,800
3	BOARD CONVEYOR	11,300
4	STACKER	6,900
5	HOG AND SCREEN	31,000
NOT SHOWN:		
	4000-LB FORKLIFT	9,000
	IN-FLOOR SAWDUST/ SLAB CONVEYOR	19,000
	TOTAL	$ 110,000



MINI-MILL MACHINERY		COST
1-2-3	CONVEYORS	$ 25,000
4-5	CROSS CONVEYORS	30,000
6	TWO-SIDE PLANER	62,500
7	GANG CROSSCUT SAW	50,000
8	GANG RIPSAW	70,000
9	CUT TO LENGTH AND DEFECT SAWS (2)	37,500
10	SORTING TURNTABLE	10,000
11	SALVAGE RIPSAW	20,000
NOT SHOWN:		
	WASTE CONVEYOR	22,000
	SAWDUST COLLECTOR	52,500
	TOTAL	$ 379,500

Figure 28-15.—Plan views of cant resawing plant (top), and operation for remanufacturing boards into pieces (bottom), with tabulation of estimated machinery costs. (Drawings after Gatchell and Reynolds 1981.)

28-14 $1.0 MILLION—MANUFACTURE OF WOOD-FOAM COMPOSITES[16]

Wood-foam composites, **xylofoam,** are mixtures of specially comminuted wood particles and foams, in which the foam is both bonding agent and binder. (see sect. 24-24 and fig. 24-63 for discussion of properties and illustration of products.)

Briefly, the wood particles are produced primarily by cleavage action on preferably green wood (fig. 18-285), screened for oversize and undersize, dried, and reclassified by air into the size range dictated by the dimensions of the product. A loose mat is formed on a moving belt. Manufacturing sequence is then as follows:

1. The mat arrives from the former to the head end of a press at 60 feet/minute, riding on its backing material or release paper.
2. Foaming resin is sprayed continuously over the top of the mat as it moves forward.
3. The top facing material or release sheet is kissed to the mat as it passes under a film control roll.
4. The composite sandwich enters the press with foam on the rise. At this point the xylofoam is carrying a cost of 15 cents/pound. Except for the allocated cost of the pressing operation, most of the additional costs are dictated by facing materials, further treatment of the products, and density.
5. With a belt press 60 feet long, and 4 feet wide, product emerges at a rate of 60 feet per minute. Production rate therefore is (assuming no down time) 240 square feet/minute or 115,200 square feet/8-hour day.

Laboratory experience (no production experience is available) suggests that this output may be profitably converted to three products.

In the manufacture of an automobile, 20 to 50 square feet of **headliners** are used for ceilings, package decks, glove compartments, and other interior structures. Usually covered with a fabric, plastic film, flocking, or paper, they form the base for many of the decorative elements in a car. Key product data follow:

Weight: 0.121 pound/square foot
Thickness: 0.150 inch
Density: 10 pounds/cubic foot
Sales price: $0.05/square foot

Interior decorative panels, half-inch as well as quarter-inch thick, of relatively light weight would find immediate use in mobile homes and recreational vehicles where weight is a major problem. They would compete with lauan and other plywoods, as well as pulp-based fiber products which are either heavy or costly. Key product data follow:

[16]Abstracted from Marra (1981).

Dimensions: 4 feet x 8 feet x 0.5 inches
Density 15 pounds/cubic foot
Overlay: Grained film
Sales price: $0.20/square foot

Thick **structural panels** can be offered in large sizes as well as the 4- by 8-foot sheets usual for the industry. With product data as follows, panel insulating and structural properties are well suited to simplified post and beam construction of buildings:

Dimensions: 4 feet x 8 feet x 4 inches
Core density: 12 pounds/cubic foot
Faces: ¼-inch strandboard (fig. 24-2)
Sales price: $1.00/square foot

Some key daily single-shift statistics for a proposed plant to manufacture these three products follow:

Statistic	Headliners	Interior decorative panels	Thick Structural panels
		Dollars/day	
Total materials cost	2,070	19,900	93,630
Operating cost	1,650	1,650	1,650
Total cost	3,720	21,550	95,280
Sales revenue	5,760	23,040	115,000
Return over costs	2,040	1,490	19,720

To compute operating cost, exclusive of materials cost, it was assumed that the plant machinery could be purchased and installed for $1,000,000, but that land and buildings would be rented. The proposed plant is operated by seven men, including the plant manager.

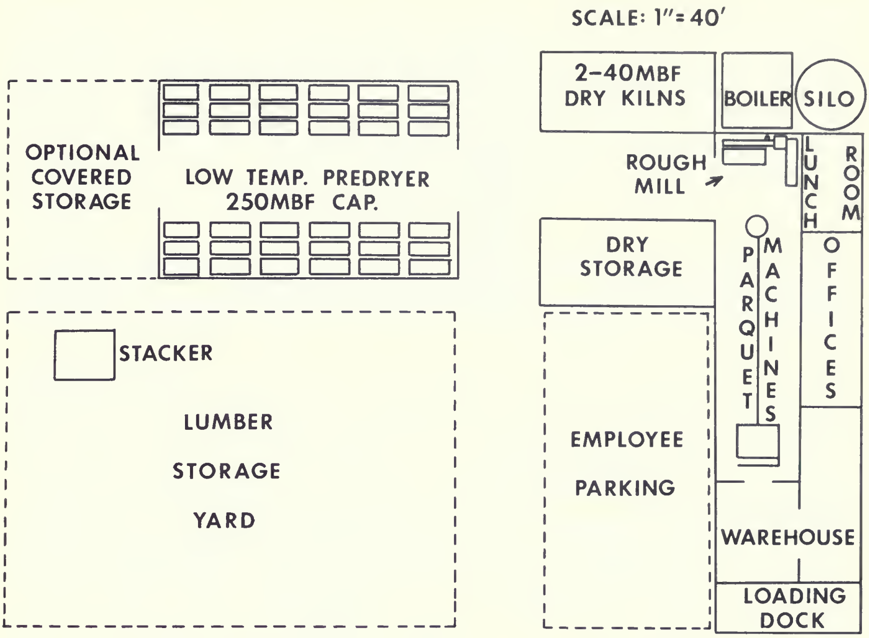
28-15 $1.7 MILLION—MANUFACTURE OF PARQUET FLOORING[17]

Hardwood parquet flooring (fig. 28-16) can be profitably manufactured to serve a substantial market (see also sect. 22-3 and fig. 22-10). Made predominantly from low-grade oak lumber, it uses clear pieces as short as 6 inches long. The highly mechanized process crosscuts, planes, and rips boards automatically into strips, called fingers, less than an inch wide by 5/16-inch thick. After the fingers are graded, they are assembled semi-automatically into the normal mosaic pattern and bonded together with a backing material. A plant (fig. 28-17) employing 36 people with one line operating two shifts daily can be expected to earn a return on investment before taxes of better than 30 percent. Key statistics for the proposed enterprise are as follows:

[17]Abstracted from Martens and Hansen (1981).

Figure 28-16.—Mosaic parquet oak flooring 5/16-inch thick. Each group of five 9⅜-inch-long strips is assembled on a web bonded to the back of the square. (Photo from Martens and Hansen 1981.)

Capital investment	$1,729,305
Operating cost, annual	$1,510,737
Sales, annual	$2,098,200
Net profit, annual (before income tax)	$ 587,463
Return on sales	28.0 percent
Return on investment	34.0 percent
Employees	36
Energy requirement, annual	
Electrical	561,733 kWh
Oil equivalent (gasoline, oil, and gas)	1,000 gallons
Wood residue	2,500 tons
Wood requirement, annual (ovendry basis including bark)	4,970 tons



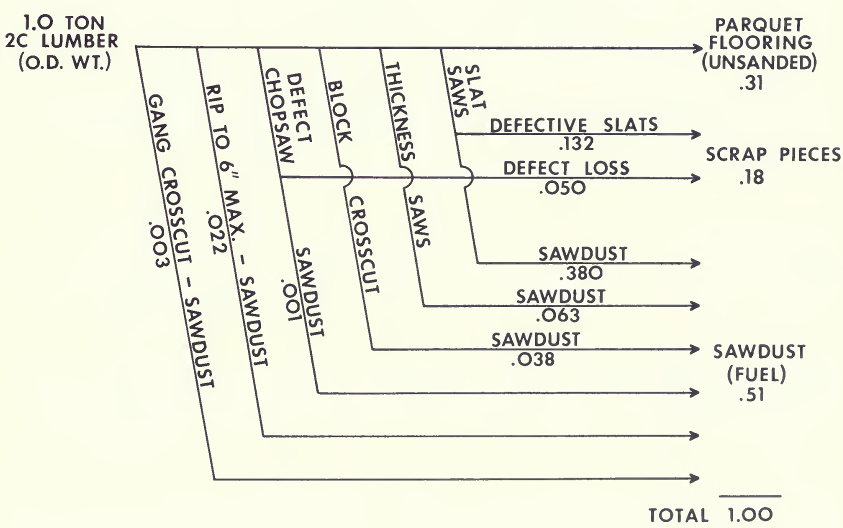


Figure 28-17.—(Top) Plant layout for manufacture of parquet flooring. (Bottom) Materials balance for manufacture of unsanded parquet flooring from No. 2 Common red oak lumber, ovendry-weight basis. (Drawings after Martens and Hansen 1981.)

In the proposed operation, 3300 Mbf of rough, green, random-width and length No. 2 Common 4/4 red oak lumber is purchased annually at a delivered price of $210/Mbf. Each Mbf of lumber yields about 1,000 square feet of parquet flooring 5/16-inch thick and 9⅜ inches square (fig. 28-16). About 31 percent of the lumber weight is converted to parquet squares (fig. 28-17 bottom), which sell—unfinished—for $0.65/square foot.

28-16 $3.2 MILLION—MANUFACTURE OF PARALLEL-LAMINATED VENEER FOR FURNITURE FRAME STOCK[18]

The increasing cost of hardwood lumber makes alternative materials attractive to furniture manufacturers. One such material which appears to lower the cost of producing furniture parts is hardwood laminated-veneer-lumber (LVL). LVL panels could be produced in a facility similar to a softwood plywood plant. Alternative panel configurations would be targeted for specific furniture applications, based on the extent to which the surfaces and edges of particular furniture parts are exposed (visible) in the furniture. See figure 22-16 for illustration of furniture frame stock and section 22-5 for additional data on properties of LVL frame stock. In addition to cost savings to the furniture manufacturer, LVL offers increased structural reliability because of its more uniform properties. A mix of red oak panels for exposed and unexposed applications appears to offer an LVL manufacturer the best opportunity to maximize the value added to the mix of high and low quality log input. The LVL plant should be located in an area capable of supplying about 4.2 million board feet of veneer-quality and 9.7 million board feet of sawlog-quality red oak and yellow-poplar logs per year. Key statistics for the proposed enterprise are as follows:

Capital investment	$3,162,000
Operating cost, annual	$6,570,600
Sales, annual	$7,200,000
Net profit, annual (before income tax)	$629,400
Return on sales	9 percent
Return on investment	20 percent
Employees	69
Energy requirement	
Electrical	100 kWh/Mbf
Wood residue for process steam	6.8×10^6 Btu/Mbf

These data are based on single-shift operation, 325 days per year, with daily output of 29 Mbf of LVL selling at an average price of $800/Mbf fob mill; daily log consumption of red oak and yellow-poplar to yield this amount of product should be about 45 Mbf, International ¼-inch log scale.

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[18]Abstracted from Hoover et al. (1981a).

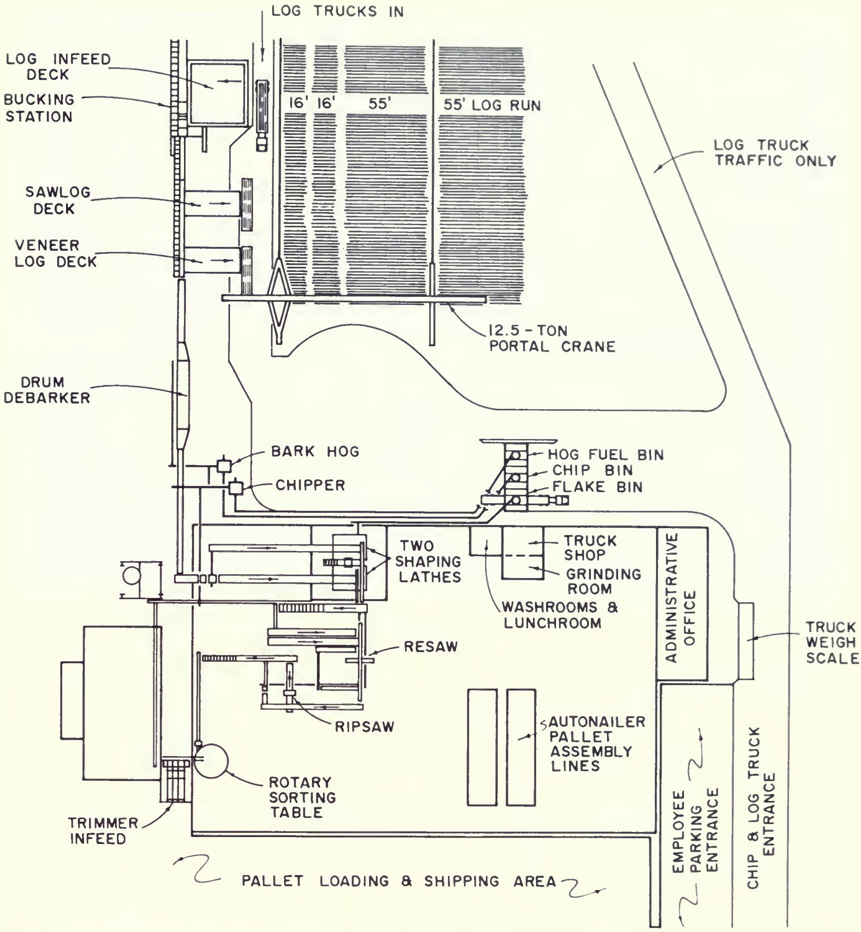

Figure 28-18.—Plant layout for large-scale manufacture of pallet parts. (Drawing after Koch and Gruenhut 1981.)

28-17 $3.2 MILLION—LARGE-SCALE MANUFACTURE OF PALLET PARTS PLUS FLAKES AND PULP CHIPS[19]

In this plant (fig. 28-18), planned for Loganville, Ga., weight-scaled oak, sweetgum, and yellow-poplar logs—mostly tree-length—are offloaded by crane and sorted into inventory. They are then crane-transferred to a log cut-up deck to yield sawlogs, veneer logs, and 3- to 4-foot-long, 6- to 14-inch-diameter bolts. The latter are drum-debarked and converted on two shaping-lathe headrigs into cants (figs. 28-19 top and 18-104D top) for resawing into pallet lumber. The sawlogs and veneer logs are resold. Annual purchased log volume (6- to 24-inch-diameter) is 14 million board feet Doyle log scale (3,817,250 cubic feet).

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[19]Abstracted from Koch and Gruenhut (1981).

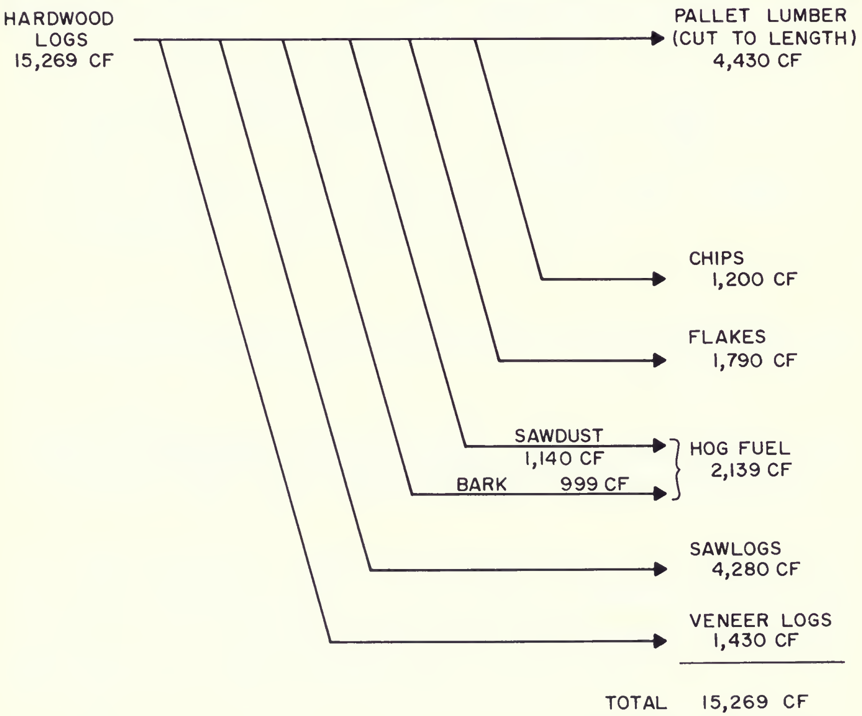

Figure 28-19.—(Top) Shaping lathes can produce cants in a variety of shapes for resawing; flakes residual from the machining operation are typically 3 inches long and 0.015 inch thick for use in manufacture of structural flakeboard; see also figure 18-104D top. (Bottom) Materials-balance diagram for pallet-part manufacture, daily basis, single-shift. CF = cubic feet. (Drawing after Koch and Gruenhut 1981.)

Annual pallet lumber production is 13.3 million board feet, lumber scale (1,107,500 cubic feet). Annual sales of sawlogs and veneer logs total 4.5 million board feet Doyle log scale (1,427,500 cubic feet). Annual production of byproducts (green-weight basis) is comprised of 13,400 tons of flakes and shavings, 9,000 tons of pulp chips, and 14,450 tons of hog fuel (mostly sawdust and bark). Other key statistics and the foregoing data are based on single-shift operation, 250 days per year:

Capital investment (including $424,210 working capital)	$3,249,510
Operating cost, annual	2,275,500
Sales, annual	3,304,500
Net profit, annual (before income tax)	1,029,000
Return on sales	31.1 percent
Return on investment	31.7 percent
Employees	10
Energy requirement, annual	
Electrical	1,600,000 kWh
Gasoline, oil, and gas	0
Wood residues	0

The projected materials balance for the operation is shown in figure 28-19 bottom. Log purchase price was estimated at $110/Mbf, Doyle log scale. Product sales prices, fob mill, were estimated as follows:

Product	Sales price
Veneer logs	$175/Mbf Doyle log scale
Sawlogs	$150/Mbf Doyle log scale
Pallet lumber	$150/Mbf lumber scale
Flakes	$15/ton, green basis
Pulpchips	$13/ton, green basis
Hogged fuel	$ 8/ton, green basis

28-18 $4.2 MILLION—MANUFACTURE OF DOWEL-LAMINATED CROSSTIES, PALLET LUMBER, AND PULP CHIPS[20]

In this plant, planned for southern operation, weight-scaled hardwoods—mostly tree length—are offloaded by crane and sorted into inventory. They are then crane-transferred to a log cut-up deck to yield crosstie logs, random-length sawlogs, veneer logs, 3- to 4-foot-long bolts for conversion to pallet cants, and 8½-foot bolts for conversion to half ties. All but the random-length sawlogs and veneer logs (which are resold) are drum-debarked and converted on two shaping-lathes (one 4-foot, the other 9-foot) into the mentioned products plus pulp chips (figs. 28-20 and 28-21).

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[20]Abstracted from Briede, R., and D. Hunter. 1981. Economic feasibility study for a pallet-lumber and dowelled-tie manufacturing plant. Final Report FS-SO-3201-57, dated May 11, 1982, on file at the Southern Forest Experiment Station, U.S. Department of Agriculture, Forest Service, Pineville, La.

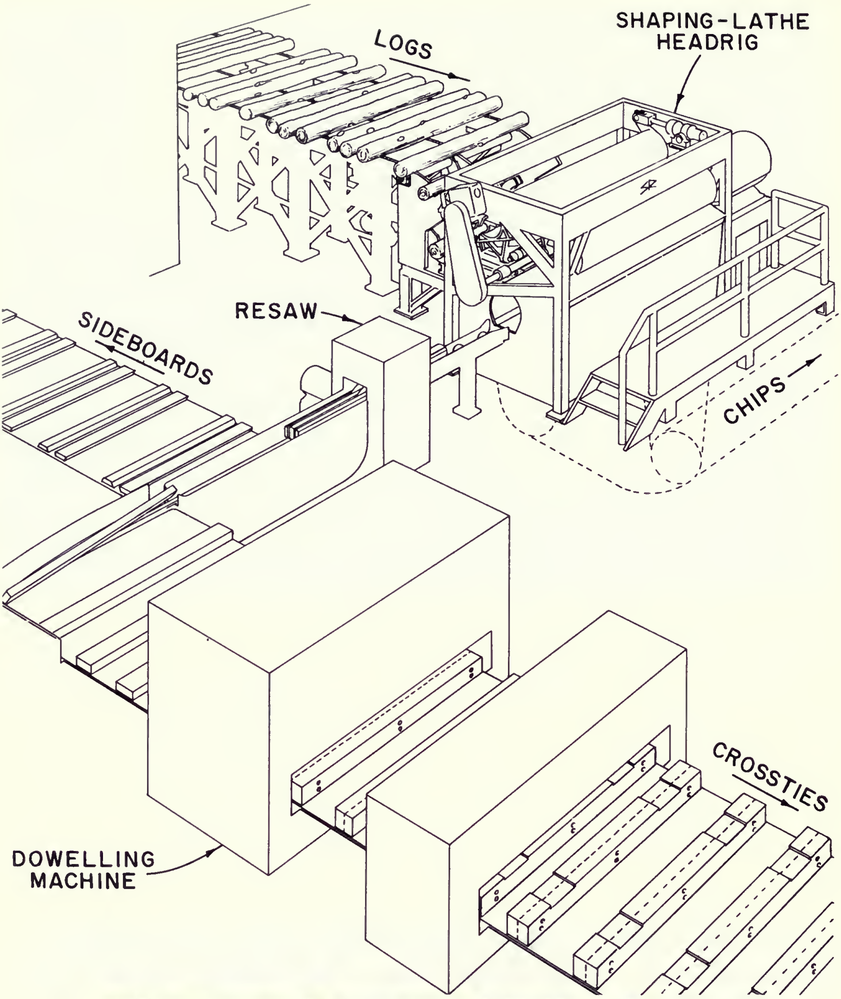

Figure 28-20.—(Top) Shaping lathe for logs 8 to 9 feet in length arranged to cut octagons yielding side lumber and 4.5- by 7-inch central cants for dowelled assembly (six steel dowels—no glue) into 7- by 9-inch crossties. (Bottom) 1-inch-long, 3/16-inch-thick oak pulp chips cut on the shaping-lathe headrig. (Drawing and photo from P. Koch.)

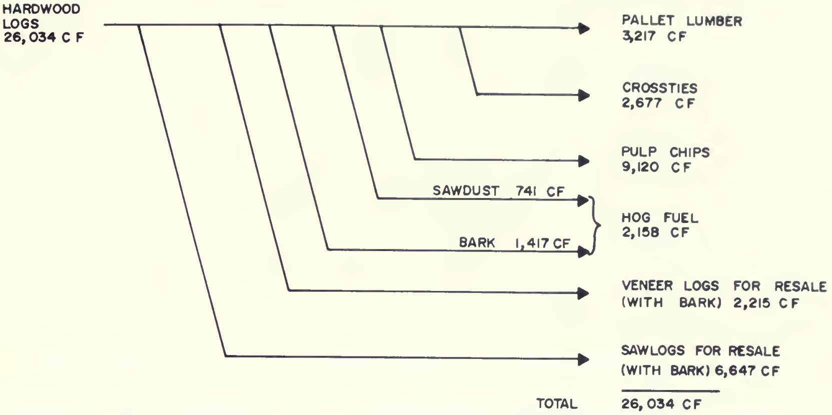

Figure 28-21.—Materials-balance (daily basis, single-shift) for manufacture of pallet stock and 7- by 9-inch, two-piece, dowel-laminated crossties. CF = cubic feet.

Annual purchased log volume (6- to 24-inch diameter at top end) is 24 million board feet Doyle scale (6,154,500 cubic feet); annual production is as follows (single-shift basis):

Product	Annual production
	Mbf, lumber scale
Two-piece, dowel-laminated 7- by 9-inch crossties	8,032
Pallet lumber	9,650

Additionally, annual sales of veneer logs and random length sawlogs total 9.2 million board feet Doyle scale.

Annual production of by-products (green-weight basis) is comprised of 68,232 tons of pulp chips and 16,140 tons of hogfuel (mostly sawdust and bark). The foregoing data and other key statistics following are based on a single-shift operation 250 days/year.

Capital investment (including working capital)	$4,179,574
Operating cost, annual	4,055,681
Sales, annual	5,079,886
Gross profit, annual (before income tax)	1,024,205
Return on sales	20 percent
Return on investment after income taxes	15.9 percent
Employees, number	14
Energy requirement, annual electrical	3,221,400 kWh

A two-shift per day operation, which doubles the output of the mill is estimated to produce a 25 percent return on sales and a 38.3 percent return on investment after taxes.

The projected materials balance for the operation (single-shift basis) is shown in figure 28-21. Log purchase price is estimated at $110/Mbf, Doyle log scale. Product sales prices, f.o.b. mill, are estimated as follows:

Veneer logs	$175/Mbf Doyle log scale
Random-length sawlogs	150/Mbf Doyle log scale
Two-piece, dowel-laminated crossties	156.86/Mbf lumber scale
Pallet lumber	150/Mbf lumber scale
Pulp chips	13/ton, green-weight basis
Hogged fuel	8/ton, green-weight basis

See figures 20-12 and 20-13, with related discussion, for additional data on dowel-laminated crossties.

28-19 $4.6 MILLION—MOLDING PALLETS FROM FLAKES[21]

Pallets molded from hardwood flakes and a binder could be used extensively in the materials handling industry. The flakes and binder are hot-pressed to form a flat deck with integral legs or posts (figs. 28-22 and 28-23). Since pallet weight is not as critical as the weight of building board, a wide variety of woods, including mixtures incorporating the denser hardwoods, can be used—provided the species blend is controlled and constant. In the proposed operation (fig. 28-24), hardwood cordwood is debarked, and cut into flakes about 0.020 inch thick, 2 inches long, and of variable width. The flakes are dried, size-classified, blended with binder resin, formed into mats, hot pressed, and trimmed. Key statistics of the proposed enterprise are as follows:

Capital investment	$4,558,555
Operating cost, annual	$5,694,720
Sales, annual	$7,600,000
Net profit, annual (before income tax)	$1,905,280
Return on sales	25.1 percent
Return on investment	41.8 percent
Employees	62
Energy requirement	
Electrical	524 kWh/hour
Wood residue	14 million Btu/hour

Cordwood is estimated to cost $40/cord delivered to the mill. One ton of cordwood (aspen in this study) plus 0.059 ton of resin and wax will yield 0.684 ton of pallets, ovendry-weight basis (fig. 28-24 bottom). At 25 pounds per pallet, ovendry basis, about 55 pallets can be made from a ton of dry cordwood. On a three-shift basis, with the plant operating 350 days per year, annual production should be equivalent to 1,600,000 40- by 48-inch pallets of the type shown in figure 28-22. The sale price of such a pallet should be about $4.75. Double-deck pallets can be made by securing a pair of single-face pallets as shown infigure 28-23; such pallets would typically weigh about 56 pounds and sell for $10 each.

Molded flake pallets are further discussed in text related to figure 24-62.

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[21]Abstracted from Haataja (1981).

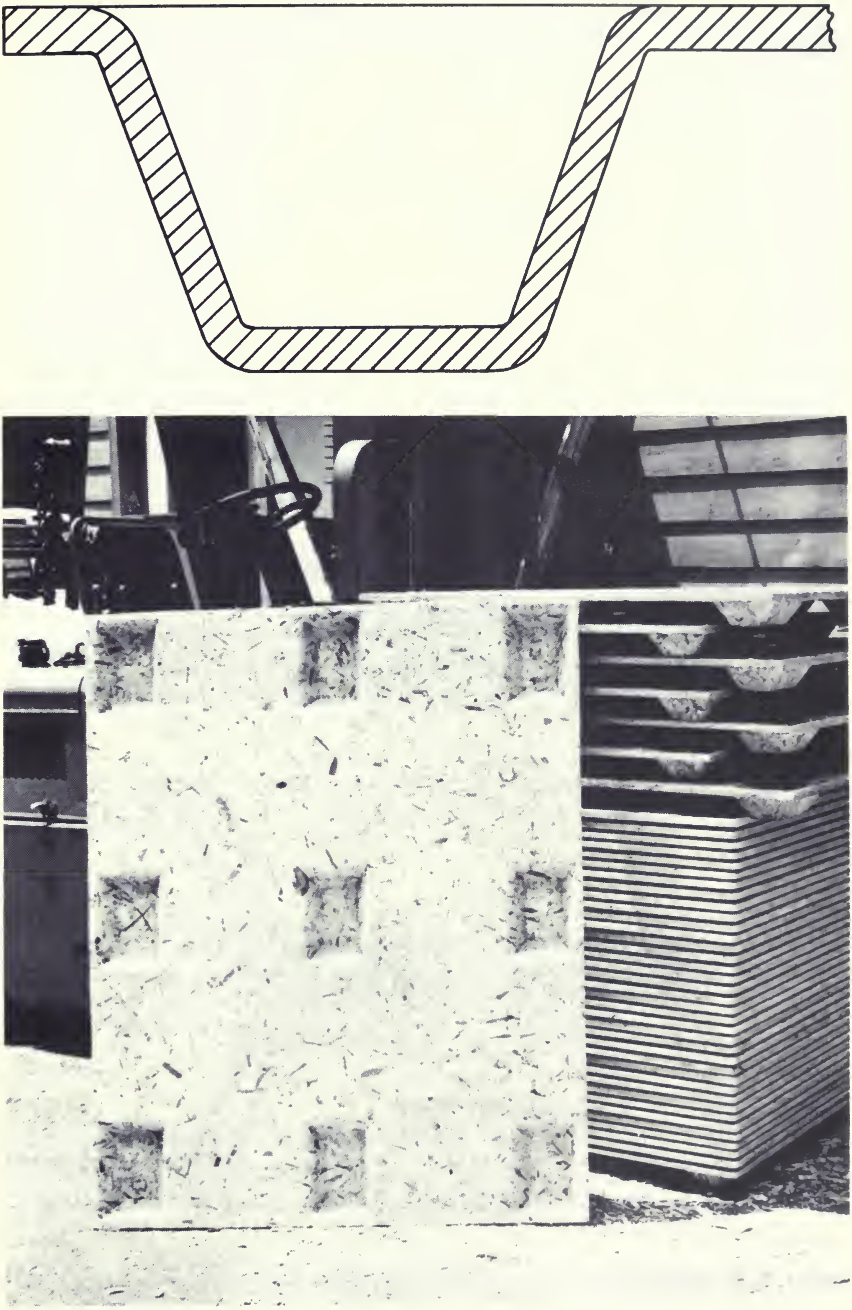


Figure 28-22.—Single-deck molded-flake pallet. (Top) Section through integral deck and 3.5-inch-deep leg. (Bottom) Plan and edge views of pallets, showing nesting capability. (Drawing and photo after from Haataja 1981.)

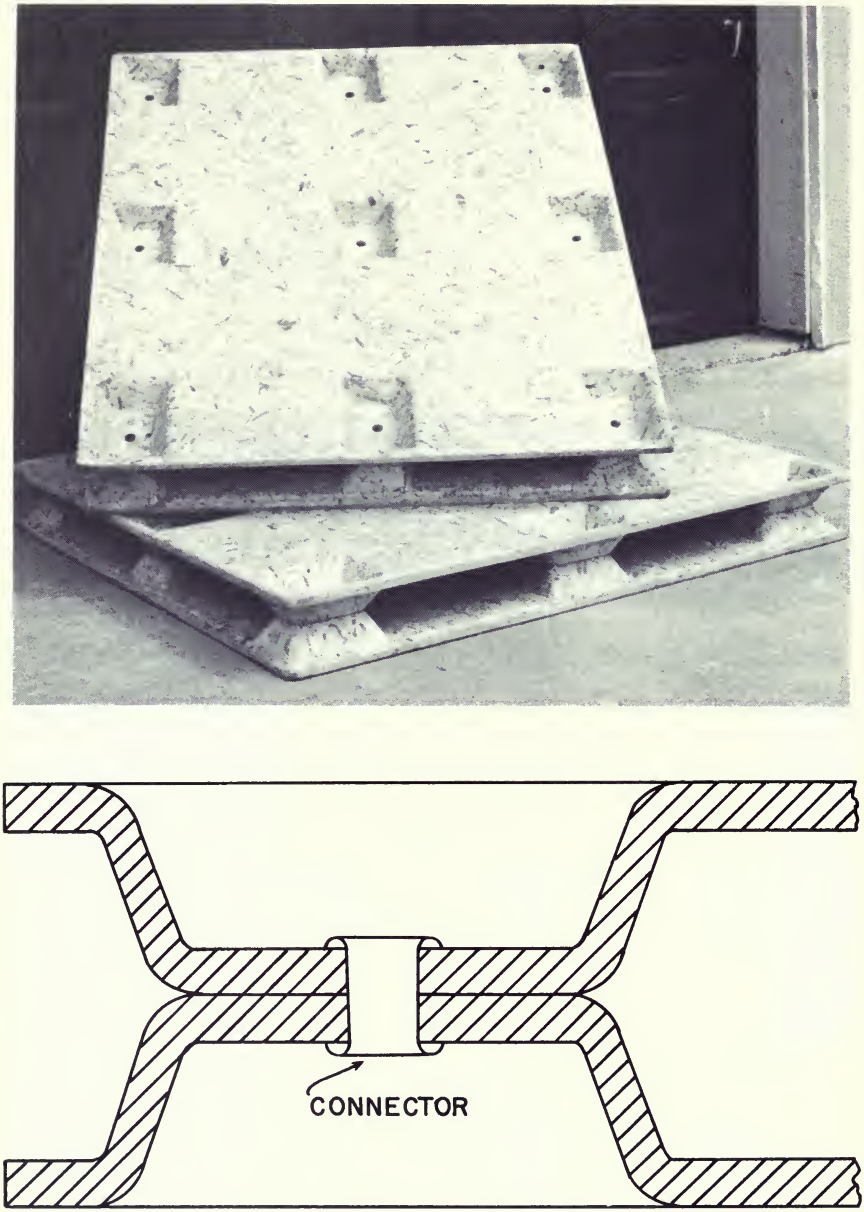


Figure 28-23.—(Top) Double-deck, molded-flake pallet. (Bottom) Section through connection of such a double-deck pallet with overall thickness of 3½ inches. (Photo and drawing after Haataja 1981.)

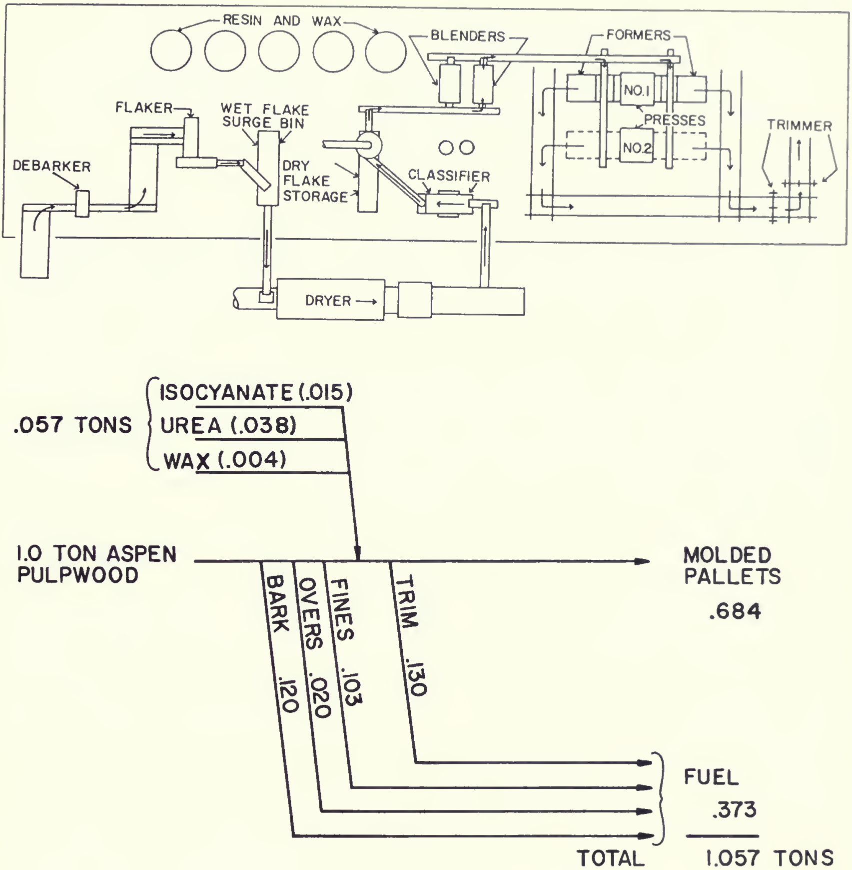


Figure 28-24.—(Top) Plant layout for annual production of 1,660,000 molded-flake pallets, three-shift basis. Each of the 92- by 112-inch hot presses has two openings. Minimum press cycle for 0.5-inch-thick pallets is 4.5 minutes. (Bottom) Materials balance, ovendry-weight basis, for manufacture of molded-flake pallets. (Drawings after Haataja 1981.)

28-20 $4.5 to $13.0 MILLION—CHARCOAL AND FUEL GAS PRODUCTION WITH A HERRESHOFF CARBONIZER[22]

The Nichols Herreshoff carbonizer (see figs. 26-32 and 26-33 with related discussion) produces charcoal and a combustible low-Btu gas on a continuous basis from bark, wood chips, scrap wood, or agricultural waste. The process normally requires a biomass feed rate of at least 100 tons/day, dry-weight basis,

[22]Abstracted from Spater and Fabian (1981).

to be economically attractive. Wood or bark typically has a moisture content of 40 percent or less (wet-weight basis); an increase in moisture content to 60 percent reduces the capacity of a Herreshoff carbonizer by one-third.

Wood or bark pieces admitted to the carbonizer should not exceed 1 by 1 by 4 inches, and if the proportion of fines (80-mesh or smaller) exceeds 5 percent, capacity of the carbonizer will be substantially reduced. About 4 tons of wood or bark (ovendry-weight basis) are required to produce 1 ton of charcoal. Systems are usually sized for production of 1 to 4 tons of charcoal per hour. Single-shift operation is not practical; the systems are designed for continuous operation, 24 hours/day, 7 days/week with annual scheduled operation totalling about 8,000 hours/year.

No auxiliary fuel is required in charcoal manufacture and an excess of low-Btu gas is produced which can be used for on-site generation of steam and electricity for sale. Typically about 25,000 pounds of steam can be produced from the excess gas yielded during production of 1 ton of charcoal. Steam, if sold, might bring about $5.75 per thousand pounds.

The charcoal can be sold in granular form at about $90/ton or it can be blended with starch binder, pressed into briquets, and sold for about $240/ton. In this study, cost of wood was estimated at $20/ton, ovendry-weight basis.

Enterprises utilizing the Nichols Herreshoff carbonizer are projected profitable in operations with charcoal outputs from 8,000 to 40,000 tons/year, requiring investments from $3.6 to $13.0 million. Key statistics for two enterprises, both converting excess gas to steam for sale, are tabulated as follows; one enterprise produces 32,000 tons/year of loose charcoal and the other 40,000 tons/year briquetted charcoal:

Statistic	Charcoal sold unbriquetted	Charcoal sold briquetted
Charcoal production rate, tons/year	32,000	40,000
Steam production rate, pounds/hour	100,000	100,000
Capital investment	$7,229,000	$13,014,000
Operating costs, annual	$4,494,000	$ 9,089,000
Sales, annual	$7,480,000	$14,200,000
Net profit, annual (before income tax)	$2,986,000	$ 5,111,000
Return on sales	39.9 percent	36.0 percent
Return on investment	41.3 percent	39.3 percent
Employees	14	69
Energy requirement, annual		
Electrical	3,775,000 kWh	5,400,000 kWh
Gasoline, oil, or natural gas	0	0
Wood residue, as feed stock (ovendry-weight basis)	128,000 tons	128,000 tons

28-21 $10.0 MILLION—MANUFACTURE OF LAMINATED-VENEER FLANGES FOR FABRICATION WITH FLAKEBOARD WEBS INTO LONG-SPAN I-BEAM JOISTS[23]

This proposed enterprise would annually convert 16,750 cords of hickory into 11,880,000 lineal feet of structural joists with laminated-veneer hickory flanges and mixed hardwood flakeboard webs (fig. 28-25 bottom). Equipment for the system (fig. 28-25 top) includes a merchandising deck for tree-length logs; debarker; chipper; round-up shaping-lathe (fig. 18-252); veneer lathe; veneer dryer; facility to laminate short, butt-jointed veneer; cut-up saws; facility to connect laminated flanges to purchased hardwood flakeboard webs in an I-beam configuration; and a chipping center facility to process veneer cores into pallet cants. Key statistics for the enterprise are as follows:

Capital investment	$9,962,529
Operating cost, annual	$7,850,116
Sales, annual	$10,237,050
Net profit, annual (before income tax)	$2,386,934
Return on sales	23 percent
Return on investment	24 percent
Employees	66
Energy requirement, annual	
Electrical, oil or gas, and wood	37,530,000 kWh

Each ton of hickory logs (ovendry weight basis) plus resin and 0.25 ton of hardwood flakeboard would yield about 0.463 ton of I-beam joists plus 0.19 ton of pallet cants (fig. 28-26). Projected costs of purchased raw material are $60/cord of hickory logs, $200/thousand square feet of ⅜-inch-thick hardwood flakeboard, and $0.50/pound of glue. Projected sales prices are $0.80/lineal foot of joist (corresponds to $480/Mbf of nominal 2- by 10-inch equivalent); $10/ton for bark, barky chips, flakes, veneer waste, and sawdust; $12/ton for clean chips; and $120/Mbf of pallet cants.

28-22 $11.9 MILLION—STRUCTURAL LUMBER MANUFACTURE[24]

Forest Service research has demonstrated that straight structural lumber can be manufactured from low- to medium-density hardwoods such as red maple, yellow-poplar, and sweetgum. The technique is referred to as an SDR system—to *s*aw full-width flitches, *d*ry the flitches, and then *r*ip to desired dimensional

[23]Abstracted from Woodson (1981).
[24]Abstracted from Harpole et al. (1981).

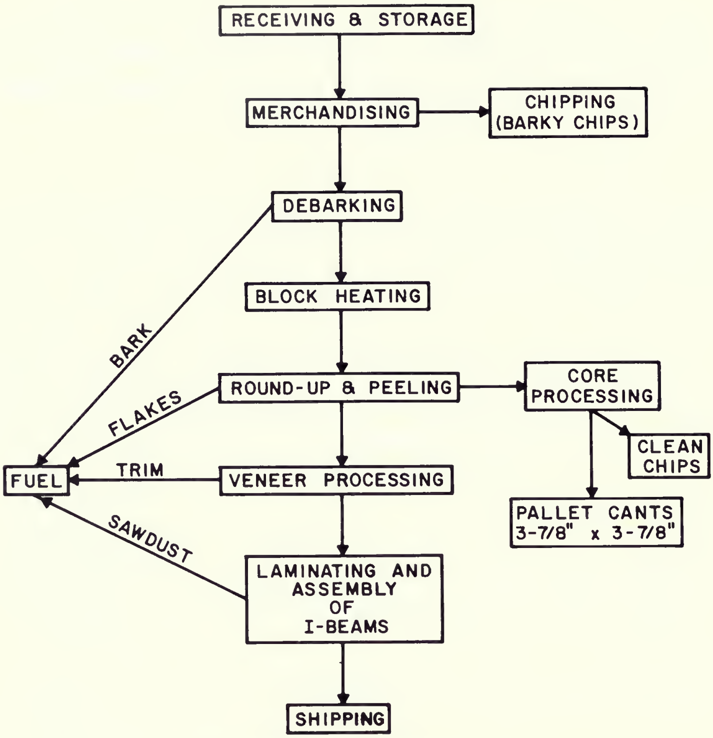


Figure 28-25.—(Top) Flow chart for facility to convert small-diameter hardwoods into laminated structural I-beams, pulp chips, pallet cants, and fuel. (Bottom) Photograph of a nominal 2- by 10-inch joist composed of short, butt-jointed hickory veneer (⅛-inch) in flanges and ⅜-inch mixed hardwood flakeboard in web. (Drawing and photo from Woodson 1981.)

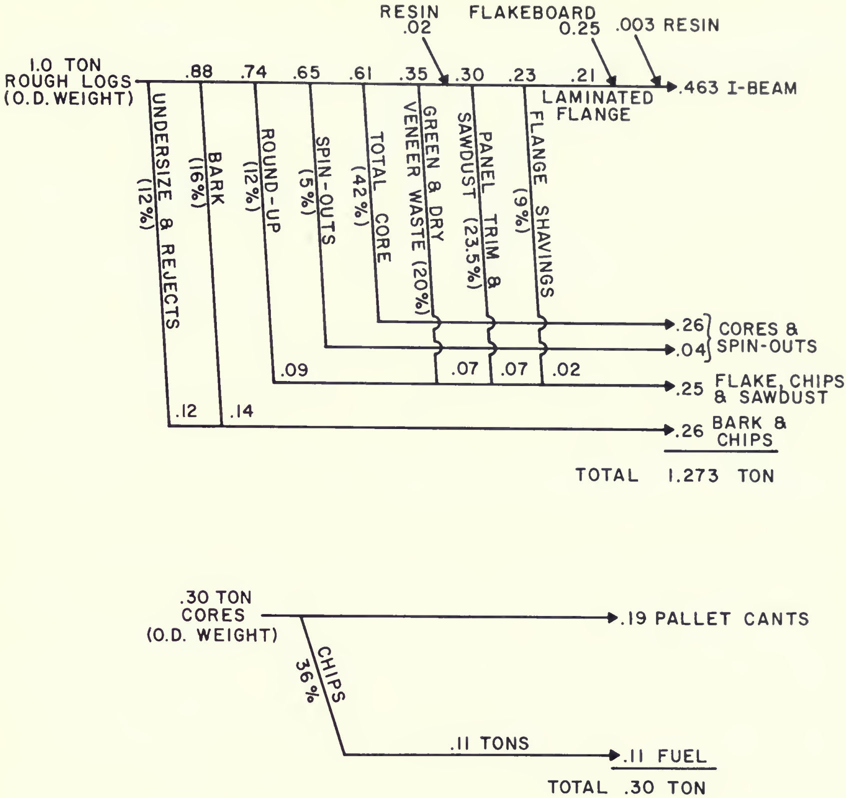


Figure 28-26.—(Top) Raw materials balance for structural I-beams from parallel-laminated hickory veneer flanges and mixed hardwood flakeboard webs. (Bottom) Raw materials balance for pallet cants from veneer cores and spinouts. All values are based on ovendry (OD) weight. (Drawing after Woodson 1981.)

lumber width. (See figure 22-63 and tables 22-27 and 22-28 with related discussion.)

About 11.5 billion cubic feet of low- to medium-density hardwood timber, mainly yellow-poplar, sweetgum and red maple, suitable for production of structural lumber, is estimated to be available from southern pine sites. Use of the SDR system to minimize warping permits recovery of about 44 percent of a sawmill's throughput of these species as structural lumber (fig. 28-27). Processing cost (excluding wood cost, taxes, and profits) should be about $67/thousand board feet. Residues, in excess of those used for fuel in kiln-drying, are estimated to be about 0.485 ovendry ton of wood chips, 0.182 ovendry ton of planer shavings and sawdust, and 0.45 ovendry ton of hogged fuel per thousand board feet of lumber produced. Although investment costs for an efficiently sized new mill are estimated to be about 12 million dollars (1980 basis), an already existing sawmill could probably adopt the SDR system with negligible new costs.

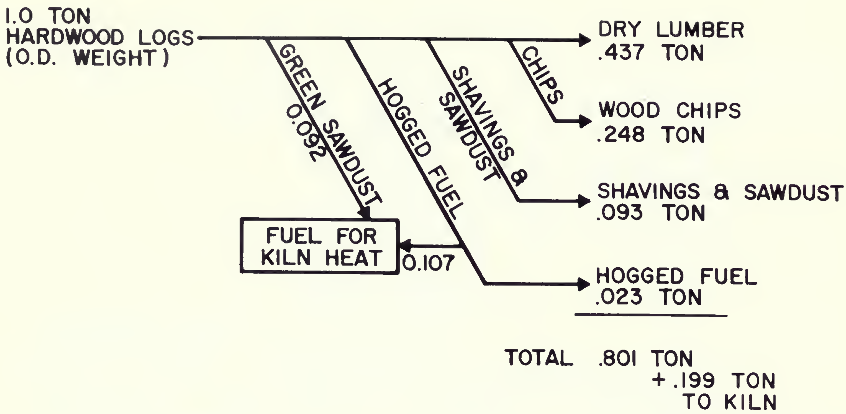


Figure 28-27.—Materials balance for SDR sawmill system based on ovendry (OD) weight. (Drawing after Harpole et al. 1981.)

Key statistics for the proposed enterprise are as follows:

Capital investment	$11,858,402
Operating cost, annual	$ 6,520,720
Sales, annual	$13,327,260
Net profit, annual (before income tax)	$ 6,806,540
Return on sales	51 percent
Return on investment	53 percent
Employees	84
Lumber output, annual	60,400 Mbf
Energy requirements/thousand board feet of output	
Electrical	69.3 kWh
Wood/bark fuels	4.8 x 10^6 Btu

Raw material costs and net profit are based on purchasing logs at a cost of $51.72/Mbf of lumber recovered, selling residues totalling $10.69/Mbf of lumber recovered, and selling the lumber at $220.65/Mbf fob mill.

Annually, the proposed enterprise would consume (ovendry-weight basis) about 117,961 tons of logs with bark. Lumber produced would total 60,400 Mbf or 51,438 tons, ovendry basis (table 28-4).

TABLE 28-4.—*Estimate of SDR sawmill roundwood requirement and product output, annual basis* (Harpole et al. 1981)

	Per year	Per Mbf of lumber[1]
	Tons, ovendry basis	
Roundwood input[2]		
Bark and log trim	15,386.2	0.255
Trimmed logs	102,575.1	1.698
Total	117,961.3	1.953
Product outputs		
Fuel for dry-kilns[3]	23,488.6	0.389
Dry lumber[4,5]	51,437.5	0.852
Wood chips[5]	29,304.5	0.485
Dry sawdust and shavings[5]	11,004.6	0.182
Hogged fuel[5]	2,726.1	0.045
Total	117,961.3	1.953

[1]Assumes 117,961.3 ovendry tons of low- to medium-density hardwood will yield 60,400 Mbf of lumber.

[2]Assumes an average ovendry weight of 28.7 pounds/cubic foot, at green volume.

[3]Annual heat-energy requirements for kilns are estimated to be 288,936 x 10^6 Btu. Assumes drying from 85 percent to 10 percent MC, dry basis; ovendry weight at green volume of 28.7 pounds/cubic foot; and 2,700 Btu/pound of H_2O removed. Heat-energy to steam assumed to be 6,150 Btu/ovendry pound of wood/bark fuel.

[4]Assumes about 1,703 pounds/Mbf of lumber, or about 60,400 Mbf of lumber output per year.

[5]Marketable output.

28-23 $14.0 MILLION—MANUFACTURE OF PLATEN-PRESSED FLAKEBOARD CORES FOR DECORATIVE HARDWOOD PLYWOOD[25]

In the United States six plants annually produce in aggregate about 437 million square feet, surface measure, of ¼-inch-thick decorative hardwood plywood for wall panels. Core material for about 150 to 200 million square feet of this market is imported 1/6-inch rotary-peeled lauan veneer, costing about $143/thousand square feet surface measure, delivered. Most of this is assembled with a 1/25-inch back veneer and a 1/28-inch (or slightly thicker) decorative hardwood face veneer to compose a ¼-inch wall panel. Manufacturers are concerned about future supply and cost of the lauan core veneer.

The proposed enterprise would annually manufacture 150 million square feet, surface-measure 1/6-inch basis, of hardwood platen-pressed 4- by 8-foot sheets of flakeboard in which flakes are oriented. In such boards with flakes 0.015- to

[25]Abstracted from Briggs (1981).

0.025-inch thick, linear expansion in the direction of flake alignment is 0.15 to 0.20 percent when cycled between 50- and 90-percent relative humidity. Such an oriented core, when assembled with face and back in a ¼-inch-thick panel will have linear expansion of 0.15 to 0.28 percent across the 4-foot width of the panel. This low value is needed in wall panels.

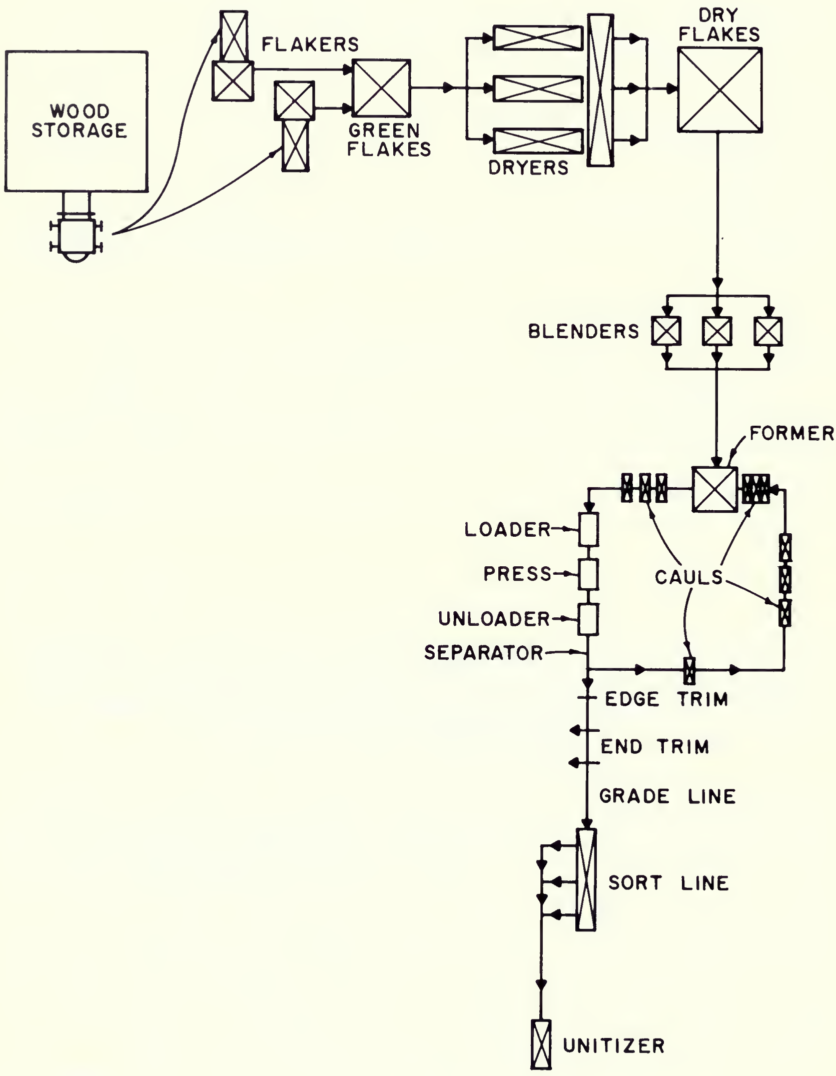


Figure 28-28.—Plan view of plant to make 150 million square feet annually, three-shift basis, of 1/6-inch oriented flakeboard from hardwood. The hot press has 30 openings and 4- by 8-foot platens. (Drawing after Briggs 1981.)

The proposed plant (fig. 28-28) would employ a 30-opening 4- by 8-foot hot press and operate three shifts/day, 7 days/week, 50 weeks/year to produce the 150 million square feet of 1/6-inch-thick flakeboard. Cost of hardwood delivered to the plant is estimated at $33/cord and selling price of the 1/6-inch-thick flakeboard is estimated at $100/thousand square feet surface measure fob plant, net after all selling costs, discounts, and commissions.

Key statistics for the enterprise are as follows:

Capital investment	$14,000,000
Operating cost, annual	$6,150,000
Sales, annual	$15,000,000
Net profit, annual (before income tax)	$ 8,850,000
Return on sales	59 percent
Return on investment	63 percent
Employees	71
Energy requirements	
Electricity	3,500 connected horsepower
Wood residue (all produced in the plant), annual	227 x 10^9 Btu

28-24 $15.0 MILLION—MANUFACTURE OF THIN PLATEN-PRESSED PARTICLEBOARD TO COMPETE WITH IMPORTED LAUAN PLYWOOD[26]

Most imported lauan plywood is thin and in grades suitable for printing and overlaying. In 1978 the average price (landed in the U.S.) was about $92/thousand square feet surface measured, ⅛-inch basis; through the first 8 months of 1979 the price averaged $121—an increase of about 32 percent, and there is concern about future supplies.

The enterprise proposed (fig. 28-29) is designed to manufacture in the United States a thin platen-pressed particleboard to be a substrate for printing and overlaying, and eventual marketing as decorative wall surfaces. Thickness is typically ⅛-inch thick, but can be as thick as ¾-inch. Panels usually measure 4 by 8 feet, but it is proposed that they be manufactured in a single-opening press measuring 8 by 48 feet and cut to size before shipment.

Shavings and sawdust (in a ratio of 2:1) of low-density hardwoods are proposed as raw material, with cost—delivered to mill—of $19.00/ton, ovendry-weight basis. With urea resin cost of $0.182/pound and wax cost of $0.393/pound, the cost of wood, resin binder, and wax per 1,000 square feet of ⅛-inch-thick panel should total about $11.19.

[26]Abstracted from Springate and Roubicek (1981a).

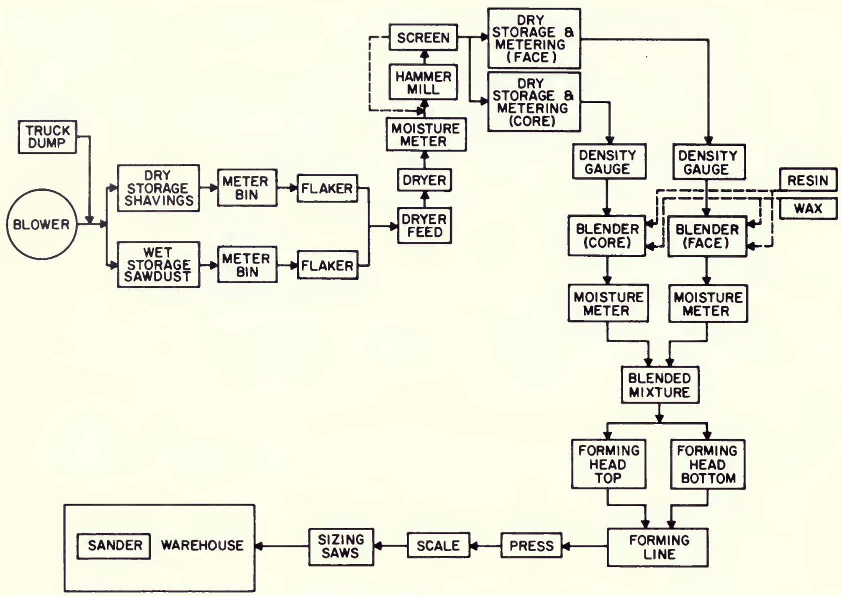


Figure 28-29.—Flow plan for manufacture of thin particleboard for overlaying and printing. The single-opening hot presss measures 8 by 48 feet. When operated 220 days/year, three-shift basis, annual output is 125 million square feet, ⅛-inch basis; if operated 330 days/year, output is estimated at 165 million square feet. (Drawing after Springate and Roubicek 1981a.)

Key statistics for the proposed operation are as follows for three-shift operation 250 and 350 days/year, ⅛-inch basis (capital investment is $15,000,000):

	250 days/year	330 days/year
	---Dollars/1,000 square feet---	
Operating cost	44.96	42.41
Selling price, net	80.00	80.00
Profit (before income tax)	35.04	37.59

Return on sales for the 250- and 330-day years are estimated at 43.8 and 47.0 percent, respectively; returns on investment are projected at 29.2 and 41.3 percent.

28-25 $24.7 MILLION—WAFERBOARD PRODUCTION COSTS COMPARED WITH THOSE FOR PLYWOOD[27]

It seems likely that structural flakeboard (waferboard), mostly made of hardwoods, will be a strong competitor of softwood plywood for residential roof and wall sheathing, and for floor decks. North American flakeboard plant locations and capacities are shown in figure 24-1 and table 24-1. Because structural flakeboard (fig. 24-2) and sheathing plywood compete for the same markets, entrepreneurs need data comparing southern production costs of the two products. Springate and Roubicek (1981b) provide such a comparison between ½-inch-thick, three-ply southern pine C-D exterior sheathing plywood and competitive 7/16-inch-thick structural flakeboard made of southern hardwoods (a mixture of species with 60 percent having specific gravity, based on ovendry weight and green volume, less than 0.60, and the balance of denser species).

Production data for the two operations are shown in table 28-5; on a ⅜-inch basis, the plywood plant has annual production of 106,667,000 square feet and the structural flakeboard plant 110,000,000.

Capital cost of the plywood plant is estimated at 20,360,000, and that of the flakeboard plant at $24,650,000; annual returns on investment, before income tax, are estimated to be 2.6 percent and 20.6 percent, respectively, based on net fob-mill sales prices of $211.66 and $201.08/thousand square feet of ½-inch-thick plywood and 7/16-inch flakeboard, respectively.

TABLE 28-5.—*Production data for comparable plants manufacturing ½-inch southern pine three-ply CDX sheathing plywood and 7/16-inch structural flakeboard made of southern hardwoods* (Springate and Roubicek 1981b)

Statistic	Plywood plant	Structural flakeboard plant
Annual production, million square feet	80.0 (½-inch basis)	94.4 (7/16-inch basis)
Annual production, million square feet ⅜-inch equivalent basis	106.7	110.0
Operating days per year	240	320
Shifts per day	2	3
Panels produced per day (4 by 8 feet)	10,417 (½-inch thick)	9,219 (7/16-inch thick)
Number of presses and size	Two presses, 4 by 8 feet, 36-opening)	One press, 4 by 16 feet, 24-opening)
Wood required annually, and cost	36,000 Mbf Doyle scale of peelers at $306/Mbf	92,400 cords of pulpwood at $31/cord
Resin and wax cost, annual	$814,000	$2,959,000
Employees	108	67

[27]Abstracted from Springate and Roubicek (1981b).

Key statistics for the two enterprises are as follows (costs of general administration, working capital, interest, and investment tax credit are not included):

Statistic	Plywood plant	Structural flakeboard plant
Capital investment	$20,360,000	$24,650,000
Operating cost, annual	$16,401,000	$11,510,000
Sales, annual	$16,933,390	$16,589,100
Net profit, annual (before income tax)	$532,390	$5,079,100
Return on sales	3.1 percent	30.6 percent
Return on investment	2.6 percent	20.6 percent
Employees	108	67

28-26 $28.0 MILLION—CONVERSION OF WHOLE STEMS INTO PALLET PARTS AND COMPOSITE PANELS[28]

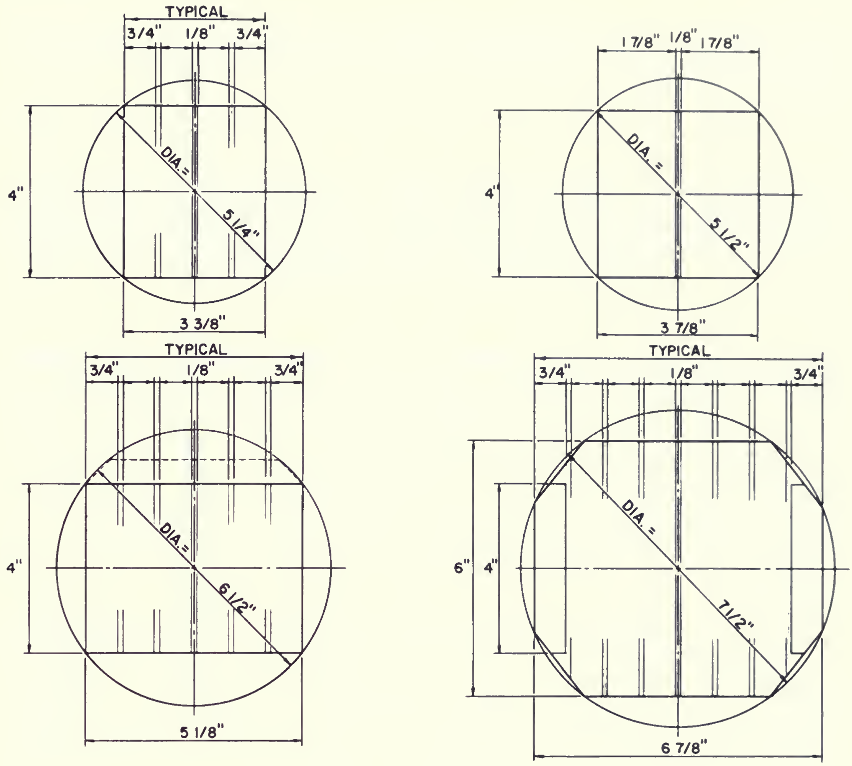
On a daily basis, 36,201 cubic feet (bark not included) of tree-length stems of southern hardwoods—mostly oak and averaging less than 12 inches dbh—are converted by shaping-lathe headrigs into cants (fig. 28-30 top) for remanufacture into lumber pallet parts (fig. 18-104D top), and into cylinders (figs. 18-104C and 18-252) yielding rotary-peeled veneer. Flakes from the shaping-lathes, together with other flaked residue, are pressed into 4- by 8-foot oriented-strand core sheets. These are combined with veneer faces and backs to yield structural composite panels (fig. 24-53) for use as sheathing or pallet decking.

Daily output is based on two-shift operation of log decks and green veneer production and three-shift production of lumber and composite panels. It is expected to amount to 12,254 cubic feet (150,672 pieces totaling 196,063 board feet) of lumber pallet parts plus 11,250 cubic feet (180,000 surface square feet, or 5,625 sheets) of ¾-inch-thick 4- by 8-foot composite structural panels (fig. 28-30 bottom). Recovery of lumber pallet parts and composite panels is about 10.4 square feet surface measure (¾-inch basis) per cubic foot of log input.

If lumber pallet parts are sold (fob mill) for $160/thousand board feet and the composite panels at $300/thousand square feet (¾-inch basis), operating results and other essential data would be as follows for operation 350 days per year:

Capital investment, including working capital	$28,024,200
Operating cost, annual	$19,691,804
Sales, annual	$28,172,000
Net profit, annual (before income tax)	$ 8,480,196
Return on sales	30.1 percent
Return on investment (before income tax)	30.3 percent
Employees	353
Energy requirement, annual	
Electrical energy purchased	20,961,408 kWh
Oil purchased (Bunker C., boiler standby)	50,000 gallons
Diesel fuel and propane for lift trucks and front-end loaders (oil equivalent)	170,000 gallons
Wood residues burned (O.D. weight basis), all available from mill residues	67,000 tons

[28]Abstracted from Roubicek and Koch (1981).



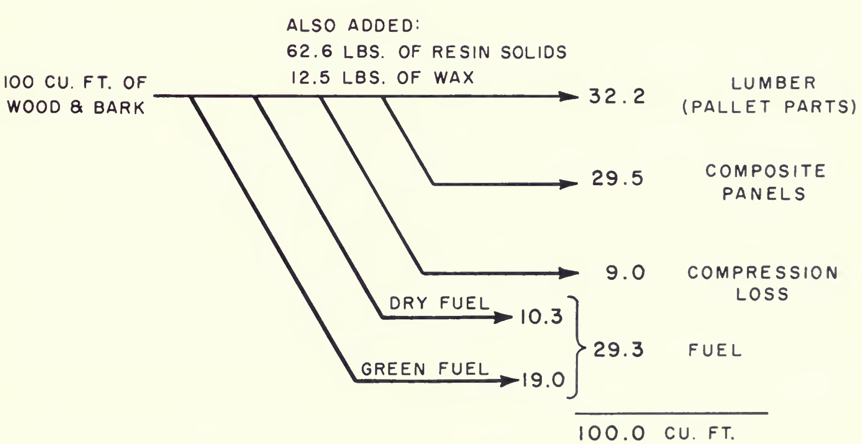


Figure 28-30.—(Top) Cant dimensions and resawing patterns for bolts of four diameters. (Bottom) Materials balance diagram, based on cubic volume, for manufacture of lumber pallet parts and composite panels. (Drawings after Roubicek and Koch 1981.)

In computing cost of manufacture, all wood was assumed purchased at $40/100 cubic feet delivered to the mill site. Annual consumption of wood is estimated at 11,946,330 cubic feet.

28-27 $8.2 to $28.9 MILLION—OPPORTUNITIES IN FOUR SOUTHERN LOCATIONS FOR PRODUCTION OF STRUCTURAL FLAKEBOARD[29]

Most analysts of the structural panel business in the South agree that it is more expensive to manufacture sheathing plywood than structural flakeboard. Data in table 28-5 (assembled in 1981) and related discussion indicate an annual cost of $16,401,000 to manufacture 80.0 million square feet of ½-inch southern pine three-ply CDX sheathing plywood ($205.01/thousand square feet), whereas costs to manufacture competitive 7/16-inch southern hardwood flakeboard should be about $11,510,000 for 94.4 million square feet ($121.93/thousand square feet).

Koch's (1978) analysis of the potential competitive situation of southern hardwood structural flakeboard was predicated on equal thickness of flakeboard and sheathing plywood, i.e., ½-inch. Emerging industrial practice indicates, however, that 7/16-inch-thick flakeboard will serve where ½-inch sheathing plywood now serves; thus Koch's analysis[29], which follows, probably understates the economic competitive position of flakeboard.

PLYWOOD PRICE AND FREIGHT STRUCTURE

Flakeboard sheathing will compete in price and function with CDX plywood sheathing made from Douglas-fir and southern pine. To enter the market, ½-inch flakeboard probably must undersell three-ply southern pine, the most economical ½-inch plywood sheathing, because it is heavier and harder to nail. It might be noted, however, that flakeboard weighs no more than gypsum board which carpenters handle routinely without undue difficulty. Some manufacturers contemplating flakeboard production feel that floor underlayment provides easiest market entry, because the heavy flakeboard panels are more easily handled at floor level than on roofs.

Mill prices and delivered prices for sheathing are dependent on the cost of transportation to market. For example, based on December 1977 freight rates,

[29]Slightly condensed from Koch (1978).

east Texas mills undersold West Coast mills in all eastern markets studied; moreover, the east Texas plywood mills received (fob mill) about $11 more per thousand square feet (MSF) for ½-inch, three-ply sheathing than did West Coast mills (tables 28-6 and 28-7).

Plywood mills throughout the South generally obtain fob mill prices that enable them to meet delivered prices by east Texas mills, i.e., all the southern mills in 1977 delivered plywood to market destinations at about the same price (table 28-7 right-hand column).

TABLE 28-6.—*Price per MSF paid by retailers at eight locations for ½-inch CDX Douglas-fir three-ply sheathing plywood, based on average 1977 mill prices and December 1977 freight rates*

Retail location	Rail freight per CWT from Portland[1]	Freight/MSF[2]	Fob West Coast mill price[3, 4]	Price paid by retailer for sheathing
	Dollars			
Houston	2.63	40.11	211	251
Kansas City	2.39	36.45	211	247
St. Louis	2.63	40.11	211	251
Chicago	2.66	40.57	211	252
Tampa	3.20	48.80	211	260
Mobile	2.99	45.60	211	257
Pittsburgh	3.16	48.19	211	259
New York	3.20	48.80	211	260

[1]85,000-lb, minimum per carload, rate on first four destinations and 75,000-lb minimum on last four destinations.

[2]Based on 1,525 lb/MSF

[3]Average for 1977; from this price, the retailer got only a 2-percent cash discount for payment in 10 days.

[4]4- and 5-ply sheathing sells fob mill at a price about $9 higher than these values for 3-ply.

TABLE 28-7.—*Price per MSF paid by retailers at eight locations for ½-inch CDX southern pine three-ply sheathing plywood, based on average 1977 east Texas mill prices and December 1977 freight rates*

Retail location	Rail freight per CWT from East Texas[1]	Freight/MSF[2]	Fob East Texas mill price[3]	Price paid by retailer for sheathing
	Dollars			
Houston	0.44	6.71	222	229
Kansas City	1.05	16.01	222	238
St. Louis	1.04	15.86	222	238
Chicago	1.30	19.83	222	242
Tampa	1.35	20.59	222	243
Mobile	.86	13.12	222	235
Pittsburgh	1.75	26.69	222	249
New York	2.13	32.48	222	254

[1]Based on average shipment weight of 115,000 lb per car.
[2]Based on 1,525 lb/MSF.
[3]Average for 1977; from this price retailer got only a 2-percent cash discount for payment in 10 days.

THE RAW MATERIAL

Hardwood species mix varies with location (chapter 2), but throughout the South (except in northern Arkansas and southern Missouri) a mix of approximately 60 percent hard hardwoods and 40 percent softwoods and soft hardwoods is available. From such a mix, a structural flakeboard can be fabricated to a shipping weight of 47 to 50 pounds/cubic foot.

In northern Arkansas and southern Missouri less than 10 percent of the hardwood resource is soft hardwoods and southern pine is in limited supply. Oaks and hickories, however, are plentiful. Flakeboards containing mostly oak and hickory may have shipping weights of 50 to 54 pounds/cubic foot, slightly higher than that of boards made with a mix containing softwoods and soft hardwoods. In this analysis, flakeboards from all southern locations have been assigned a shipping weight of 2,083 pounds/1,000 square feet of ½-inch board, or 50 pounds/cubic foot.

Chapter 2, and numerous publications containing resource data indicate that hardwood resources are adequate for flakeboard manufacturing operations at many southern locations. Optimum sites at which to manufacture flakeboard are not solely determined by wood supply, however. Price and freight structure in eastern, southern, and midwestern plywood markets are also major factors.

PLANT LOCATION AND FREIGHT COSTS

As previously noted, mill prices for sheathing are dependent on the cost of transportation to market (tables 28-6 and 28-7).

Because the wood resource for flakeboard is distributed throughout the South, many locations can advantageously serve large markets. Four such locations, with associated markets, are listed (table 28-8).

The towns named as possible mill sites are not necessarily optimum; they served, however, as locations from which to base transportation charges to markets. Rail transport costs to representative markets range from about $10 to over $25/MSF of ½-inch flakeboard (table 28-9). Rail freight from Crockett, Tex. to Kansas City seems disproportionately high ($25.88); lower transport costs could perhaps be achieved from a different location in the general area.

Approximate costs to truck ½-inch flakeboard from these locations are:

Origin and destination	Minimum load	
	24,000 pounds	30,000 pounds
	$/MSF	
Crocket, Tex.		
Houston	—	21.45
Kansas City	61.03	—
Hoxie, Ark.		
St. Louis	30.00	—
Chicago	47.91	—
Waycross, Ga.		
Tampa	—	29.16
Mobile	—	36.66
Grafton, W. Va.		
Pittsburgh	28.33	27.29
New York	43.12	41.24

ESTIMATED SALES PRICE OBTAINABLE

To predict fob mill prices for ½-inch flakeboard sheathing, a delivered price at which the retailer will switch from plywood to flakeboard must first be estimated. Because flakeboard from southern hardwoods is heavier and harder to nail than plywood, it will probably have to be offered at a price perhaps $20/MSF lower than plywood. At 1977 plywood prices this suggests fob mill prices in the range from $192 to $218/MSF, depending on mill and market locations (table 28-9).

It is recognized that plywood prices were at record high levels in 1977. In 1981 and 1982 they were significantly lower and in the low market of 1974, fob mill prices for ½-inch plywood were $100/MSF lower than the 1977 average. Over the several decades immediately ahead, however, it seems likely that prices indicated in the right-hand columns of table 28-9 will be obtainable.

TABLE 28-8.—*Mill locations and their associated markets*

Mill location	Major market	Extended market
Texas-Louisiana border (e.g., Crockett, Tex.)	Dallas-Ft. Worth	St. Louis
	Houston	Kansas City
	Waco	Wichita
	San Antonio	Topeka
	Austin	Oklahoma City
	Abilene	Tulsa
Arkansas-Missouri border (e.g., Hoxie, Ark.)	St. Louis	Chicago
	Kansas City	Indianapolis
		Cincinnati
		Topeka
South Georgia (e.g., Waycross)	Savannah	Mobile
	Atlanta	Birmingham
	Jacksonville	Huntsville
	Tampa	
	Miami	
	Gainesville	
	Orlando	
	Tallahassee	
Northern West Virginia (e.g., Grafton)	Columbus	Boston
	Cleveland	New York
	Washington, D.C.	Buffalo
	Pittsburgh	
	Wheeling	

PRODUCTION COST

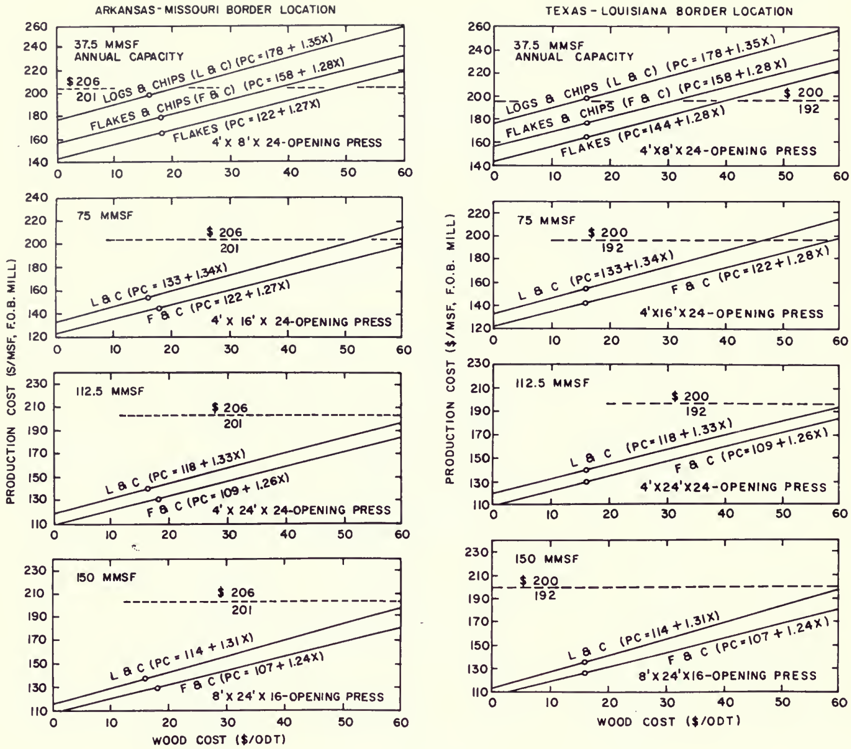
Total mill price must include all **production costs,** the latter defined for the purposes of this analysis as including the costs of raw material (wood, resin, and wax), manufacturing, selling, overhead, discounts, commissions, and a profit on the entire capital requirement sufficient to yield about 15 percent return after state and Federal taxes.

These production costs vary according to plant location, plant capacity and form of wood entering the plant (i.e., roundwood requiring debarking or residual bark-free chips or flakes residual from other manufacturing operations). The relationships among these variables are mathematically expressed in table 28-10 and illustrated in figures 28-31 and 28-32.

TABLE 28-9.—*Potential mill-market location, fob mill sales prices, freight costs, and estimated delivered sales prices for ½-inch structural exterior flakeboard sheathing*

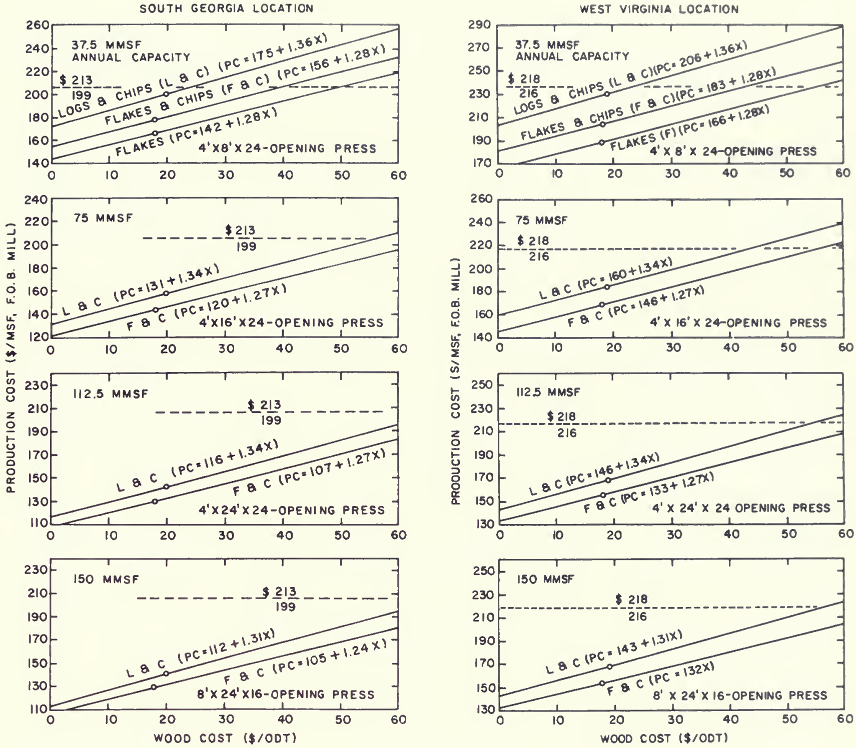
			Flakeboard Freight to[1]		Price delivered to retailer[2]		Estimated flakeboard sales price fob mill[3]	
Mill Location	Major market	Extended market	Major market	Extended market	Major market	Extended market	Major market	Extended market
			-Dollars/MSF-					
Crockett, Texas	Houston	Kansas City	9.17	25.88	209	218	200	192
Hoxie, Arkansas	St. Louis	Chicago	11.71	20.78	218	222	206	201
Waycross, Georgia	Tampa	Mobile	10.14	15.62	223	215	213	199
Grafton, West Virginia	Pittsburgh	New York	10.55	18.33	229	234	218	216

[1]Based on 90,000-lb car containing 43,207 MSF, ½-in flakeboard with shipping weight of 50 pounds/cubic foot.
[2]Priced to undersell ½-in 3-ply CDX southern pine plywood sheathing by $20/MSF, based on 1977 average plywood prices.
[3]From this price the retailer will get only a 2-percent discount for payment of invoice within 10 days.



M 146 502, M 146 499

Figure 28-31.—Estimated production cost (PC) of ½-inch-thick structural flakeboard at two locations versus wood cost (x) per ovendry ton. Production cost, as here used, includes the costs of raw materials (wood, resin, and wax), manufacturing, selling, overhead, discounts, commissions, (5, 3 and 2 percent), and a profit on the entire capital requirement sufficient to yield about 15 percent return after state and federal taxes. Single data points indicate a 1976 wood cost estimate, 60 percent dense hardwood/40 percent soft hardwood or softwood. Dashed line indicates probable fob mill price obtainable in primary and extended markets, based on average 1977 plywood prices (tables 28-7, 8 and 9) and December 1977 rate freight rates. (Drawing after Koch 1978.)



M 146 500, M 146 498

Figure 28-32.—Estimated production cost (PC) of ½-inch-thick structural flakeboard at two locations versus wood cost (x) per ovendry ton. See caption of figure 28-31 for further explanation. (Drawing after Koch 1978.)

TABLE 28-10.—*Total mill costs, including wood, discounts, and commissions, and 15 percent after-tax profit, to manufacture 1 MSF of ½-inch structural exterior flakeboard from mixed southern species*[1] (Derived from Vajda 1978 and Harpole 1978b)

MIll location and raw material	Intercept a	Slope b	Estimated[1] wood cost x	Total mill cost[2]	Estimated achievable sales price fob mill[3]
			Dollars/ ovendry ton	*....Dollars/MSF....*	
37.5 MMSF ANNUAL CAPACITY, ½-INCH BASIS					
Texas-Louisiana border					
Flakes[4]	144.12	1.28	16	165	192
Flakes and chips[5]	158.16	1.28	16	179	to
Roundwood and chips[6]	177.94	1.35	16	200	200
Arkansas-Missouri border					
Flakes	144.26	1.28	18	167	200
Flakes and chips	158.31	1.28	18	181	to
Roundwood and chips	178.13	1.35	16	206	206
South Georgia					
Flakes	141.83	1.28	18	165	199
Flakes and chips	155.46	1.28	18	179	to
Roundwood and chips	175.24	1.36	20	202	213
West Virginia					
Flakes	166.14	1.28	18	189	216
Flakes and chips	183.36	1.28	18	206	to
Roundwood and chips	206.02	1.36	19	232	218
75 MMSF ANNUAL CAPACITY, ½-INCH BASIS					
Texas-Louisiana border					
Flakes and chips	121.61	1.27	16	142	192 to
Chips and roundwood	132.96	1.34	16	154	200
Arkansas-Missouri border					
Flakes and chips	121.72	1.27	18	145	200 to
Roundwood and chips	133.10	1.34	16	155	206
South Georgia					
Flakes and chips	119.68	1.27	18	143	199 to
Roundwood and chips	130.85	1.34	20	158	213
West Virginia					
Flakes and chips	145.89	1.27	18	169	216 to
Roundwood and chips	160.44	1.34	19	186	218

See Footnote at end of Table.

TABLE 28-10.—*Total mill costs, including wood, discounts, and commissions, and 15 percent after-tax profit, to manufacture 1 MSF of ½-inch structural exterior flakeboard from mixed southern species*[1] (Derived from Vajda 1978 and Harpole 1978b)—Continued

MIll location and raw material	Intercept a	Slope b	Estimated[1] wood cost x	Total mill cost[2]	Estimated achievable sales price fob mill[3]
			Dollars/ ovendry ton	*Dollars/MSF*	
112.5 MMSF ANNUAL CAPACITY, ½-INCH BASIS					
Texas-Louisiana border					
Flakes and chips	109.11	1.26	16	129	192 to
Roundwood and chips	117.94	1.33	16	139	200
Arkansas-Missouri border					
Flakes and chips	109.21	1.26	18	132	200 to
Roundwood and chips	118.05	1.33	16	139	206
South Georgia					
Flakes and chips	107.27	1.27	18	130	199 to
Roundwood and chips	115.82	1.34	20	143	213
West Virginia					
Flakes and chips	133.26	1.27	18	156	216 to
Roundwood and chips	145.87	1.34	19	171	218
150 MMSF ANNUAL CAPACITY, ½-INCH BASIS					
Texas-Louisiana border					
Flakes and chips	106.52	1.24	16	126	192 to
Roundwood and chips	114.27	1.31	16	135	200
Arkansas-Missouri border					
Flakes and chips	106.61	1.24	18	129	201 to
Roundwood and chips	114.38	1.31	16	135	206
South Georgia					
Flakes and chips	104.69	1.24	18	127	199 to
Roundwood and chips	112.11	1.31	20	138	213
West Virginia					
Flakes and chips	132.41	1.24	18	155	216 to
Roundwood and chips	142.97	1.31	19	168	218

[1]Based on 1976 regional wood prices and assuming that flakes residual from other manufacturing operations are priced the same as residual bark-free pulp chips; assumes 60 percent dense hardwoods and 40 percent soft hardwoods or softwoods. Costs are expressed in terms of wood cost per ovendry ton (x) in regression equations of the form: Production cost = a + bx.

[2]Includes selling allowance of 2 percent fob mill selling price plus $.50/MSF of rated annual output per year.

[3]From table 27-8B.

[4]100 percent flakes.

[5]40 percent flakes and 60 percent chips.

[6]40 percent chips and 60 percent barky roundwood.

CAPITAL REQUIREMENTS

Capital requirements during the first 10 years of plant life will vary with location, type of wood, and plant capacity, but can be summarized as follows (Vajda 1978):

Annual plant capacity and raw material	Capital requirement
MMSF, ½-inch basis	*Million dollars, 1978*
37.5	
Flakes	8.2– 8.7
Flakes and chips	9.4– 9.9
Chips and roundwood	11.5–12.2
75	
Flakes and chips	13.4–14.2
Chips and roundwood	15.8–17.1
112.5	
Flakes and chips	17.2–18.3
Chips and roundwood	19.9–22.1
150	
Flakes and chips	22.7–24.9
Chips and roundwood	25.9–28.9

For all plants, capital costs were estimated to be least in the Georgia location, and most in West Virginia.

CONCLUSIONS AND DISCUSSION

Except for mills with smallest annual capacity using roundwood, all flakeboard plants could be profitable at all locations using any of the forms of wood supply. If wood costs are similar, large plants will be more profitable than small plants.

The amount by which estimated fob mill sales price exceeds (or falls short of) estimated mill cost, including 15-percent after-tax profit on entire capital requirement, varies with location (table 28-11).

TABLE 28-11.—*Amount by which estimated fob mill sales price[1] exceeds (or falls short of) estimated mill costs[2] including 15-percent after-tax profit on entire capital requirement, for various mill locations and capacities*

Mill location and annual capacity (MMSF)	Raw material entering mill		
	Flakes	Flakes and chips	Logs and chips
	Dollars/MSF, ½-inch basis		
Texas-Louisiana border			
37.5	31	17	(4)[3]
75.0	—	54	42
112.5	—	67	57
150.0	—	70	61
Arkansas-Missouri border			
37.5	36	22	(3)
75.0	—	58	48
112.5	—	71	64
150.0	—	74	68
South Georgia			
37.5	41	27	(4)
75.0	—	63	48
112.5	—	76	63
150.0	—	79	68
West Virginia			
37.5	28	11	(15)
75.0	—	48	31
112.5	—	61	46
150.0	—	62	49

[1]Average of values in last column in table 28-9.

[2]From column "Total mill cost" in table 28-9. Should wood cost increase $15/ovendry ton from the values indicated in the center column of table 28-9, values tabulated above would be diminished by about $20/MSF.

[3]Values in parentheses represent costs that exceed sales price.

These amounts are based on 1976 wood costs. For each dollar per ovendry ton that wood costs exceed those in table 28-10, amounts will be reduced by $1.24 to $1.36/MSF. For example, if wood costs are $15/ovendry ton higher than values in table 28-10, spreads will be reduced $18.60 to $20.40/MSF.

Assuming flakes can be purchased for the same price as chips, plants will operate most profitably on residual flakes (fig. 18-102) such as those produced on the equipment illustrated in figures 18-104ABCD and 18-152. A mixture of flakes and chips will yield more profit than a mixture of chips and roundwood.

All locations should accommodate profitable mills, but the south Georgia and the Arkansas-Missouri locations appear to offer greatest profit potential. Although West Virginia is adjacent to markets that should pay most for sheathing (because of high freight costs from competing regions), manufacturing costs are estimated to be somewhat higher than in other southern locations, and estimated profit is therefore lower.

Best board properties will be achieved through use of precisely manufactured flakes (chapter 24). With present knowledge, precisely manufactured flakes cannot be cut from ordinary pulp chips or even from maxi-chips; flakes derived from such chips must therefore be used only in panel cores and not in faces.

As previously explained, a small-capacity plant (37.5 MMSF/annum) might be supplied completely by residual flakes from a pallet, crosstie, post, and stud mill using a 9-foot shaping-lathe headrig operating three shifts (fig 18-104D).

Plants of all sizes could be supplied with such flakes for use in faces, supplemented with maxi-chips to be ring-flaked and used in cores. Alternatively, roundwood could be processed through disk or drum flakers to yield face flakes, and maxi-chips could be ring-flaked for cores. (See sect. 18-25 for description of these flakers).

28-28 $31.6 to $49.2 MILLION—MANUFACTURE OF COM-PLY JOISTS[30]

COM-PLY joists are structural composites with sandwich construction (fig. 24-58) designed to serve interchangeably in size and function with 2- by 8-inch or 2- by 10-inch, nominal size, sawn joists in framing floors of houses. Joist lengths of 12 feet for 2 by 8's and 14 feet for 2 by 10's are proposed for the enterprise because these lengths are most commonly used by builders; COM-PLY joists can be made in any length, however. Net width and depth of the composite joists are the same as for kiln-dry sawn and planed joists, i.e., 1½ by 7¼ inches for 2 by 8's and 1½ by 9¼ inches for 2 by 10's. The composite joists are comprised of an oriented flakeboard core platen-pressed to 1½inch thickness and then ripped to widths of 5.25 inches for 2 by 8's and 6.75 inches for 2 by 10's. Four parallel-laminated veneer strips for 2 by 8's and five for 2 by 10's, ¼inch thick and 1½ inches wide, are then glued to top and bottom edges of the composite joists to bring them to the standard sizes of 1½ by 7¼ inches and 1½ by 9¼ inches.

[30]Abstracted from Koenigshof (1981).

Koenigshof's (1981) analysis of an enterprise utilizing 15 percent dense southern hardwoods, 35 percent low- or medium-density hardwoods and 50 percent southern pine, assumes the cost of tree-length wood delivered to the mill at $0.54/green cubic foot. In addition to the tree-length wood, some additional wood is purchased in chip form at $30/ton, ovendry-weight basis. About 2,011 pounds of wood and 157 pounds of bark, ovendry-weight basis, plus 131 pounds of resin and wax (dry solids basis) are required to yield 1 Mbf of 2 by 8's with ovendry weight of 1,983 pounds (fig. 28-33).

Net, fob-mill sale price of the COM-PLY joists is estimated at $270/Mbf for the 2 by 8's and $317/Mbf for the 2 by 10's.

An investment of $49.2 million is required for production of 185,200,000 board of feet of these composite joists annually, and $31.6 million for annual production of 99,600,000 board feet. Respective manufacturing costs of the two factories are $171/Mbf and $182/Mbf of joists. After-tax internal rate of return

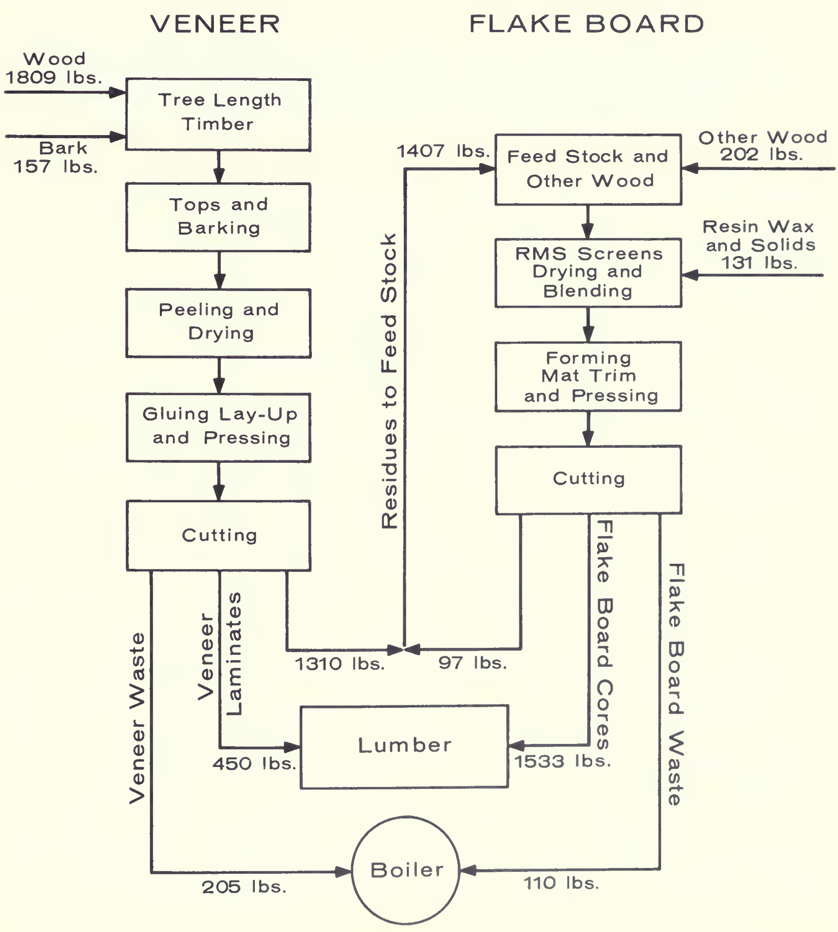


Figure 28-33.—Flow plan and materials balance, ovendry-weight basis, for manufacture of 2- by 8-inch COM-PLY joists. (Drawing after Koenigshof 1981.)

for the larger factory is estimated at 36.9 percent and for the smaller factory 29.6 percent. Investment cost and prices used were those prevailing in 1979.

Some key statistics describing the two proposed enterprises are as follows (based on a production mix of 45 percent 2 by 8's and 55 percent 2 by 10's):

Statistic	Lager enterprise	Smaller enterprise
Capital investment	$49,200,000	$31,600,000
Annual production of joists, Mbf	185,000	99,600
Manufacturing cost per Mbf	$171	$182
Sales price per Mbf, fob mill	$296	$296
Profit (before income tax) per Mbf	$125	$114
After-tax internal rate of return, percent	36.9	29.6
Employees, number	233	161
Annual cost of energy additional to wood residues from operations. Electric power assumed to cost $0.03/kWh and thermal energy $0.25/therm	$2,577,600	$1,377,800

28-29 $33.0 MILLION—MANUFACTURE OF THICK ROOF DECKING FROM OAK PARTICLES[31]

Roof sheathing and floor decking of hardwood structural flakeboard can probably compete successfully in the residential building market (sect. 28-25 and 28-27). Hoover et al. (1981b) conclude that a somewhat thicker and less dense panel (1-⅛- to 1-3/16-inch thick with density of 40 to 45 pounds/cubic foot) made from red oak flakes and particles can compete in the market for industrial and commercial roof decking. The oak panel has face layers of oriented high-quality flakes and a lower density core of particles cut on a ring flaker (fig. 24-48). It is designed to support 45 pounds/square foot with a deflection limit of 1/180 of the span length for decking continuous over two 6-foot spans, thus competing with 22-gage, wide-ribbed steel decking which sells (1980) in the Atlanta, Ga. area for about $420/thousand square feet; cost of the steel decking at the job site is $600 to $650/thousand square feet.

Availability of an oak roof-deck panel would permit wood products manufacturers to assemble all-wood bulding systems more likely to be competitive with steel systems, than is presently possible.

The proposed manufacturing enterprise, sited in Georgia, would require an investment of $33 million and would annually consume about 103,025 cords of red oak (297,000 tons, green basis) purchased at an estimated cost of $35/cord. Annual output for three-shift operation 325 days/year is estimated at 50 million square feet, 1-⅛-inch basis. Of total manufacturing cost of $411.72/thousand square feet, resin binder accounts for about 25 percent and wood about 17 percent. If sold at $500/thousand square feet, 1-⅛-inch basis, return on the $33 million investment would be about 13 percent before income taxes.

[31]Abstracted from Hoover et al. (1981b).

Key statistics projected for the enterprise are as follows:

Capital investment	$33,000,000
Operating cost, annual	$20,586,000
Sales, annual	$25,000,000
Net profit, annual (before income tax)	$ 4,414,000
Return on sales	18 percent
Return on investment (before income tax)	13 percent
Employees	130
Energy requirement per thousand square feet	
Electrical	325 kWh
Wood residue (self generated and purchased) or oil and gas for non-electrical energy requirement	22×10^6 Btu

Wood residue from plant operations is estimated insufficient, so an additional 4,200 tons of hog fuel, ovendry basis, must be purchased annually in addition to the cordwood.

28-30 $40.0 MILLION—EVALUATION OF A NEW FACILITY TO MANUFACTURE HARDBOARD SIDING BY THE SCREENBACK PROCESS[32]

In the years 1972 through 1979, 7,688 to 7,843 million square feet of hardboard, ⅛-inch basis, were manufactured in the United States, of which 55 to 57 percent was medium-density hardboard siding (MDS). From 1978 through 1980 total manufacturing capacity for MDS in the United States was about 1,282 million square feet (7/16-inch basis), probably just adequate to satisfy demand generated by the 2,023,000 housing starts in 1978.

This 1980 capacity was in plants averaging about 200 million square feet output per year (⅛-inch basis) which had book value then of about $10 million each, or a book value of $50/thousand square feet capacity, ⅛-inch basis. A new plant of the design proposed, if built in 1980, would have a book value of $150/ thousand square feet capacity (⅛-inch basis) with estimated cost escalation of 9 percent annually to 1990 if built in later years.

The enterprise analyzed is a proposed new facility located on a 100-acre tract with a 200-acre tract within pumping range (1 mile or less) for irrigation disposal of waste water; such disposal is essential. Performance of existing plants suggests that the screenback process for single-line forming and hot pressing of wet mats to manufacture smooth-one-side 7/16-inch medium density prime-painted siding affords greatest opportunity for utilization of undebarked (rough) southern hardwoods, with the oak-hickory-ash content not to exceed 50 percent.

By this process (fig. 28-34), chipped wood is pressure-refined (sec. 23-6 and fig. 25-21) in a first stage, followed by atmospheric refining. The fibers, after forming in a mat, are hot-pressed to a density of about 44 pounds/cubic foot (1,600 pounds/thousand square feet, 7/16-inch basis).

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[32]Abstracted from Stewart (1981).

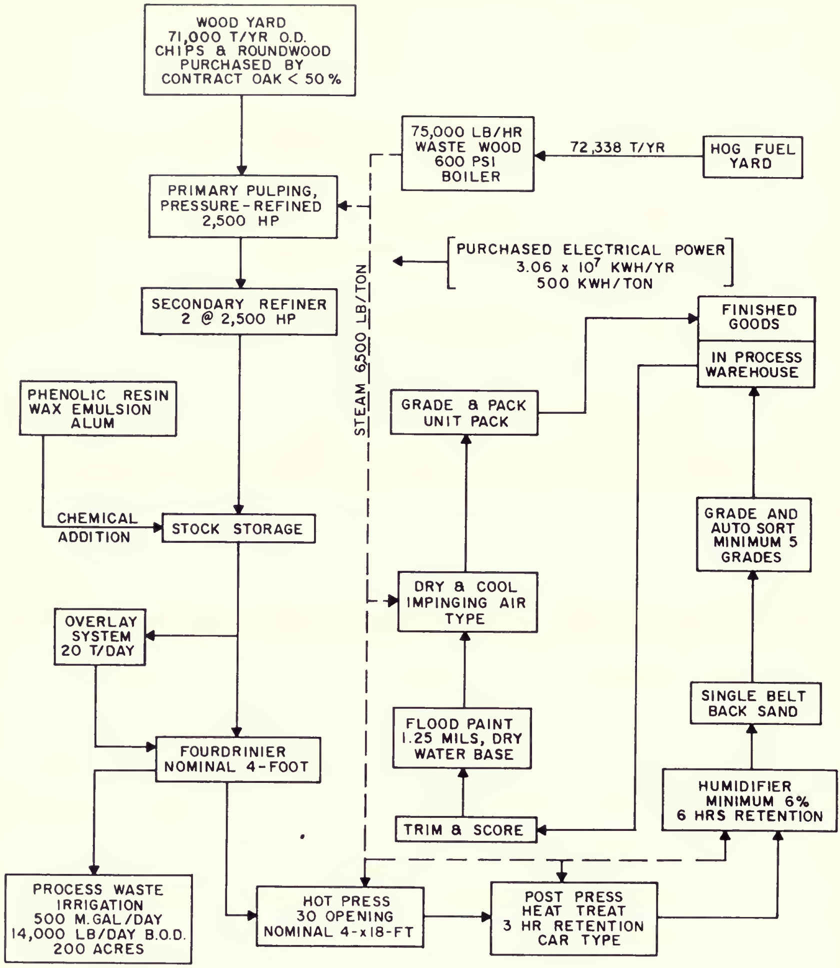

Figure 28-34.—Flow diagram for manufacture of medium-density hardboard siding by the screenback process. (Drawing after Stewart 1981.)

Output is projected ot be 200 tons/day or 61,200 tons/year; this amounts to 76,500,000 square feet/year, 7/16-inch basis, or 267,000,000 square feet/year, ⅛-inch basis.

Annual wood requirement, including bark, is estimated at 71,000 tons, ovendry basis. Water requirement is 500,000 gallons/day (153 million gallons/year) to be discharged to direct land-irrigation to satisfy requirements for zero discharge. Needed thermal energy is produced in a 600-psi boiler fired with wood residue.

Plant cost, including land and all facilities, is estimated at $40 million. Annual operating costs, not including depreciation, sales, or administrative overhead above that of the plant manager are estimated at $10,700,000; this corresponds to a manufacturing cost of \$140/thousand square feet, 7/16-inch basis. The plant would employ 220 people, and annually consume 3.06 x 10^7 kWh of electrical energy and 4.0 x 10^7 Btu of wood residue for energy.

Because of the depressed state of the housing market, no sales price of the product can be realistically projected, so return on investment is not calculated. The plant proposed would have competitive advantages derived from low wood cost, economical thermal energy, and efficient waste-water disposal.

In-place operations can be expanded by expenditure of \$80 to \$100/thousand square feet (⅛-inch basis) of additional annual capacity; the new capacity analyzed would cost \$150/thousand square feet. This suggests the liklihood of expansion of existing plants, rather than construction of new plants, should national output of hardboard siding need to be increased.

28-31 $50.0 MILLION—INTEGRATED PLANT TO MANUFACTURE STRUCTURAL FLAKEBOARD, DECORATIVE PLYWOOD, AND FABRICATED JOISTS[33]

This enterprise proposes to rehabilitate annually—by clear felling, site preparation, and planting—25,000 acres of level to rolling land averaging about 490 cubic feet per acre of stemwood in small hardwood trees 5 inches in diameter at breast height (dbh) and larger, and of many species, plus an equal volume of above-ground biomass in stembark and tops, and in trees smaller than 5 inches in dbh. By usual utilization procedures, such wood is an unmerchantable residue from the harvest of merchantable southern pines. Since the operation incidentally prepares the site for planting, timber purchasing can be facilitated by arrangements which will leave the land planted to trees of owner's choice.

On an annual basis, 398,265 tons (ovendry basis) of such wood and bark will be harvested and converted in an energy self-sufficient plant to the following: 208,688 tons of structural flakeboard (see chapter 24) sheathing and decking (sold at \$200/ton), 16,298 tons of decorative hardwood plywood (\$400/ton), and 20,191 tons of long fabricated joists (fig. 24-57) with parallel-laminated veneer flanges and flakeboard webs (\$600/ton), for a total product yield of about 60 percent—all on a dry-weight basis (fig. 28-35).

Following are projected operating results and other essential data for a three-shift operation:

Capital investment, including working capital	\$50,000,000
Operating costs, annual	\$40,000,000
Sales, annual	\$60,371,400
Net profit, annual (before income taxes)	\$20,371,400
Return on sales	33.7 percent
Return on investment	40.7 percent
Number of mill employees (harvesting and planting are contracted)	250

[33]Abstracted from Koch (1982).

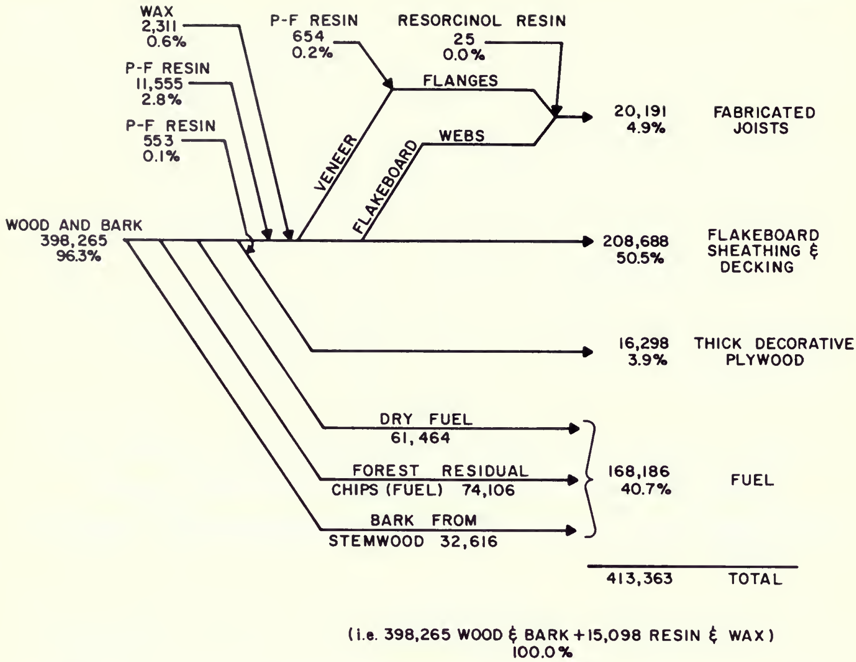

Figure 28-35.—Annual materials balance for manufacture of structural flakeboard, decorative plywood, and fabricated joists from low-grade southern hardwoods and forest residues. Values shown are in tons, ovendry-weight basis. (Drawing after Koch 1982.)

Energy requirement, annual	
Electrical energy purchased	0 kWh
Diesel fuel and propane for front-end loaders and lift trucks (oil equivalent)	150,000 gallons
Wood residues burned (ovendry-weight basis), all available from mill residues	168,186 tons

Two recently developed machines are keys to this operation. One is the swathe-felling mobile chipper (fig. 28-11), which follows conventional logging of merchantable hardwood trees above 5 inches dbh, harvesting 80 percent of remaining above-ground wood in tops, branches, and uncut cull trees for core flakes of structural panels. The other key machine in the operation is a shaping-lathe (fig. 18-252) to produce high-quality flakes while rounding 52-inch-long bolts prior to rotary-peeling them.

28-32 $69.0 MILLION—COMPLETE-TREE PROCESSING USING SHAPING-LATHE HEADRIGS[34]

BRUSH (Biomass Recovery and Utilization with Shaping-lathe Headrigs) is a system conceived by Koch (1976ab) for removing and utilizing unwanted hardwoods, leaving the sites ready for planting with pine. Puller-bunchers (figs. 16-32 through 16-34) lift trees with roots attached; self-propelled swathe-felling chippers (fig. 28-11) then recover residual trees and shrubs as fuel chips or mulch and prepare the site for planting. At the mill, shaping-lathe headrigs (figs. 18-104ABCD and 18-252) turn logs and bolts into cants by removing residue as flakes. The cants are converted to crossties (figs. 18-104D bottom, 20-7, 20-12, and 20-13), pallet parts, and studs, or are peeled and the thick veneer laminated into lumber. Flakes are pressed into structural flakeboard (chapter 24). Returns from the products reduce type conversion costs, which otherwise would be prohibitively expensive. Since there are no ongoing BRUSH enterprises, the study is based on descriptions of component machines and assumed resource conditions.

Figure 28-36 depicts the material balance for utilization of complete trees. From the 585,000 tons (ovendry-weight basis) of wood harvested annually, the mill produces 391,950 tons of salable products. Structural flakeboard accounts for 52.6 percent of the tons of product produced. The only other product whose tonnage exceeds 15 percent of the total is laminated lumber, 16.4 percent. Products sold will include 675 thousand dowel-laminated crossties, 51,570 thousand board feet of laminated lumber, 31,980 thousand board feet of pine studs, 31,500 thousand board feet of pallet parts, and 215,172 thousand square feet of structural flakeboard.

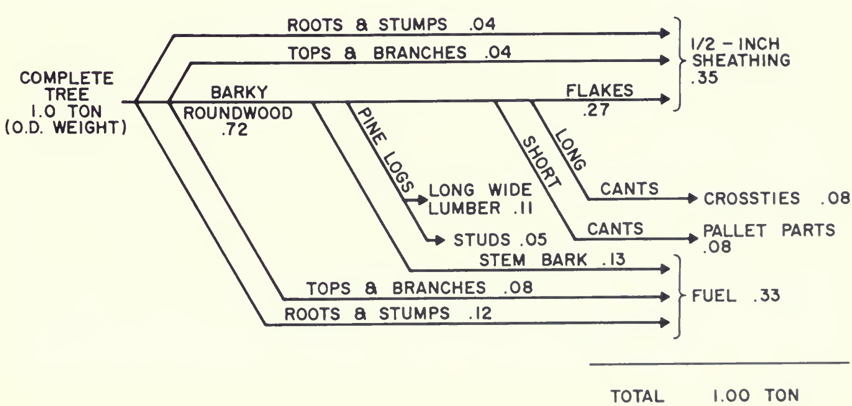

Figure 28-36.—Yield from one ton of wood and bark, ovendry-weight basis, harvested by the BRUSH process. (Drawing after Anderson 1981.)

[34]Abstracted from Anderson (1981).

The prices assigned to these products were: $9 each for crossties, $425/thousand board feet for long and wide laminated lumber, $225/thousand board feet for pine studs, $180/thousand board feet for pallet parts, and $175/thousand square feet for structural flakeboard. The highest price per ovendry ton was for long and wide laminated lumber, $340, and the lowest price was for pallet parts, $116.77.

At the prices listed, the quantity of products produced and sold had a total value of $78,512,972.

Key statistics describing the enterprise are as follows:

Capital investment	$68,991,000
Operating cost, annual	$32,988,745
Sales, annual	$78,512,972
Net profit, annual (before income tax)	$45,524,227
Return on sales	58.0 percent
Return on investment	66.0 percent
Employees	862
Energy requirement, annual	
Electrical (purchased)	0 kWh
Diesel fuel	1,230,000 gallons
Wood residues from operations	3.32×10^9 Btu

28-33 $93.6 MILLION—PRODUCTION OF ETHANOL, FURFURAL, AND LIGNIN PRODUCTS BY HYDROLYSIS[35]

Acid hydrolysis of wood to sugars has followed two routes, dilute-acid hydrolysis at elevated temperatures and concentrated-acid hydrolysis at lower temperatures. This analysis is part of a larger study reexamining process conditions, kinetics and yields in the Bergius process plants for wood hydrolysis operated in Mannheim and Regensburg in Germany during World War II using superconcentrated hydrochloric acid.

Use, at low temperatures, of concentrated hydrochloric acid (30 percent) for prehydrolysis of hemicelluloses to xylose followed by super-concentrated hydrochloric acid (>40 percent) for hydrolysis of cellulose to glucose permits separation and high yield of the three major components of hardwood, i.e., xylose, glucose, and a reactive lignin (fig. 28-37 top). The xylose is then converted to furfural and the glucose is fermented to ethanol. The lignin may be further processed to phenol or resins, or burned for fuel.

Each ton of bark-free southern hardwood feedstock, ovendry-weight basis, should yield about 200 pounds of furfural, 88 pounds of acetic acid, 400 pounds (60 gallons) of ethanol, 400 pounds of carbon dioxide, and 435 pounds of lignin (fig. 28-37 bottom).

The proposed plant would daily consume about 1,109 tons of hardwood feedstock plus about 870 tons of wood fuel (ovendry-weight basis), with annual raw material consumption and product yield as shown in table 28-12.

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[35]Condensed from Nguyen and Goldstein (1981).

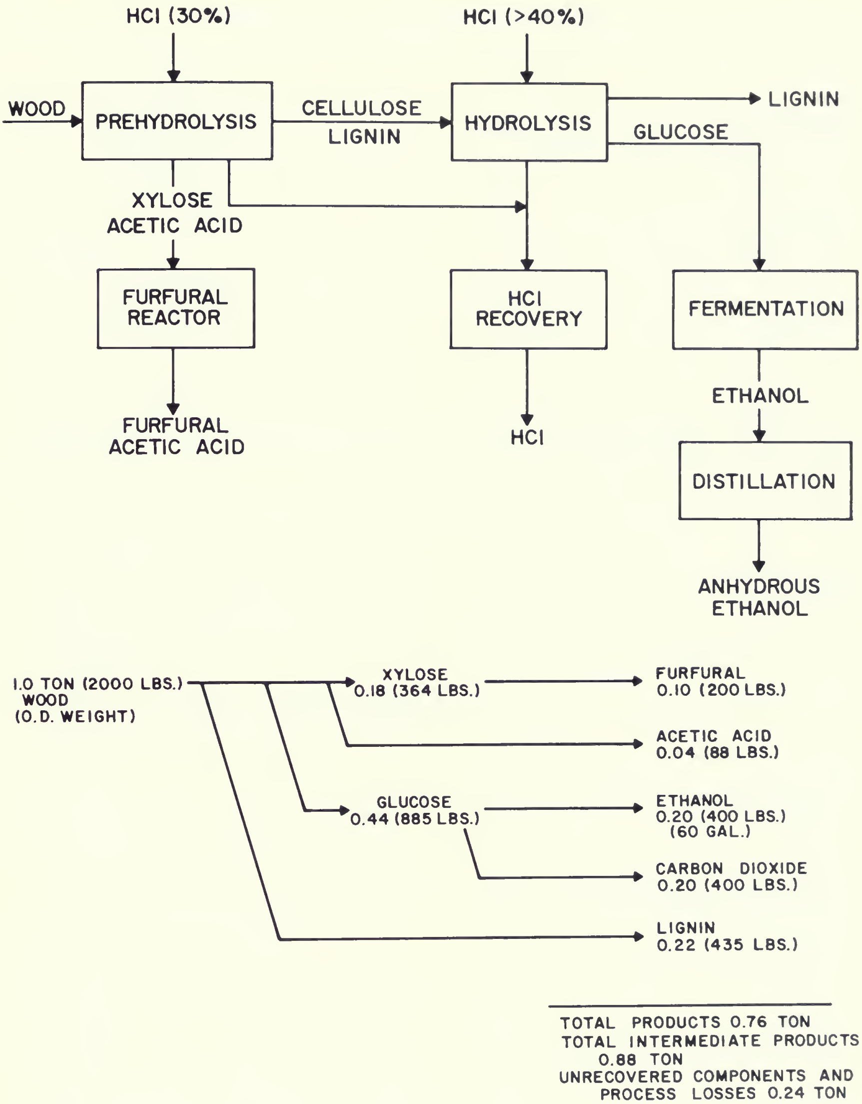

Figure 28-37.—(Top) Simplified process flow sheet for hydrolysis of wood with superconcentrated hydrochloric acid (HCl). (Bottom) Material balance for a wood hydrolysis plant, based on 1.0 ton of bark-free wood from southern hardwoods, ovendry-weight basis. The process can handle wood with bark attached, but resulting product mix will be different. (Drawings after Nguyen and Goldstein 1981.)

Key statistics projected for the enterprise are as follows:

Capital investment	$93,603,552
Operating cost, annual	$42,941,958
Sales, annual	$74,561,082
Net profit, annual (before income tax)	$31,619,124
Return on sales	42.4 percent
Return on investment	33.8 percent
Employees	100
Energy requirement, annual	
Electrical	100×10^6 kWh
Oil equivalent (gasoline, oil, and natural gas)	0
Wood residue	5×10^{12} Btu

TABLE 28-12.—*Annual product yield and consumption of raw materials in a large-scale plant for concentrated-acid hydrolysis of southern hardwoods* (Nguyen and Goldstein 1981)

Product and raw material	Yield or consumption	Selling price of product or cost of raw material, fob mill
	Million pounds/ year	*Dollars/pound*
Product (yield and selling price)		
Furfural	77.3	0.250[1]
Acetic acid	34.1	.240
Ethanol	23.4	1.650
Lignin residue	168.9	.050[2]
Raw material (consumption and cost)		
Hydrochloric acid	152.6	.065
Lime	234.3	.017
Calcium chloride	31.6	.045
Phosphate	.8	.220
Urea	.8	.065
Wood feedstock, ovendry	776.2	.010[3]
Wood fuel, ovendry	608.6	.010[3]
Water	12,529.1	$.012 \times 10^{-3}$

[1]In December 1979 the market price of furfural was $0.515/pound, but since the annual yield tabulated above is about half the present annual U.S. production of furfural, the lower price of $0.25 was assigned this product.

[2]Priced to permit economic conversion of lignin to phenol or benzene.

[3]Corresponds to $20/ton, ovendry weight basis.

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29
Trends

Most of the graphic data in this chapter were provided by D.B. McKeever and C. R. Hatfield. Readers needing further information should refer to their publication (see text footnote[1], p. 3580): Trends in the production and consumption of major forest products in the United States. U.S. Dep. Agric. For. Serv., For. Prod. Lab., Madison, Wis.

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CHAPTER 29

Trends[1]

Land managers growing trees, and manufacturers of products from hardwoods, need knowledge of product consumption and prices during past years to help them estimate future demand and plan future production. The hazards of economic forecasting are so evident that graphs presented are limited (with six exceptions—figures 2-2, 29-16E, 29-17, and 29-44, 29-49, and 29-50) to historical trends, not future activity.

Two trends seem evident, however. First, the population of the United States will continue to increase (fig. 29-1). Second, regardless of the number of houses built to satisfy shelter needs of the growing population, most houses will probably be smaller than those built in the 30 years from 1950 to 1980, and will contain less wood per housing unit (fig. 29-2).

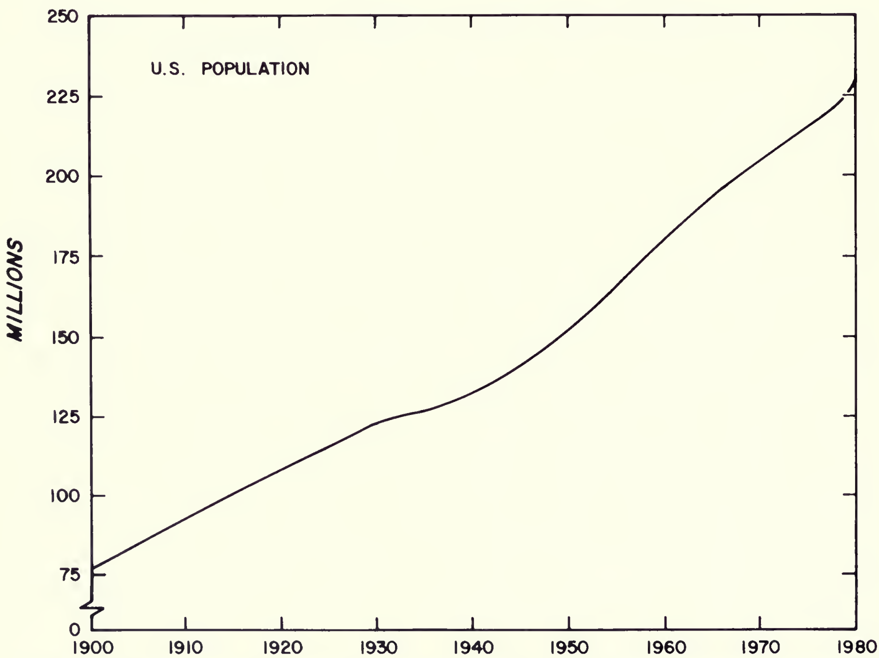

Figure 29-1.—Population of the United States, 1900-1980. (Drawing after MeKeever and Hatfield.[1])

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[1]Figures in this chapter credited to McKeever and Hatfield are from: McKeever, David B.; Hatfield, Cherilyn A. 1984. Trends in the production and consumption of major forest products in the United States. Resource Bulletins FPL 14 and 14A. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory, 59 p. and 71 p.

Figure 29-2.—Single-family residences of two types. (Top) Large two-story conventional detached house with wood framing, sheathing, floor decking, exterior decking, flooring, siding, wall panelling, and roof shakes. (Bottom) Small, mostly single-story condominiums on concrete slab with two concrete fire walls and non-wood sheathing, flooring, siding, interior wall surfaces, and roof shingles.

The new condominium units constructed in the South in 1982 often are reinforced concrete and masonry structures several stories high. Others are two stories high with wood stud walls and a second floor supported on wood joists. Typical of many condominium units successfully competing with historically conventional detached dwellings, however, is the single-floor structure (fig. 29-2 bottom).

Such single-floor dwellings typically have a concrete slab floor (1,000 to 1,800 sq ft heated), two concrete-block fire walls separating units, brick facing over non-wood sheathing, aluminum-framed windows, asphalt shingles, metal gutters, gypsum board interior walls, and wall-to-wall carpets. Wood in such units is limited to a few roof beams or trusses, plywood or flakeboard roof sheathing, studs for two exterior walls plus interior partitions, a few doors, minimal mouldings—perhaps of fiber, veneered particleboard kitchen and bath cabinets, and considerable wood furniture and wall panelling.

Regardless of the future course of housing starts, the production of paper will continue to expand (fig. 29-10AB) and its hardwood component will probably increase (fig. 29-5ABC).

It also seems likely that structural flakeboard, mostly made of hardwoods, will be a strong competitor of softwood plywood for residential roof and wall sheathing, and for floor decks (table 24-1, fig. 24-1, sects. 28-25, 28-27, 28-29, and 28-31).

High-quality hardwoods will remain in short supply, and Europe will increasingly look to the United States to supply an important proportion of their needs. Because hardwoods growing on adverse sites among southern pines are typically small and of low-quality, the pine-site hardwoods will probably not be a major factor in this fine-hardwood trade.

The pine-site hardwoods will be principally used as follows:

- In chip form for pulp and paper and for industrial fuel—possibly also for chemicals.
- In flake, fiber, or veneer form for panels, i.e., structural flakeboard, medium-density fiberboard, hardboard, and plywood.
- In solid form as pallets, crossties, furniture, flooring, and residential fuel; some species, e.g., yellow-poplar, may be used for structural lumber should softwood lumber become excessively expensive.

Possibly composite lumber (sec. 28-21, 28-28, and 28-31), made from hardwoods as well as softwoods, will challenge traditional 2 by 8, 2 by 10, and 2 by 12 softwood lumber for use as joists and rafters.

Illustrations in this chapter are listed in table 29-1 to speed reference to them. They are divided into three categories: general, capacity and production, and price trends. No illustration charting growth of southern structural flakeboard production is provided because the first two southern plants were not operational until 1983 (table 24-1 and fig. 24-1); growth of flakeboard production in the South should be substantial during the 1980's and 1990's, however.

In concluding this three-volume work, which has involved cooperation of hundreds of people over a 10-year period, and study of approximately 10,000 pieces of published literature, it is clearly evident that the hardwoods growing among southern pines are a national resource of great value. (See chapter 2). They should be used, rather than destroyed during conversion of lands to other uses. The extent to which hardwoods will occupy land economically better suited to growing southern pines or food and forage will largely depend on the action of private non-industrial forest land owners (sect. 2-9). Their actions will be determined by personal preferences and economic needs, and by needs and demands of the Nation for various types of recreational forests, wildlife habitat, watersheds, energy, food, wood and fiber, and employment.

It therefore seems reasonable to continue strong research efforts with the objective of developing scientifically derived alternatives for establishing forestry policy, practicing forestry, and utilizing the wood resource of the South. Universities, industry, and State and Federal Government should all participate in this research.

TABLE 29-1.—*Summary tabulation of illustrations in chapter 29*[1]

Group or subject	Figure number
GENERAL	
General	
Population of the United States	29-1
Photos of conventional detached dwelling and of condominium	29-2
Gross national product	29-3
Housing starts	29-4
CAPACITY, DEMAND, AND PRODUCTION	
Roundwood and residues (see also figs. 2-1 and 2-2)	
Pulpwood	29-5ABCD
Sawlogs	29-6
Veneer logs (see also fig. 22-46)	29-7
Miscellaneous industrial wood	29-8
Fuelwood	29-9AB
Pulp, paper, and panel products	
Pulp, paper, and paperboard (see also figs. 25-1 through 25-8)	29-10AB
Insulation board (see also fig. 23-3 and table 23-1)	29-11
Hardboard (see also table 23-2)	29-12ABC
Particleboard and medium-density fiberboard	29-13
Plywood (see also figs. 22-45 and 22-46)	29-14; 29-36ABC
Structural flakeboard in the South (see fig. 24-1 and table 24-1)	—
Lumber	
Hardwood and softwood lumber, general	29-15ABC
Hardwood lumber by species or species group, alphabetically arranged—ash through yellow-poplar	29-16 A through H
Hardwood lumber, future demand	29-17
Major solid wood products	
Pallets (see also figs. 22-21AB)	29-18AB
Wood containers	29-19
Cooperage	29-20
Crossties (see also figs. 22-53 and 22-54)	29-21
Mine timbers	29-22
Piling, poles, fence posts, and mine timbers	29-23
Hardwood flooring (see also figs. 22-6 and 22-10)	29-24
Millwork and prefabricated buildings	29-25

See footnote next page

TABLE 29-1.—*Summary tabulation of illustrations in chapter 29*[1]*—continued*

Group or subject	Figure number
Furniture and other remanufactured products	
Furniture, household	29-26
Furniture, office and public	29-27
Partitions and fixtures	29-28
Kitchen cabinets	29-29
Ship and boat building and repair, and for agricultural implements	29-30
Industrial pattens, signs and displays	29-31
Burial caskets	29-32
Sporting goods, musical instruments, toys and games	29-33
Travel trailers and campers	29-34
Brooms and brushes; handles	29-35AB
Plywood and veneer	29-36ABC
Excelsior and wood flour (see fig. 22-70)	—
PRICES[2]	
Stumpage	
Hardwood pulpwood	29-37
Hardwood saw timber (oak)	29-38
Southern pine[3]	29-39
Douglas-fir	29-40
Pulpwood and pulpchips	
Pulpwood	29-41AB
Pulpchips (see also fig. 25-2)	29-42
Lumber	
Hardwood lumber, price history	29-43ABC
Hardwood lumber, predicted price to 2005[4]	29-44
Crossties and No. 2 Common oak	29-45
Southern pine and Douglas-fir	29-46
Plywood	
Hardwood and softwood plywood	29-47
Paper and paperboard	
Unbleached kraft linerboard, southern	29-48
Energy	
Natural gas	29-49
Electrical	29-50

[1]For a discussion of the national supply and demand for hardwoods in 1970 and 2000, see section 2-1 and figures 2-1 and 2-2. Survey data specific to hardwood on southern pine sites are given in section 2-6. Ownership patterns are discussed in section 2-9.

[2]For a discussion of land values see: de Steiger, J.E. 1982. Forestland market values. J. of For. 80 (4): 214-216.

[3]For data on regional price variation see: Hunter, T. P. 1982. Regional price variation of southern pine sawtimber and pulpwood. For. Prod. J. 32 (9): 23-26.

[4]See also: Luppold, W.G. 1982. An econometric model of the hardwood lumber market. Northeastern Forest Experiment Station, Forest Service, U.S. Dept. of Agric., Res. Pap. NE-512. 15p.

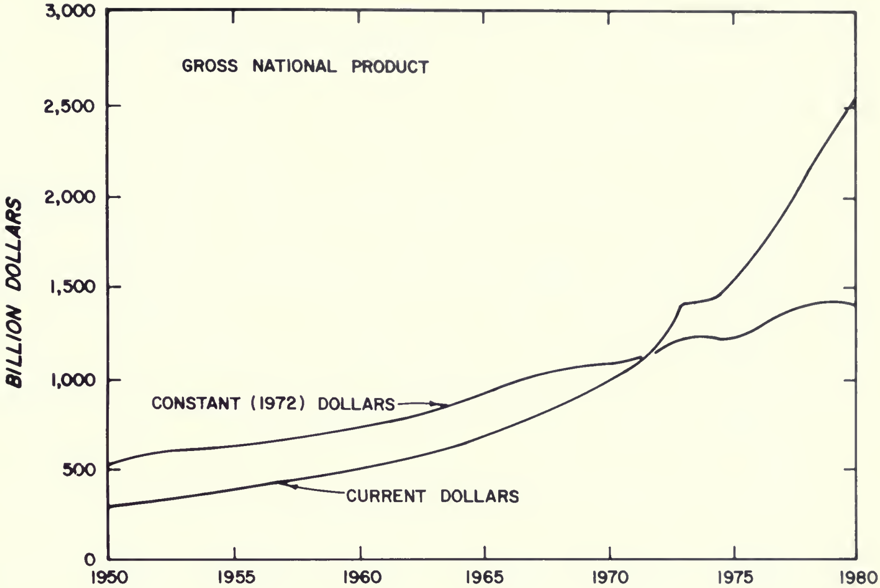
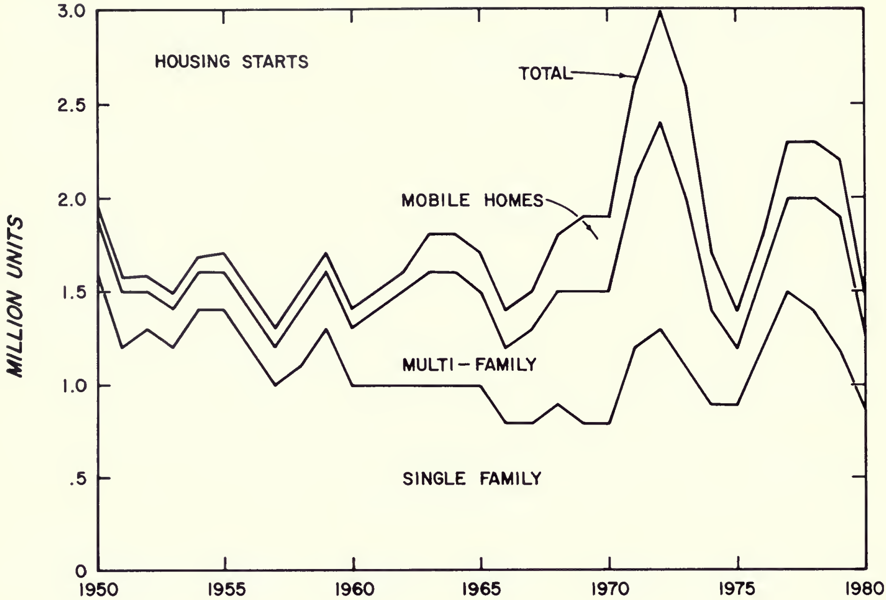


Figure 29-3.—Gross national product of the United States in current dollars and in constant (1972) dollars. (Drawing after McKeever and Hatfield.[1])



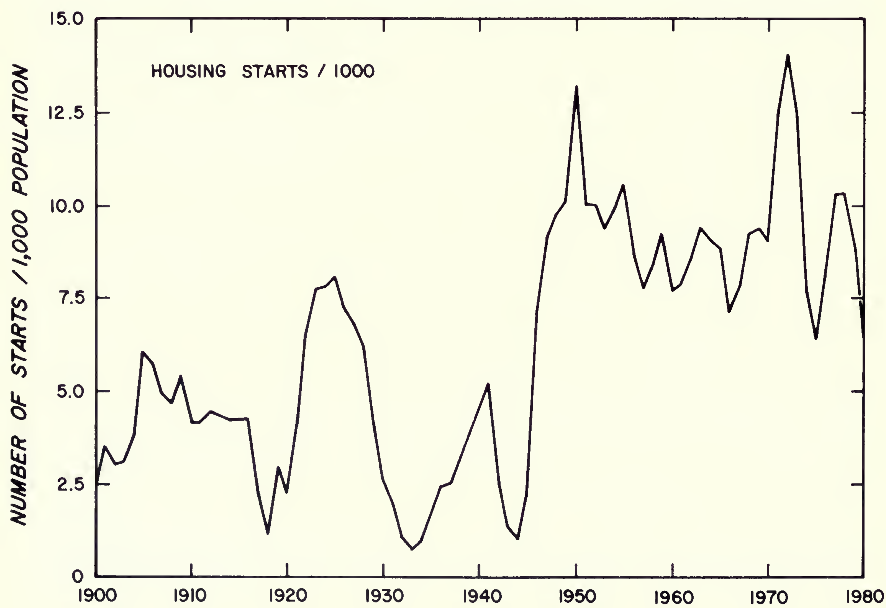


Figure 29-4.—Housing starts in the United States. (Top) Three classes of new public and privately owned units started 1950-1980. (Bottom) Housing starts per 1,000 population in the United States, 1900-1981. (Drawing after McKeever and Hatfield.[1])

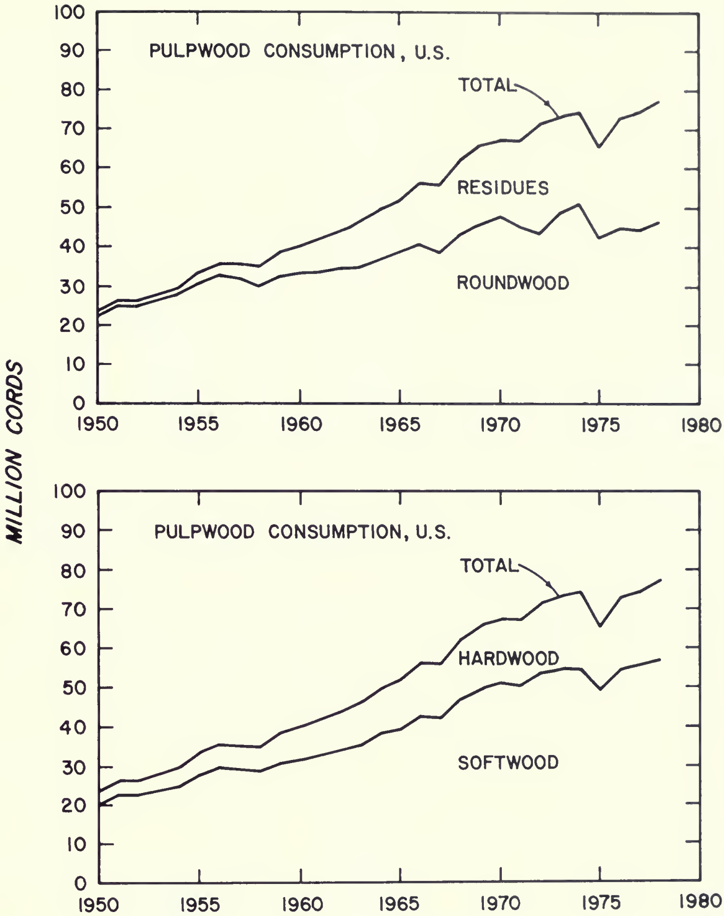


Figure 29-5A.—Annual pulpwood consumption in the United States, 1950-1978. (Top) Roundwood and residues. (Bottom) Hardwood and softwood. (Drawings after McKeever and Hatfield.[1])

Sections and Regions of the United States

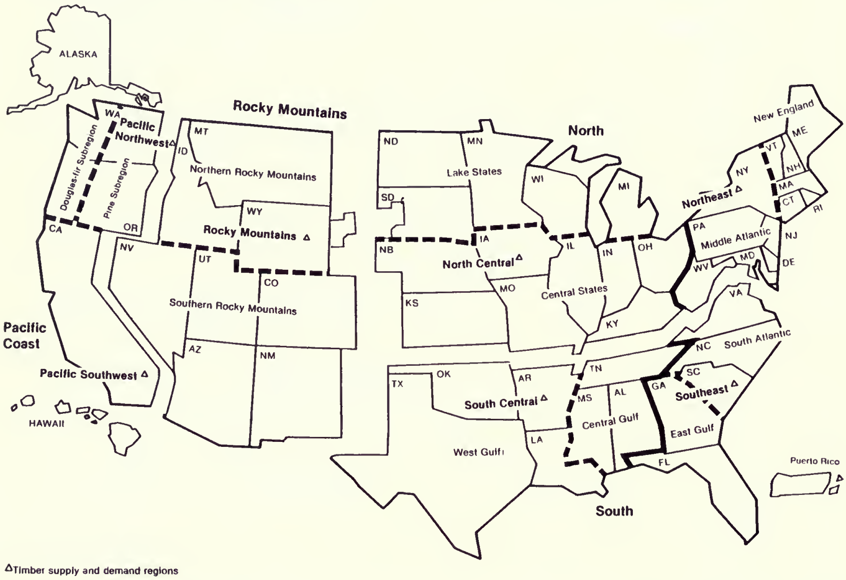


Figure 29-5B.—Statistical forest regions of the United States.

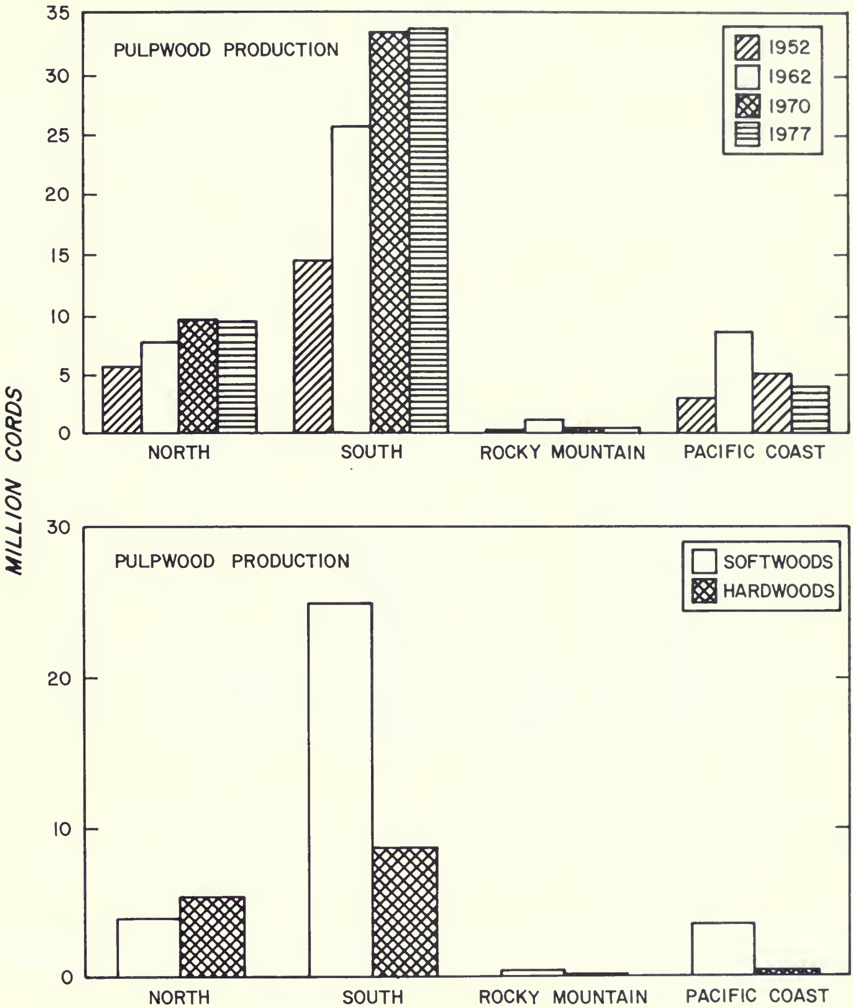


Figure 29-5C.—Regional annual pulpwood production in the United States. (Top) 1952-1977. (Bottom) Hardwoods and softwoods in 1977. (See figure 29-5B for states in each region. (Drawings after McKeever and Hatfield.[1])

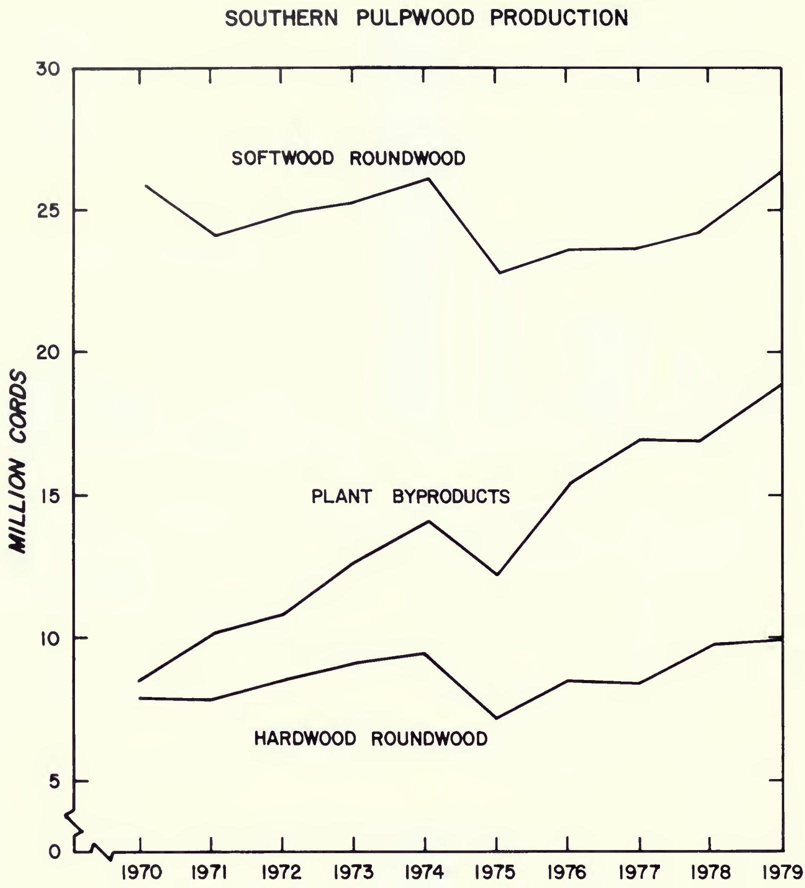


Figure 29-5D.—Pulpwood production in the 12 southern states by species group and category, 1970-1979. See figure 29-5B for included states. (Drawing after Bellamy and Hutchins 1981.)

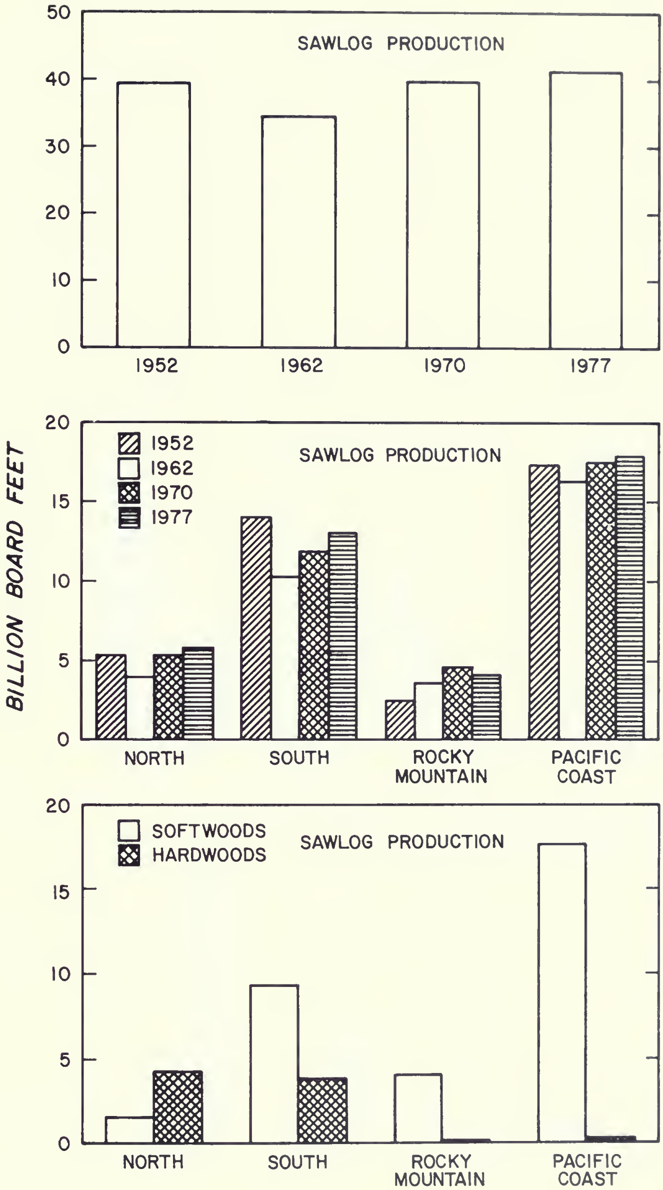


Figure 29-6.—Annual sawlog production in the United States, International ¼-inch log scale. (Top) Total, 1952-1977. (Middle) By region, 1952-1977. (Bottom) By species and region, 1977. See figure 29-5B for states in each region. (Drawing after McKeever and Hatfield.[1])

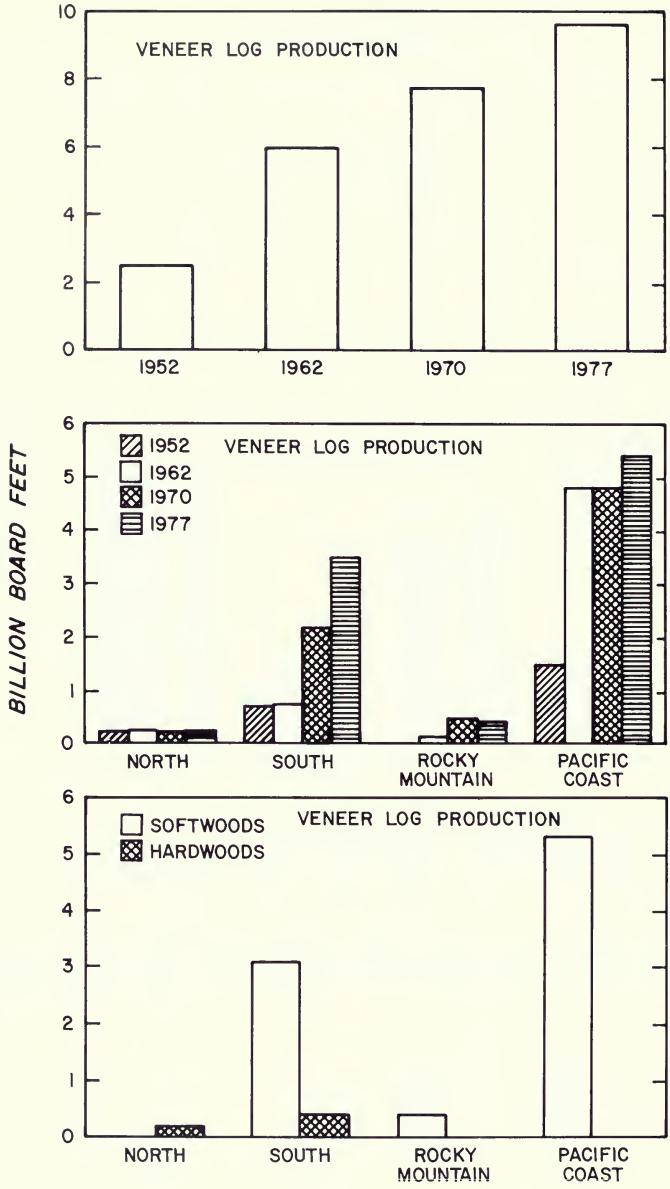


Figure 29-7.—Annual veneer log production in the United States, International ¼-inch log scale. (Top) Total, 1952-1977. (Middle) By region, 1952-1957. (Bottom) By species and region, 1977. See figure 29-5B for states in each region. (Drawings after McKeever and Hatfield.[1])

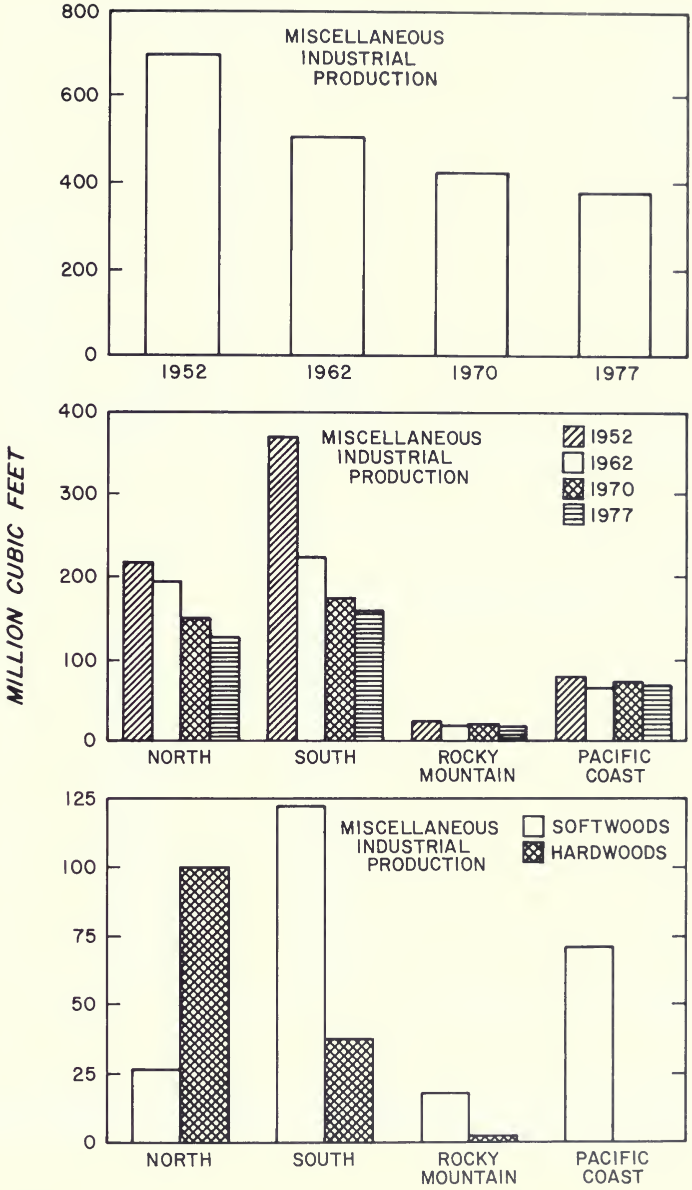


Figure 29-8.—Annual production of logs for miscellaneous industrial use (mainly cooperage, mine timbers, piling, poles, and posts). (Top) Total, 1952-1977. (Middle) By region, 1952-1977. (Bottom) By species and region, 1977. See figure 29-5B for states in each region. (Drawing after McKeever and Hatfield.[1])

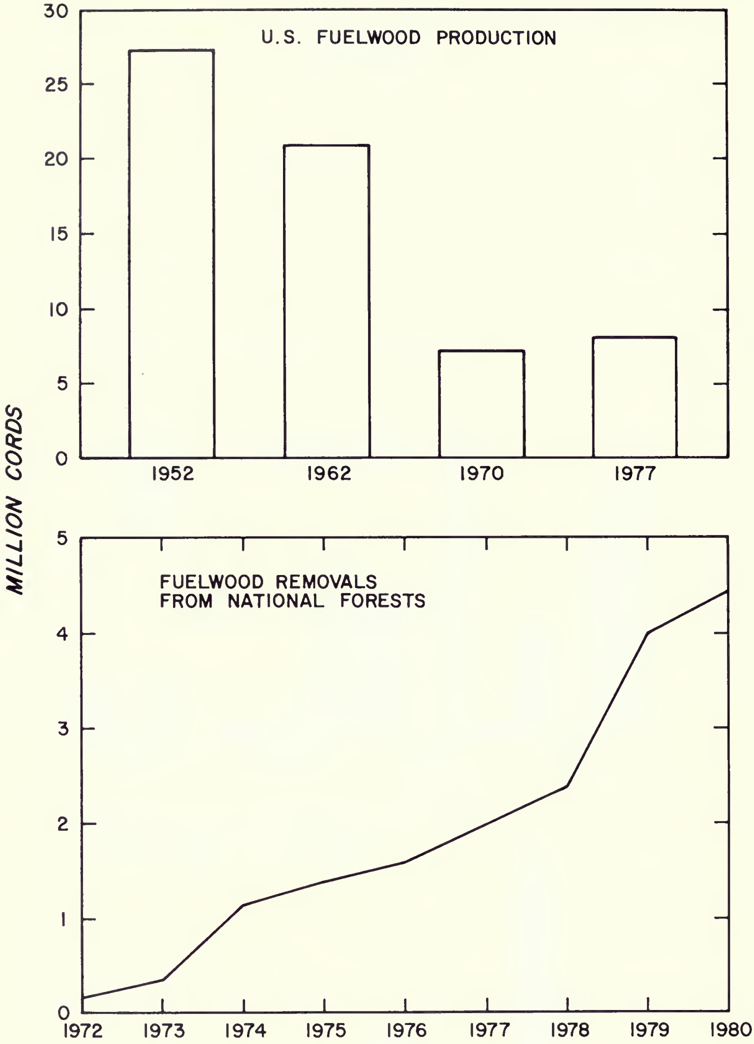


Figure 29-9A.—Annual production of fuelwood in the United States. (Top) Total, 1952-1977. (Bottom) Removals from National Forest System lands, 1972-1980. (Drawings after McKeever and Hatfield.[1])

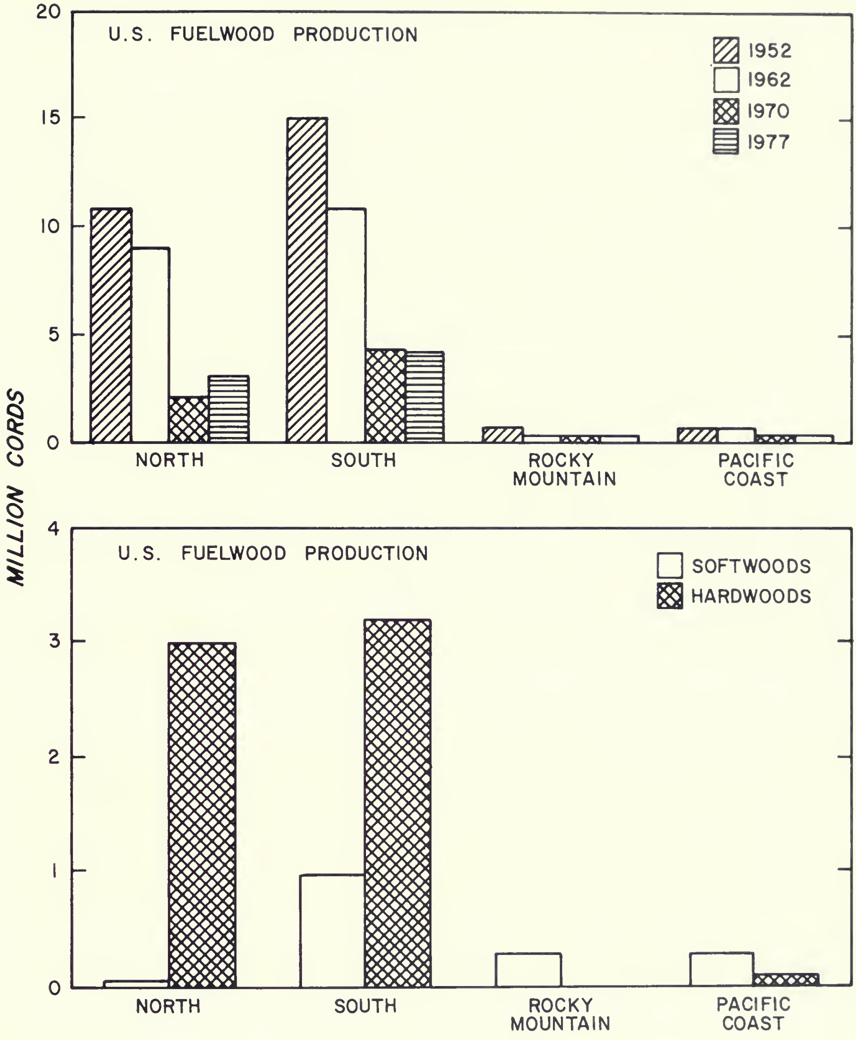


Figure 29-9B.—Annual regional production of roundwood for fuelwood in the United States. (Top) All species, 1952-1977. (Bottom) By species, 1977. See figure 29-5B for states in each region. (Drawings after McKeever and Hatfield.[1])

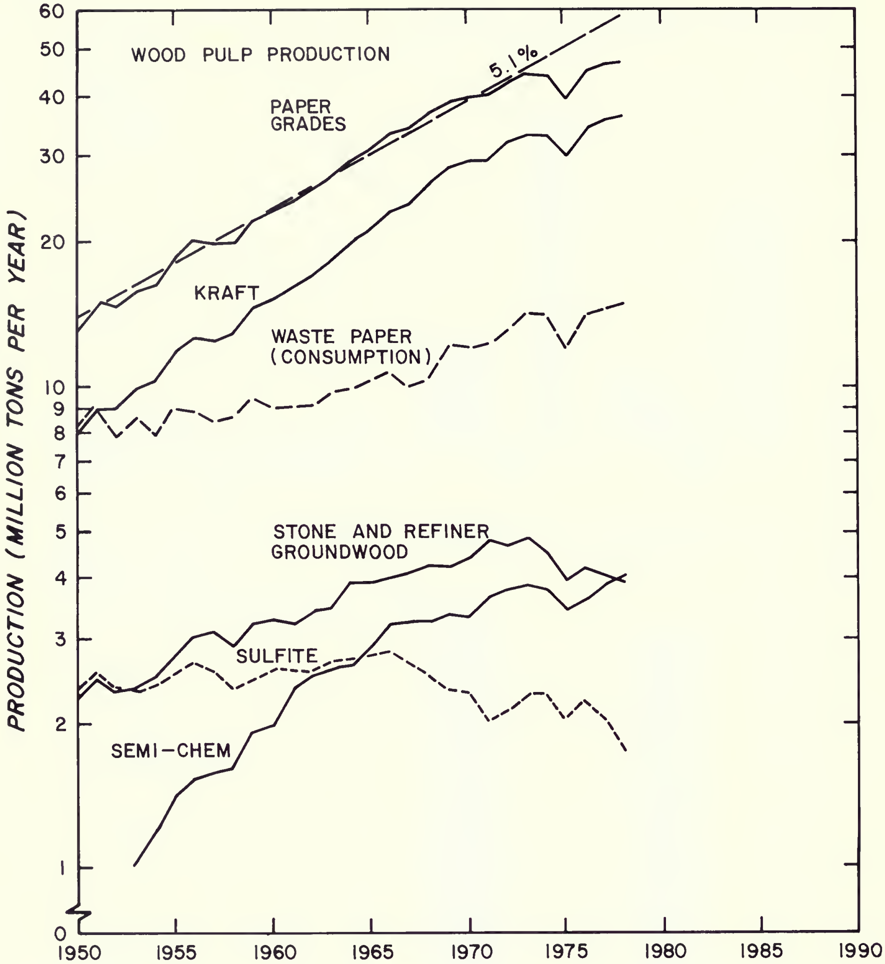


Figure 29-10A.—Production of wood pulp in the United States by type, 1950-1978. (Drawing after Whitney 1980; data from the American Paper Institute.)

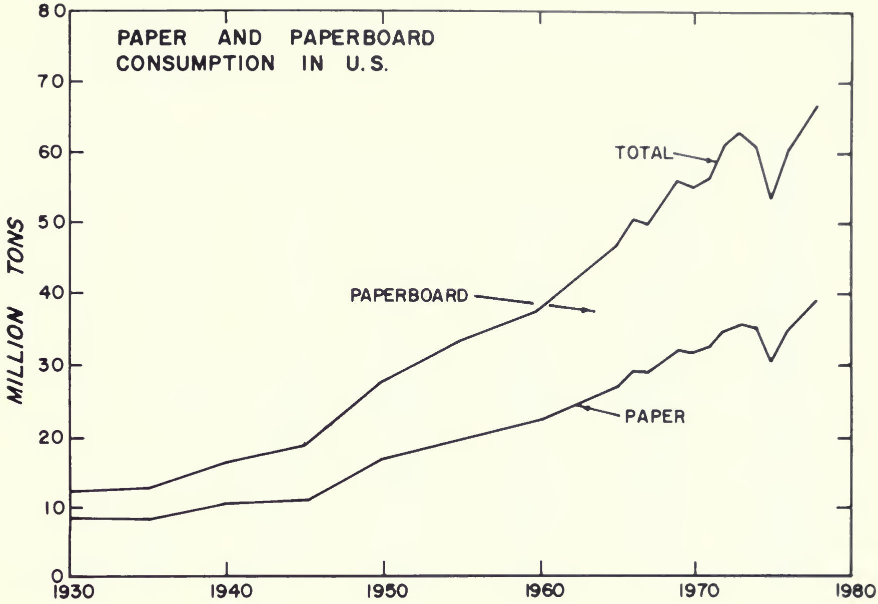


Figure 29-10B.—Annual consumption of paper and paperboard in the United States, 1930-1978. (Drawing after McKeever and Hatfield.[1]) See also figures 25-1 through 25-8.

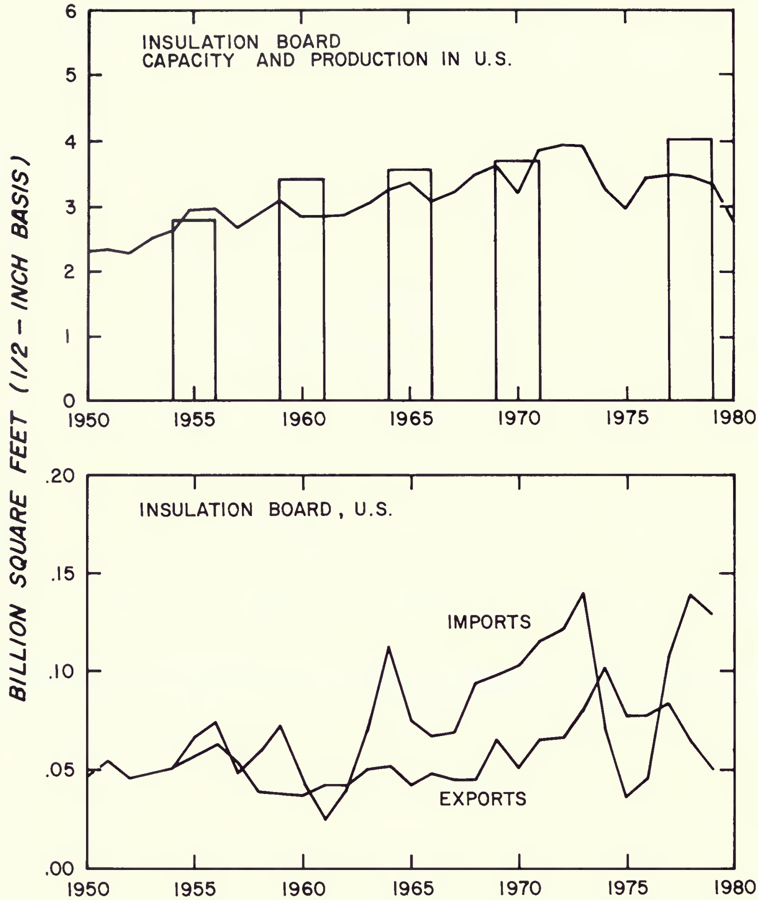


Figure 29-11.—Annual data on insulation board in the United States, 1950-1980. (Top) Production (solid line) and capacity (columns). (Bottom) Imports and exports. (Drawing after McKeever and Hatfield.[1]) See also section 23-2.

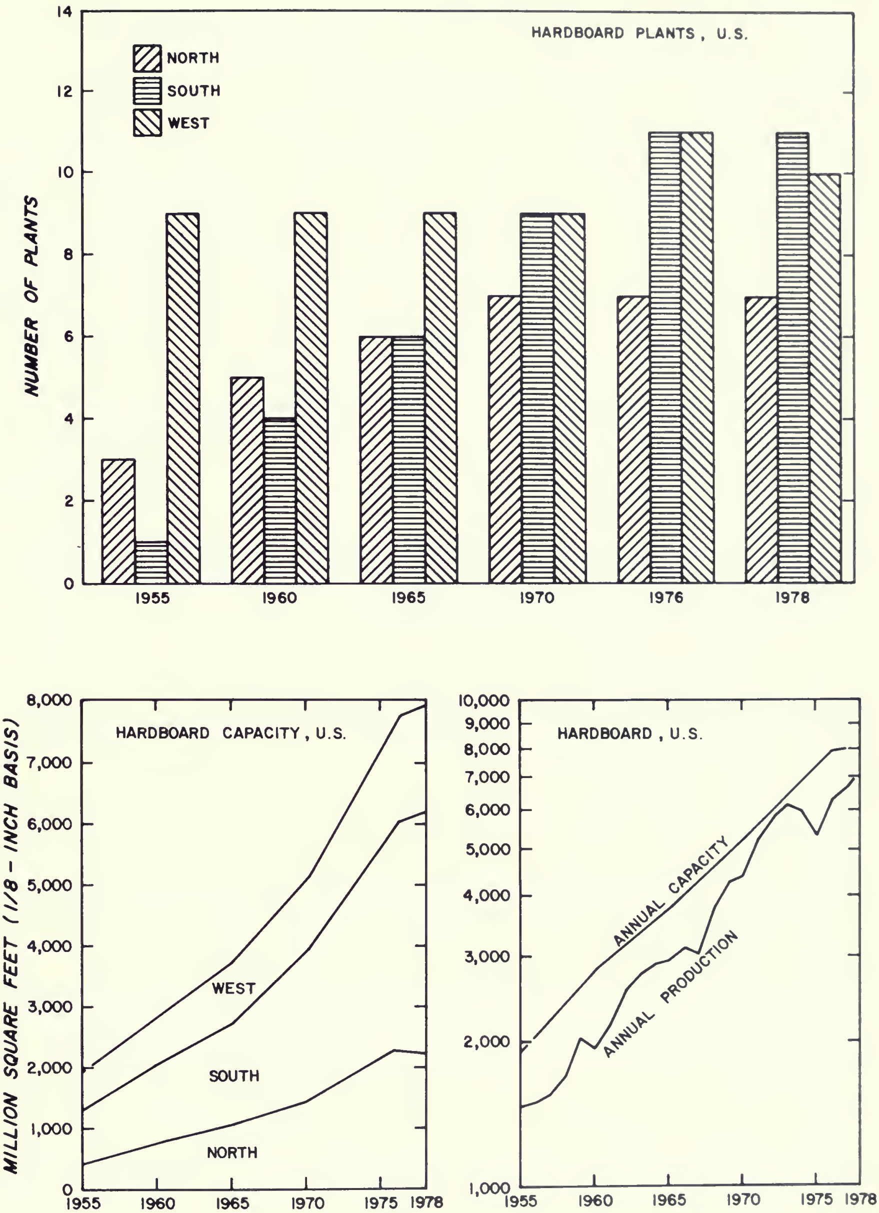


Figure 29-12A.—Data on hardboard plants in the United States, 1955-1978; see also table 23-2. (Top) Number of hardboard plants, by region. (Bottom left) Cumulative annual hardboard capacity, by region. (Bottom right) Annual capacity and production. See drawing 29-5B for states; West includes Rocky Mountains and Pacific Coast regions. (Drawing after McKeever 1979.)

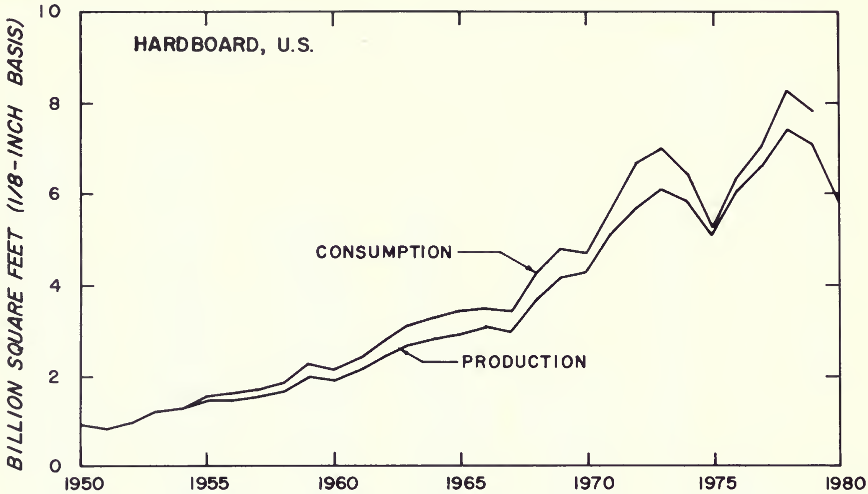


Figure 29-12B.—United States consumption and production of hardboard, 1955-1978. United States' manufacturing capacity in 1978 was a little more than 8 billion square feet. (Drawing after McKeever and Hatfield.[1])

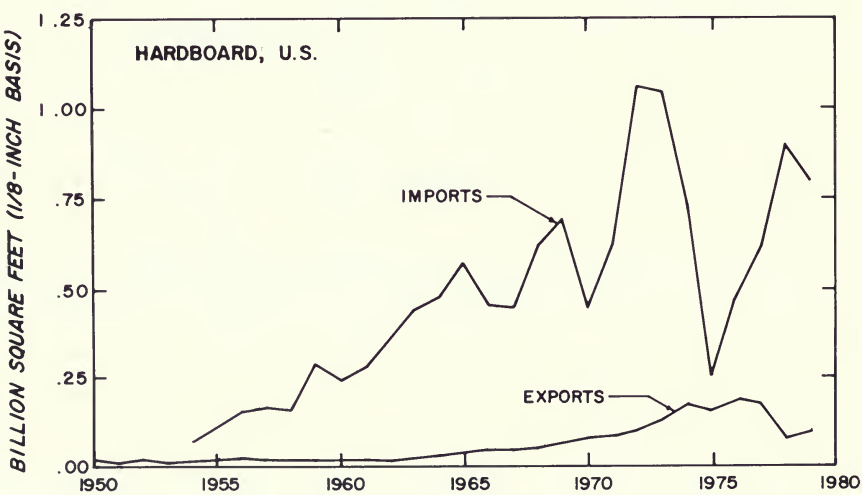


Figure 29-12C.—Hardboard imports into and exports from the United States, 1950-1980. (Drawing after McKeever and Hatfield.[1])

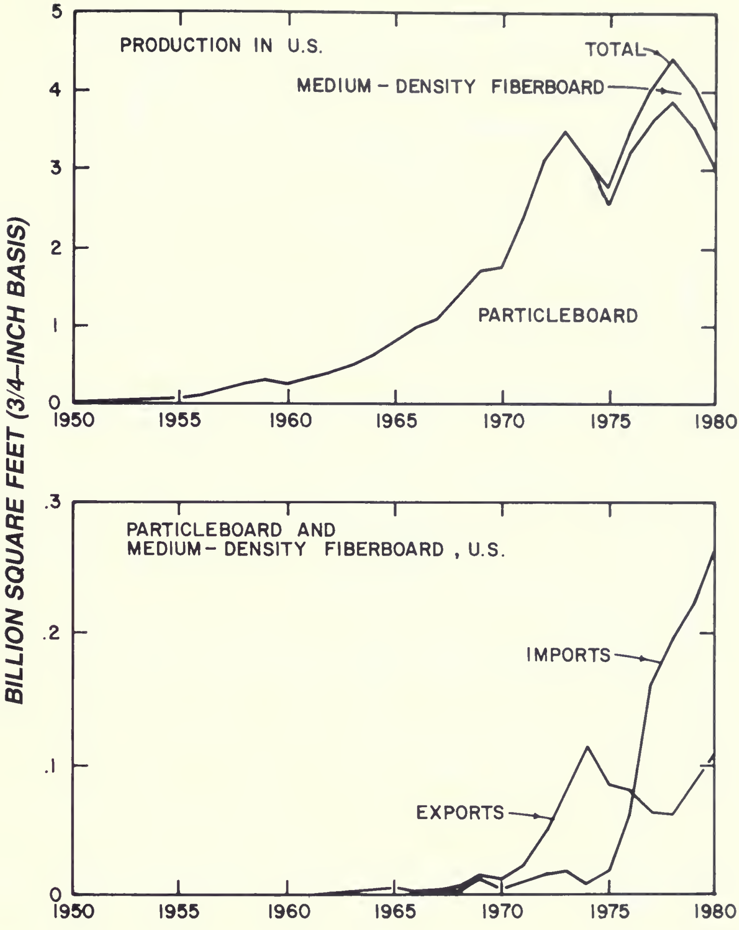


Figure 29-13.—Annual data on particleboard and medium-density fiberboard in the United States, 1950-1980. (Top) Cumulative production; capacities for particleboard only in 1956, 1966, 1971, and 1976 were 0.2, 1.2, 3.1, and 4.5 billion square feet, ¾-inch basis. (Bottom) Imports and exports. (Drawings after McKeever and Hatfield.[1])

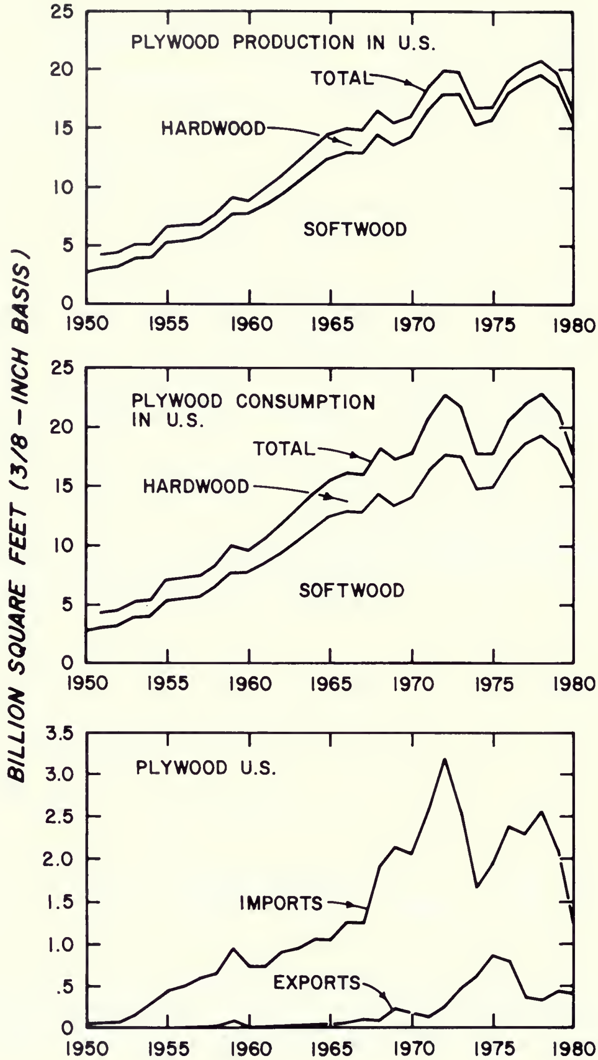


Figure 29-14.—Plywood annual data for the United States, 1950-1980. See also figures 22-45 and 22-46. (Top) Production, by species group. (Middle) Consumption, by species group. (Bottom) Imports and exports, all species. Hardwood plywood exports from 1970 through 1980 averaged about 0.05 billion sq ft per year; prior to 1970, they were less. (Drawings after McKeever and Hatfield.[1])

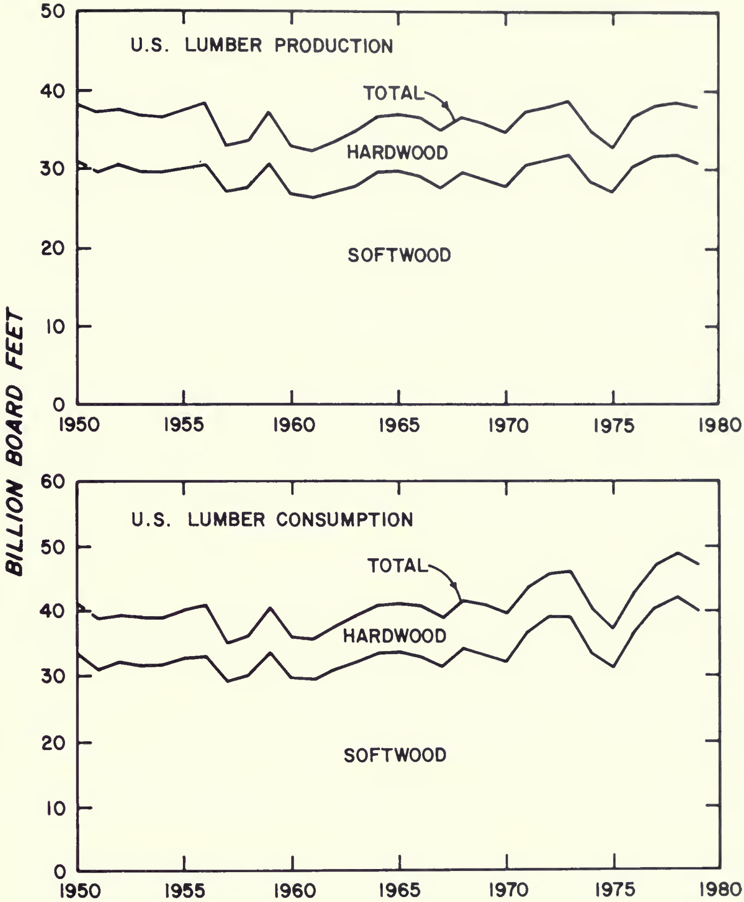


Figure 29-15A.—Annual lumber production (top) and consumption (bottom) in the United States, by species group, 1950-1979. (Drawing after McKeever and Hatfield.[1])

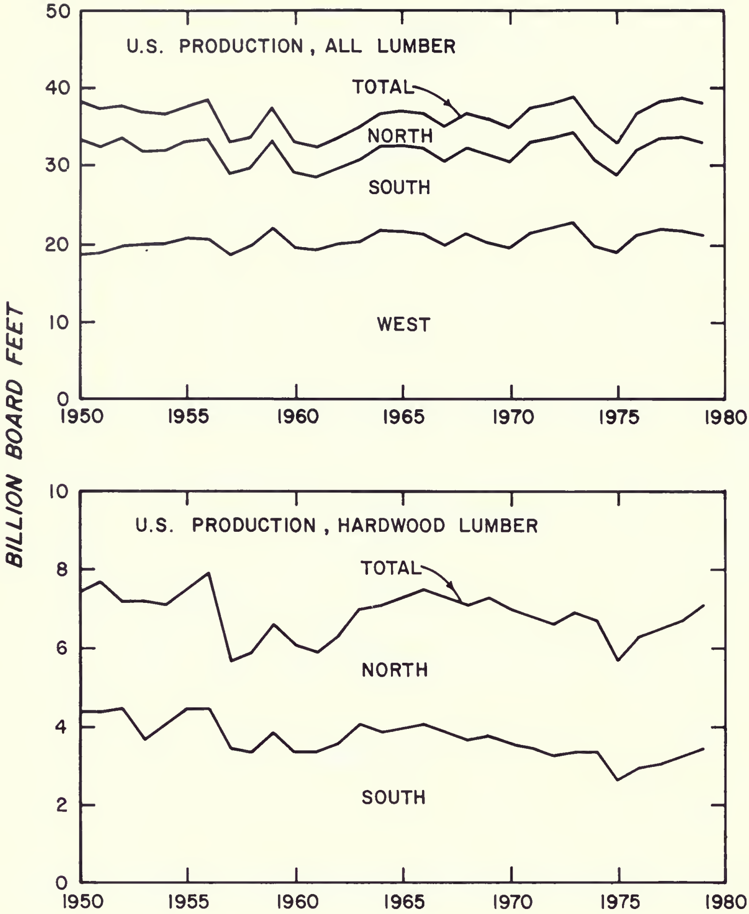


Figure 29-15B.—Annual lumber production in the United States by region, 1950-1980. (Top) All lumber. (Bottom) Hardwood lumber only. See figure 29-5B for states. (Drawing after McKeever ahd Hatfield.[1])

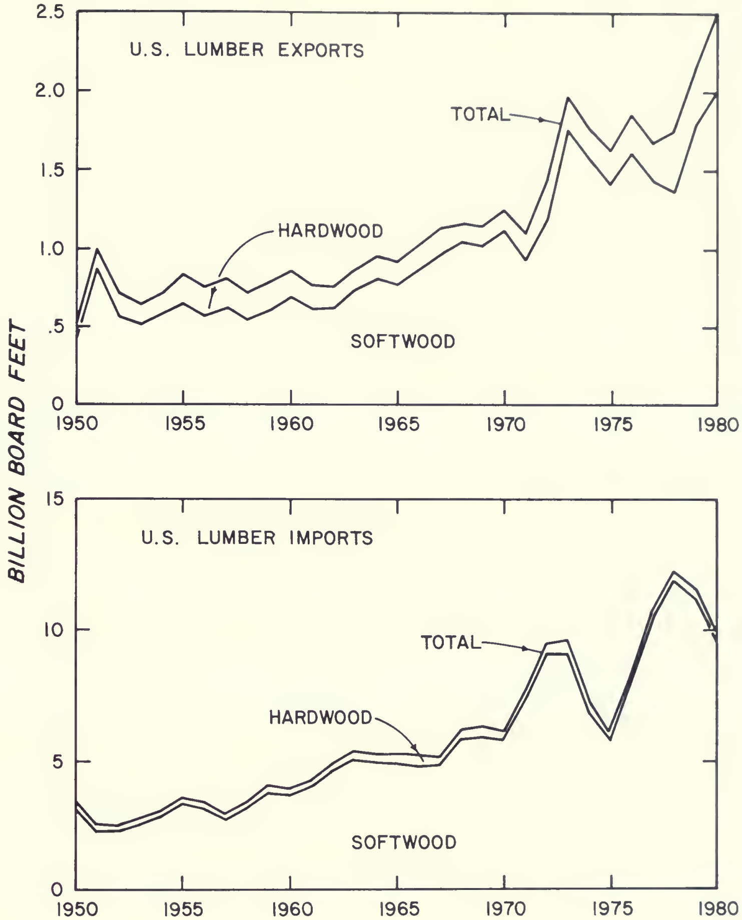


Figure 29-15C.—Exports (top) and imports (bottom) of lumber from and to the United States, by species group, 1950-1980. (Drawings after McKeever and Hatfield.[1])

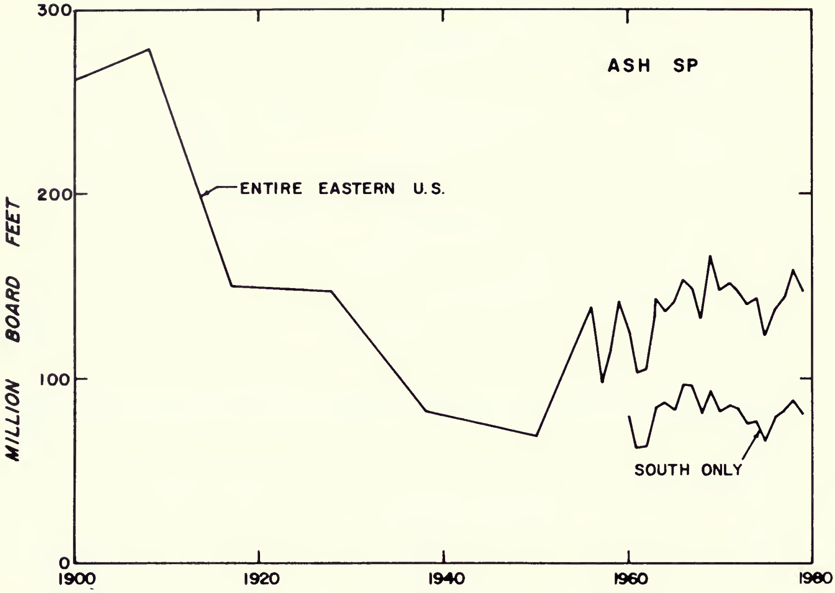


Figure 29-16A.—Production of ash lumber in the entire eastern United States, 1900-1979, and in the South only 1960-1979. See figure 29-5B for states. (Drawing after Stewart and Krajicek (1973) with additions of later data from Bureau of the Census.)

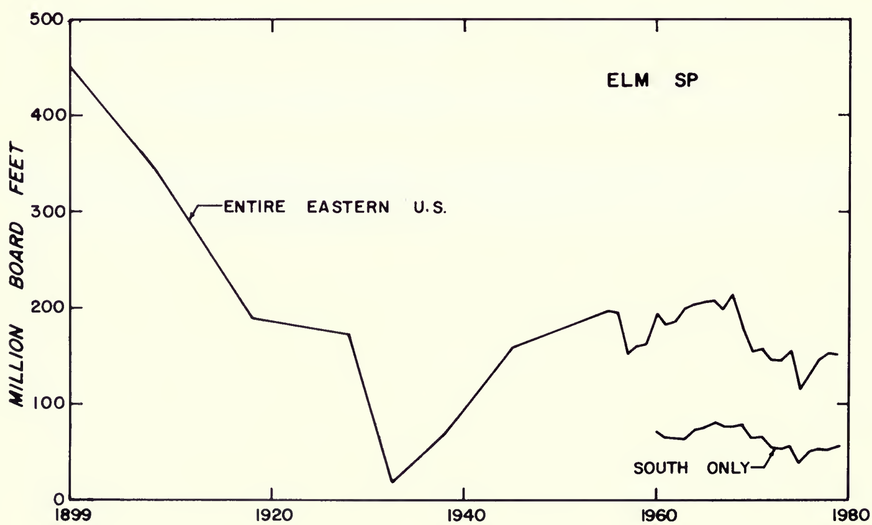


Figure 29-16B.—Production of elm lumber in the entire eastern United States, 1899-1979; and in the South only, 1960-1979. See figure 29-5B for states. (Drawing after Chen and Schlesinger (1973) with addition of later data from Bureau of the Census.)

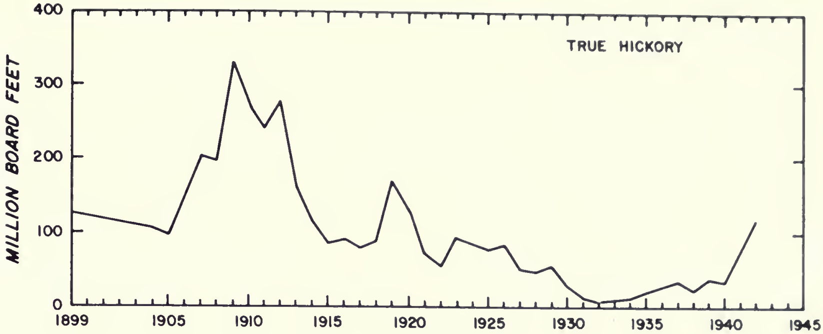


Figure 29-16C.—Production of hickory lumber (shagbark, shellbark, pignut and mockernut) in the United States 1899-1942. (Drawing after Betts 1945a.) In 1965 production of lumber from true and pecan hickories combined was 145.8 million board feet, of which about 60 percent was pecan hickory (Clark 1973).

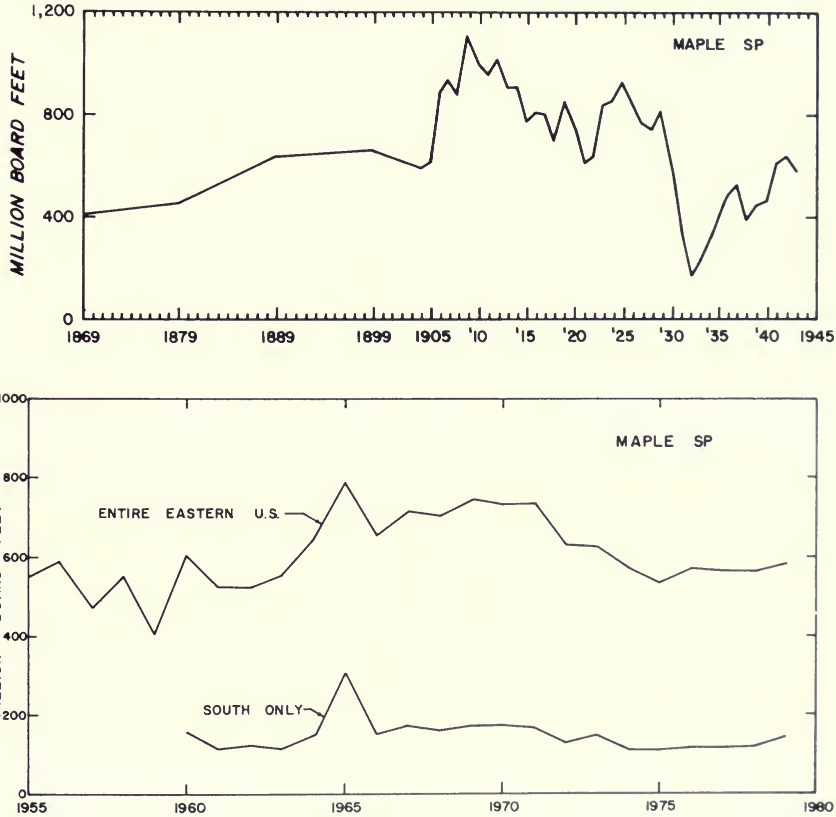


Figure 29-16D.—Production of maple lumber (*Acer* sp.). (Top) In the United States, 1869-1943; drawing after Betts (1945b). (Bottom) In the entire eastern United States, 1955-1979, and in the South only, 1960-1979. See figure 29-5B for states. (Data from Bureau of the Census.)

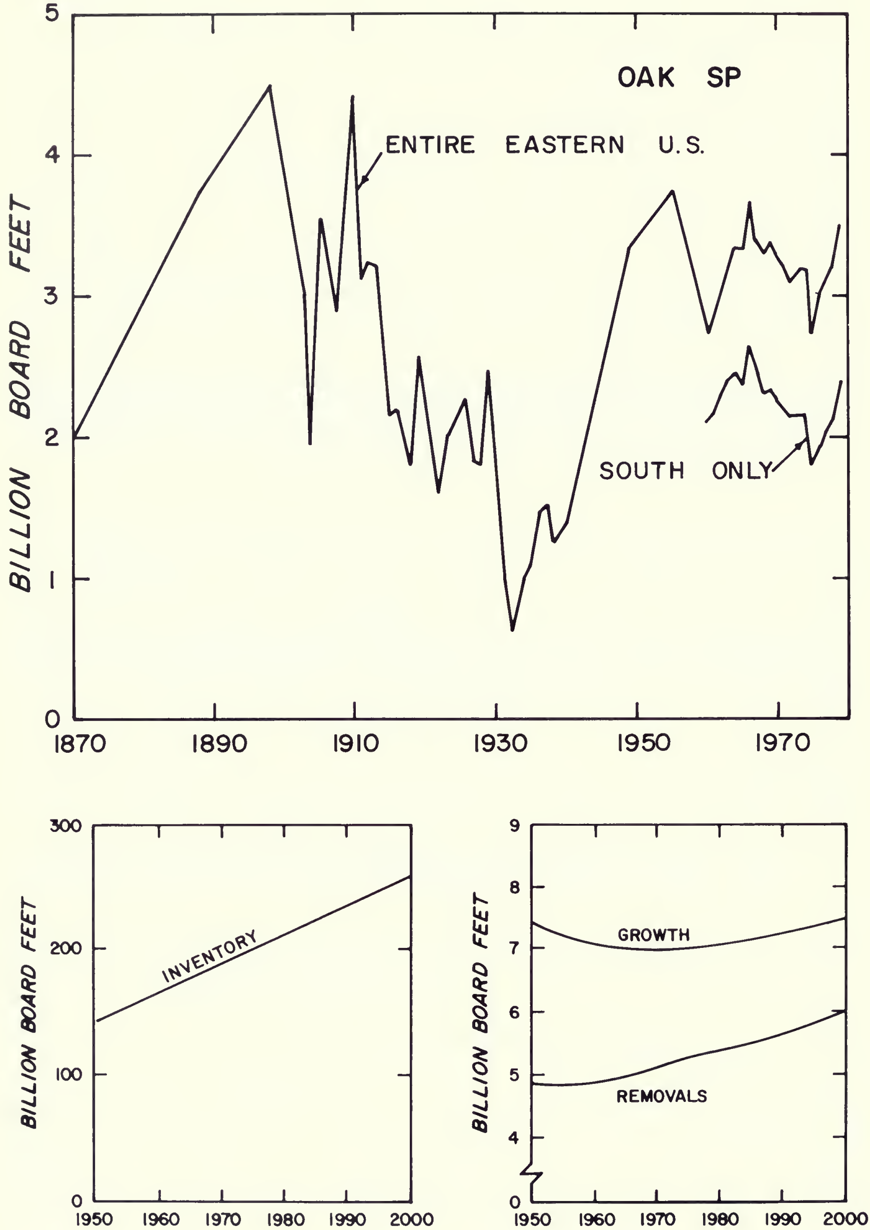
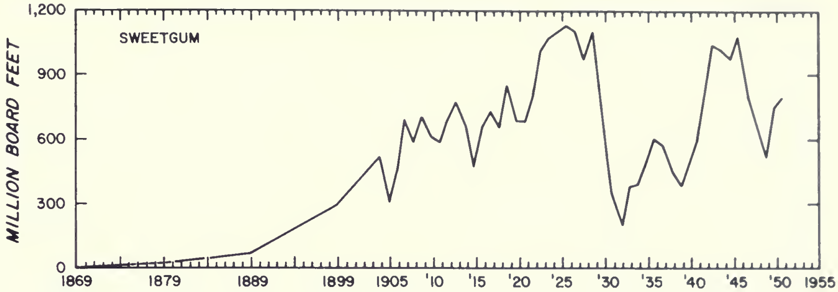


Figure 29-16E.—(Top) Production of oak sp. lumber in the entire eastern United States, 1870-1979; and in the South only, 1960-1979. (Drawing after Cooper and Watt (1973), with addition of later data from Bureau of the Census.) (Bottom) Oak sawtimber inventory, eastern United States, growth, and removals, 1950-1968, with projections to 2000 assuming continuation of 1950-1968 demand trends. See figure 29-5B for states. (Drawings after Quigley 1971.)



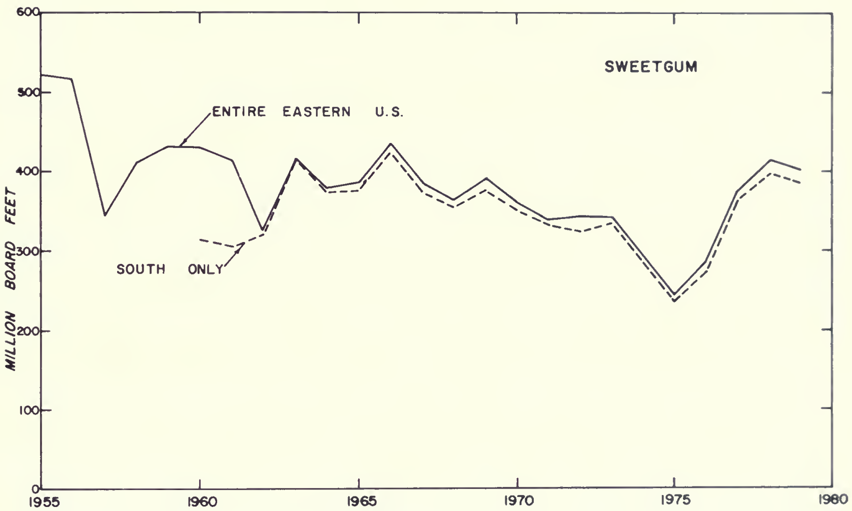
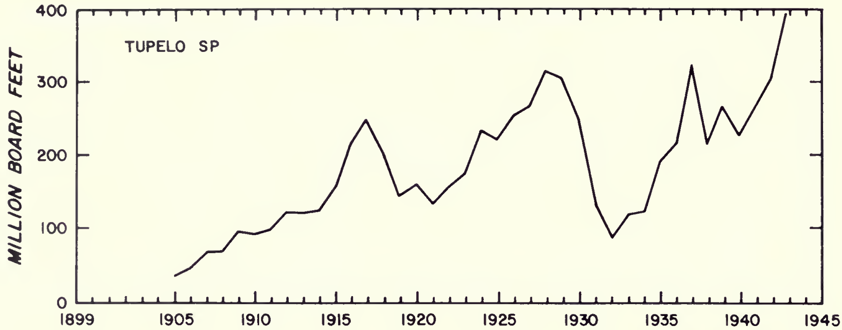


Figure 29-16F.—Production of sweetgum lumber. (Top) In the United States, all from the eastern states, 1869-1951. (Drawing after Betts 1954a.) (Bottom) In the entire eastern United States, 1955-1979, and in the South only, 1960-1979. See figure 29-5B for states. (Data from Bureau of the Census.)



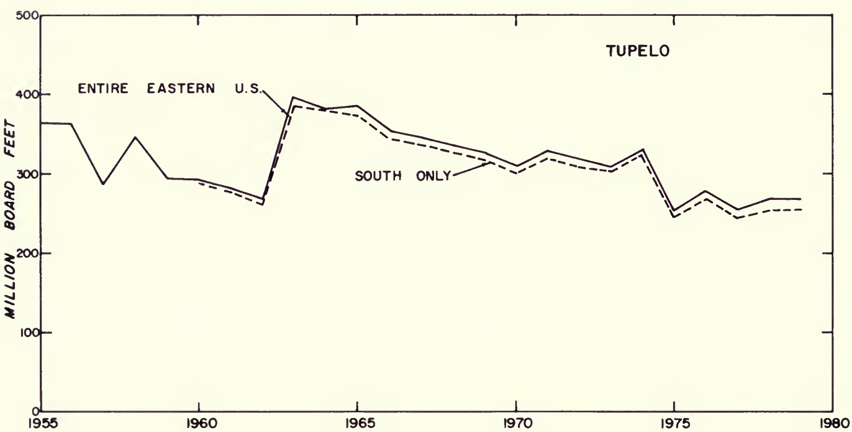


Figure 29-16G.—Production of tupelo lumber (*Nyssa* sp.). (Top) In the United States, all from the eastern states, 1905-1943. (Drawing after Betts 1945c.) (Bottom) In the entire eastern United States, 1955-1979, and in the South only, 1960-1979. See figure 29-5B for states. (Data from Bureau of the Census.)

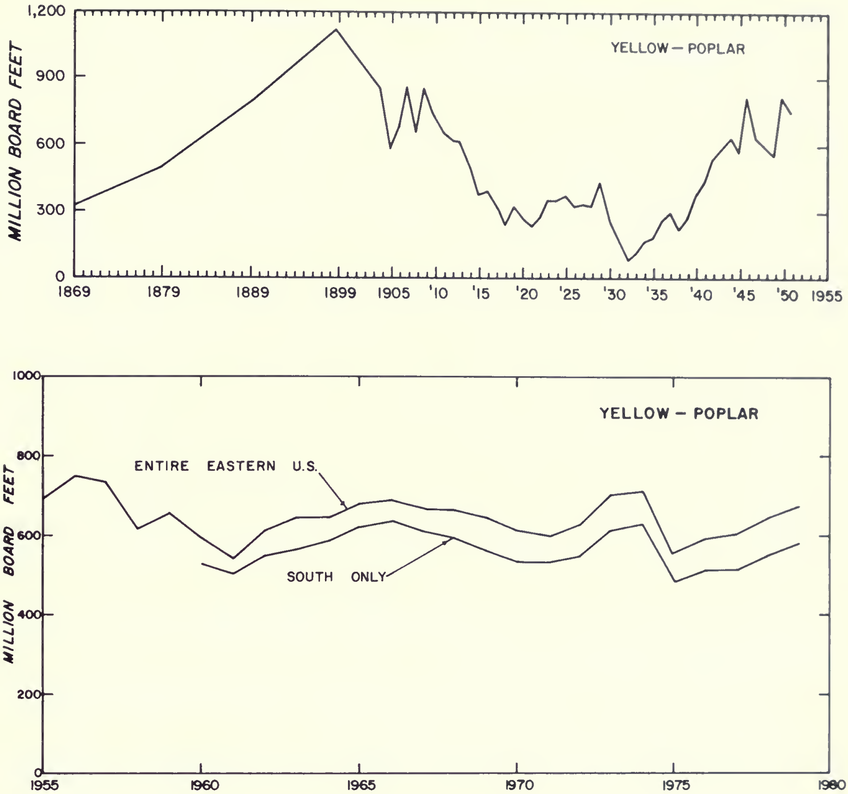


Figure 29-16H.—Production of yellow-poplar lumber. (Top) In the United States, all from the eastern states, 1969-1951. (Drawing after Betts 1945b.) (Bottom) In the entire eastern United States, 1955-1979, and in the South only, 1960-1979. See figure 29-5B for states. (Data from Bureau of the Census.)

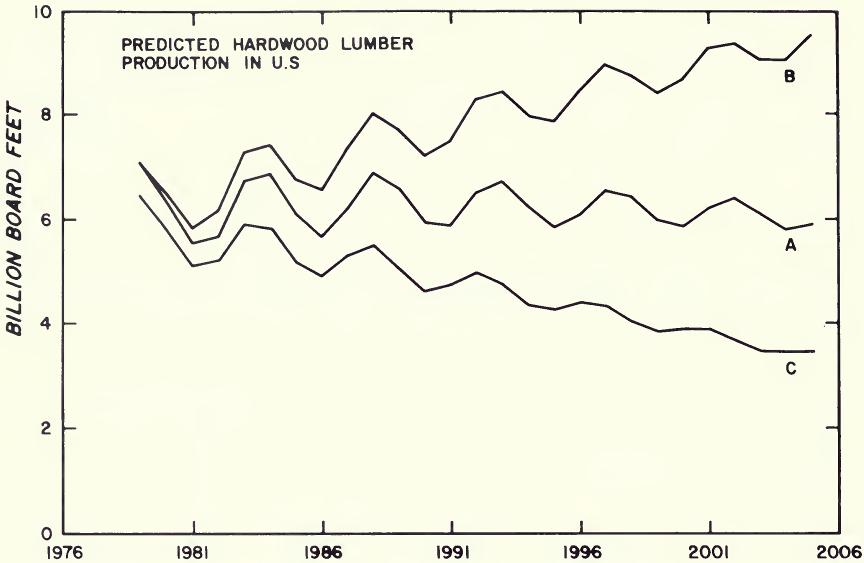


Figure 29-17.—Predicted hardwood lumber production in the United States, under three sets of assumed conditions, as follows:

Conditions A.—Status quo. Under these conditions price and wage rates are assumed to increase at 3 percent per year, while stumpage prices increase at 2 percent. Interest rate prevailing is 8 percent.

Conditions B.—An optimistic view. Conditions assumed the same as in condition A, except price of lumber is assumed to increase at 5 percent per year, rather than 3 percent per year.

Conditions C.—A pessimistic view. Assumes the high rate of inflation of 1980 and 1981 will continue until 2005 and that lumber prices and wages increase at 10 percent per year while stumpage prices increase 5 percent per year. Interest rate prevailing is 16 percent.

(Drawing after Luppold 1981, p. 93).

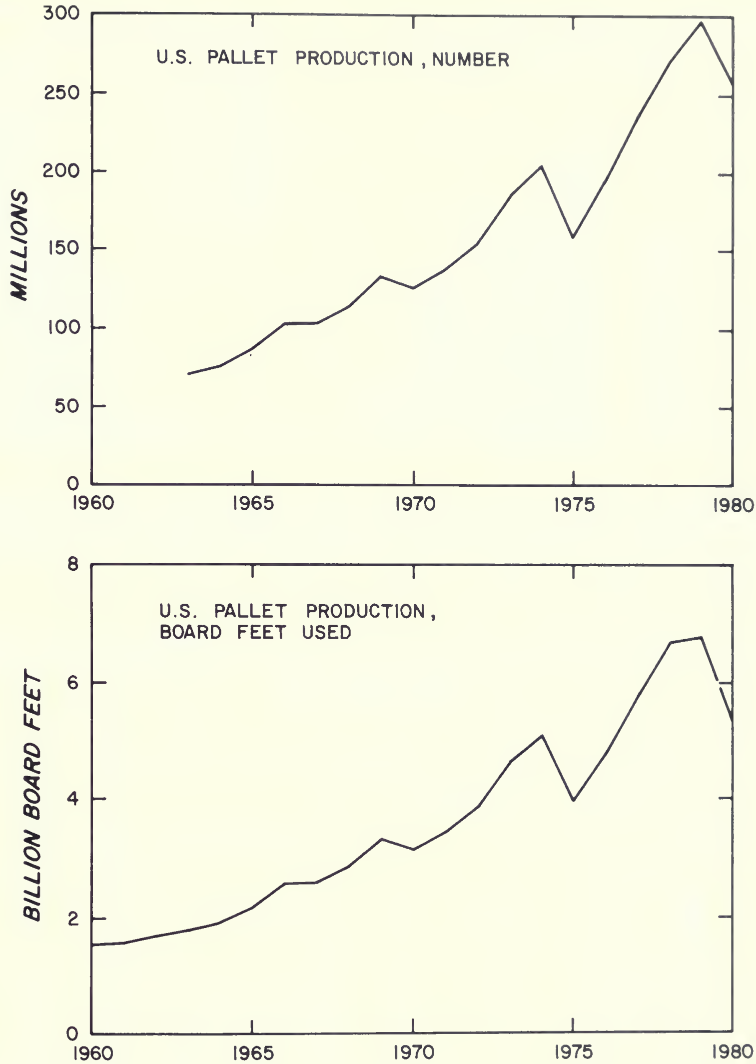


Figure 29-18A.—Pallets produced annually in the United States. (Top) Number of pallets, 1963-1980. (Bottom) Board feet of lumber used, 1960-1980. (Drawing after McKeever and Hatfield.[1]) See also figures 29-18B and 22-21AB.

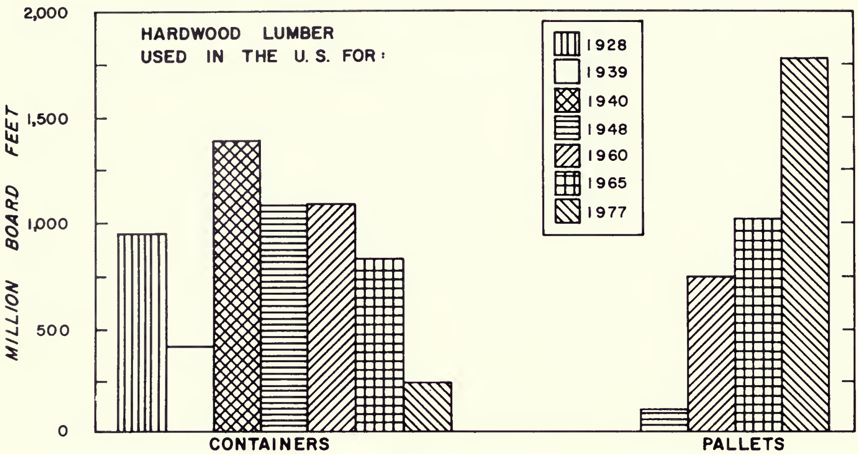


Figure 29-18B.—Hardwood lumber used annually in the United States in the manufacture of containers and pallets, 1928-1977. (Drawing after McKeever and Hatfield.[1])

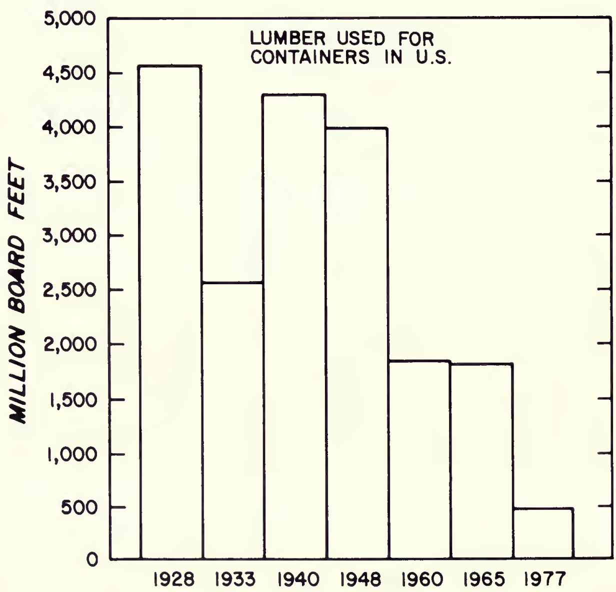


Figure 29-19.—Lumber used for wood containers in the United States, 1928-1977. In 1977 about one-third of this lumber was hardwood. (Drawing after McKeever and Hatfield.[1]) See figures 22-21AB and 29-18 for data on pallets.

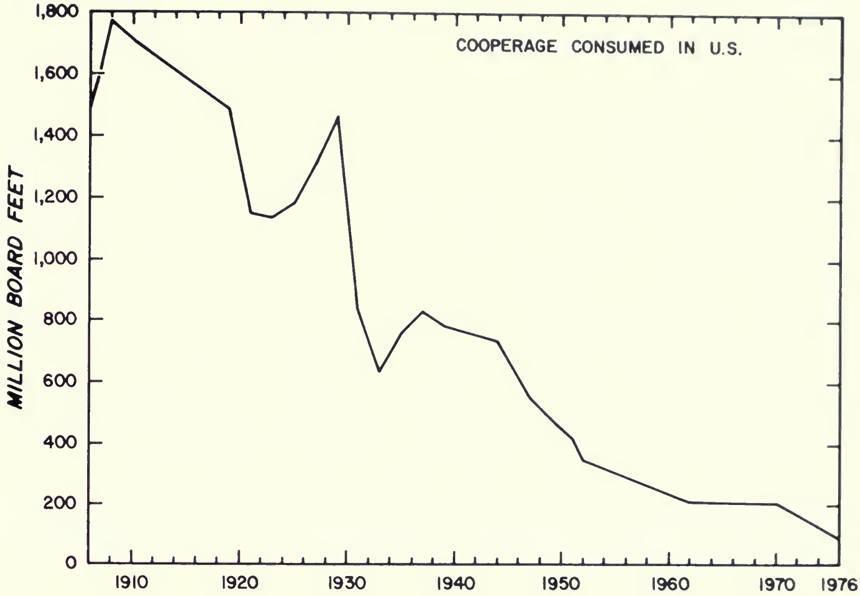


Figure 29-20.—Cooperage consumed in the United States, 1906-1976. (Drawing after McKeever and Hatfield.[1])

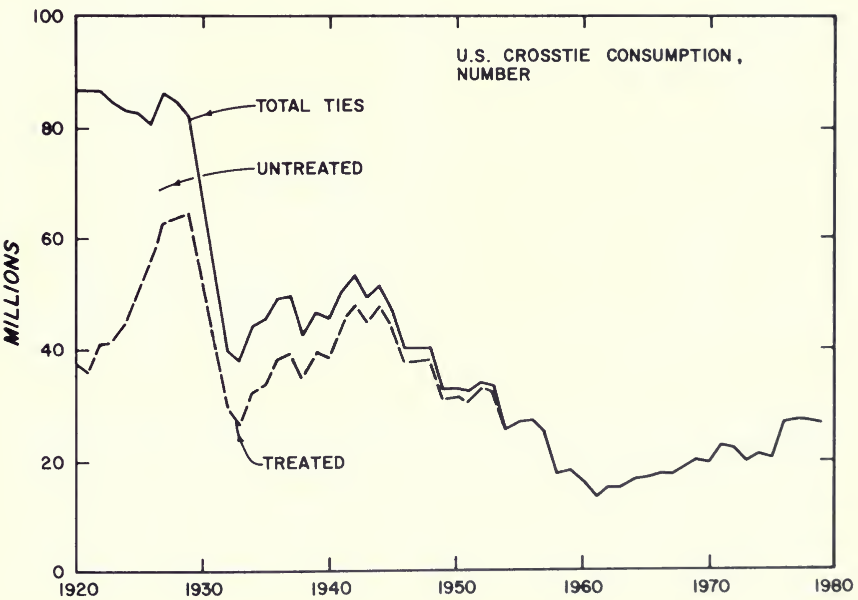


Figure 29-21.—Number of treated and untreated crossties annually consumed in the United States, 1920-1978. (Drawing after McKeever and Hatfield.[1]) See also figures 22-53 and 22-54.

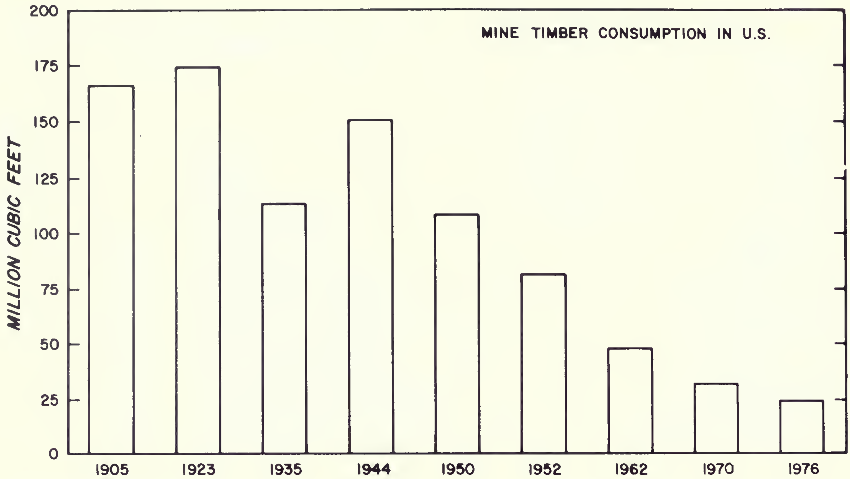


Figure 29-22.—Cubic feet of mine timbers annually consumed in the United States, 1905-1976. (Drawing after McKeever and Hatfield.[1])

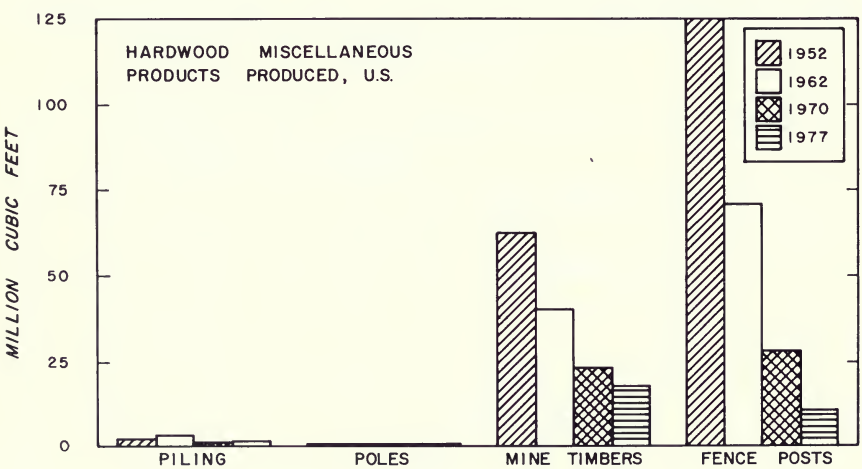


Figure 29-23.—Production of hardwood piling, poles, mine timbers, and fence posts in 1952, 1962, 1970, and 1977. Consumption of fence posts of all species, softwood as well as hardwood, declined steadily from about 900 million pieces annually in 1920 to less than 100 million pieces in 1977; pole consumption, mostly softwood, was fairly constant from 1950 to 1977 at from 5 million to 7 million pieces annually. Between 1970 and 1978, annual consumption of highway guardrail posts declined from about 300 million board feet to about 150 million board feet of all species. See figure 29-22 for long-term trend of mine timber consumption. (Drawing after McKeever and Hatfield.[1])

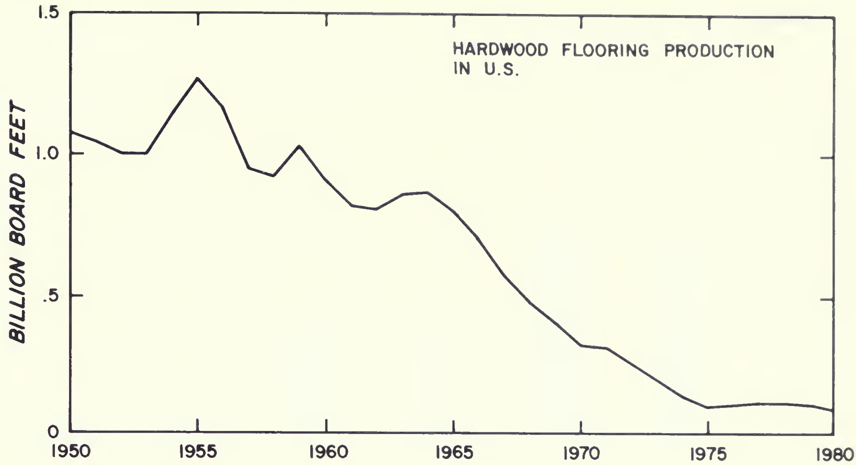


Figure 29-24.—Hardwood flooring production in the United States, 1950-1980. (Drawing after McKeever and Hatfield.[1]) See also figures 22-6 and 22-10.

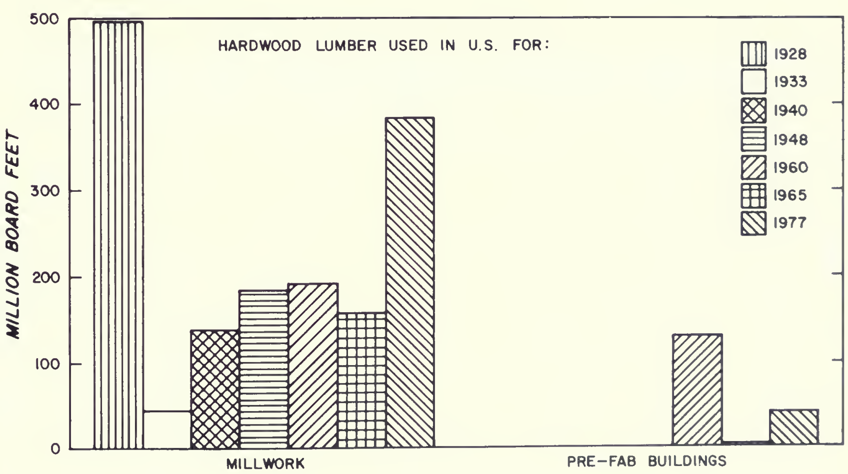


Figure 29-25.—Hardwood lumber consumed in the United States for manufacture of millwork and prefabricated buildings, 1928-1977. (Drawing after McKeever and Hatfield.[1])

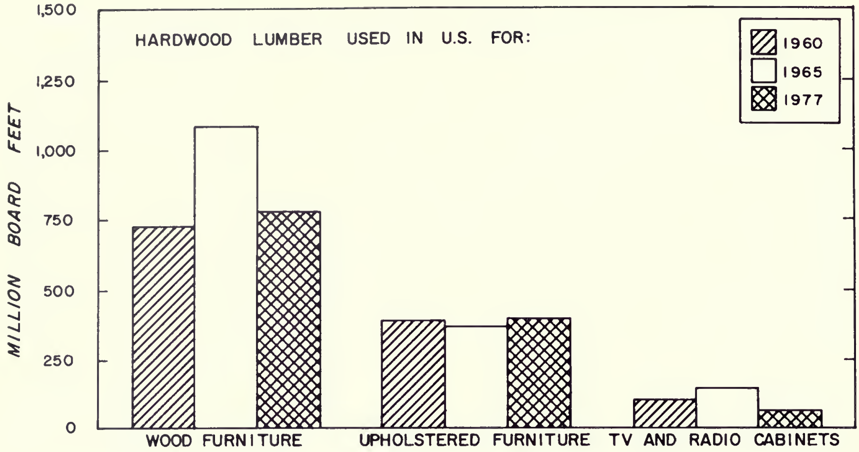


Figure 29-26.—Hardwood lumber consumed in the United States for manufacture of wood household furniture (including upholstered) and for television and radio cabinets, 1960-1977; census categories 2511, 2512, and 2517. (Data from McKeever and Hatfield.[1])

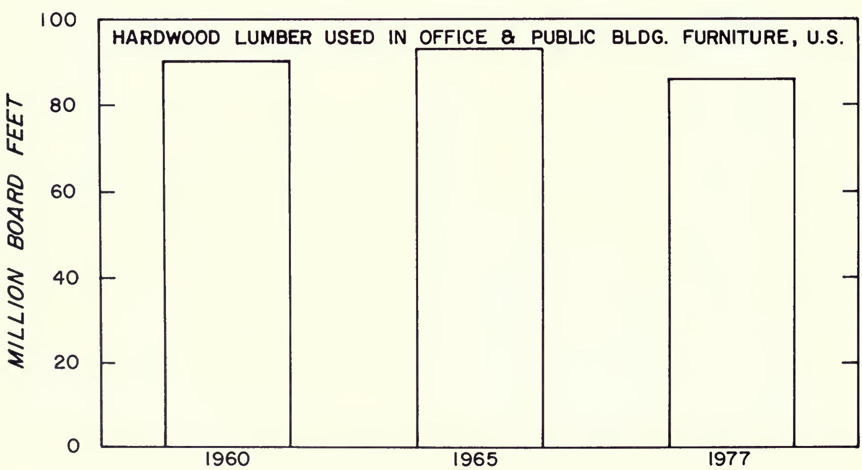


Figure 29-27.—Hardwood lumber consumed in the United States for manufacture of furniture in offices and public buildings, 1960-1977; census categories 2521 and 2531. (Data from McKeever and Hatfield.[1])

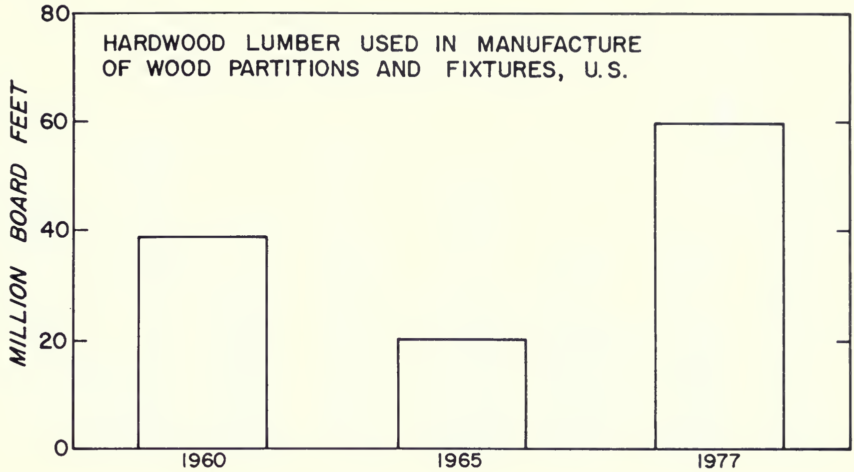


Figure 29-28.—Hardwood lumber consumed in the United States in manufacture of fixtures and wood partitions, 1960-1977; census category 2541. (Data from McKeever and Hatfield.[1])

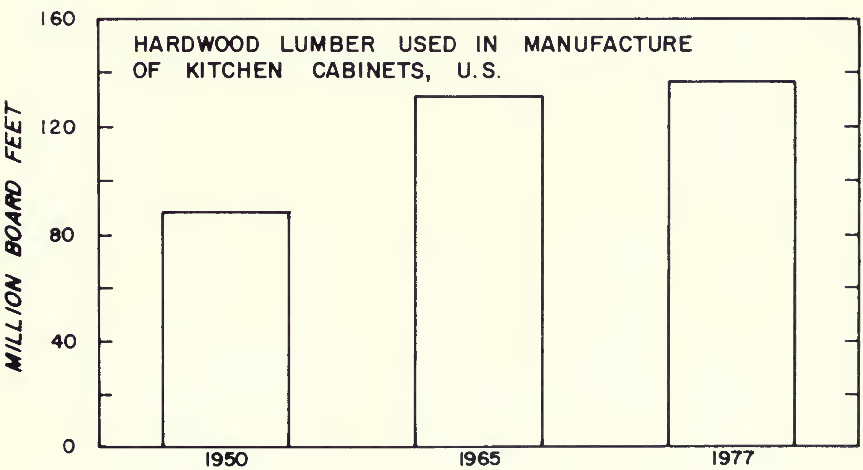


Figure 29-29.—Hardwood lumber consumed in the United States for manufacture of wood kitchen cabinets, 1960-1977; census category 2434. (Data from McKeever and Hatfield.[1])

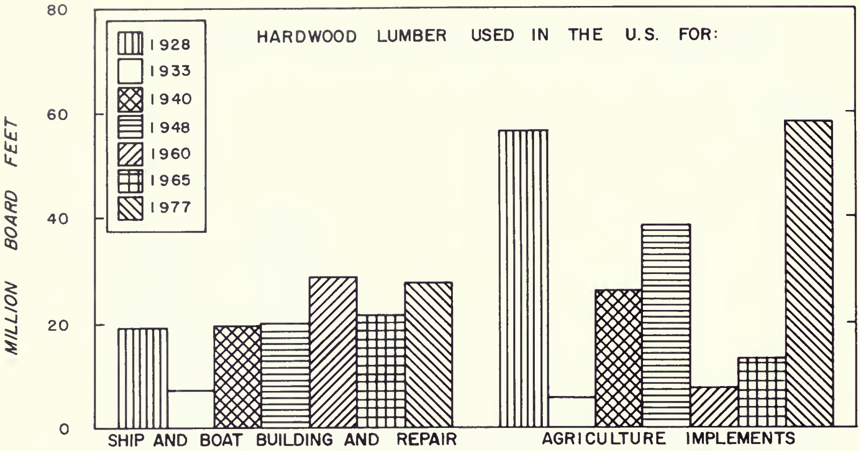


Figure 29-30.—Hardwood lumber consumed in the United States for ship and boat building and repairing, and for agricultural implements, 1928-1977. (Data from McKeever and Hatfield.[1])

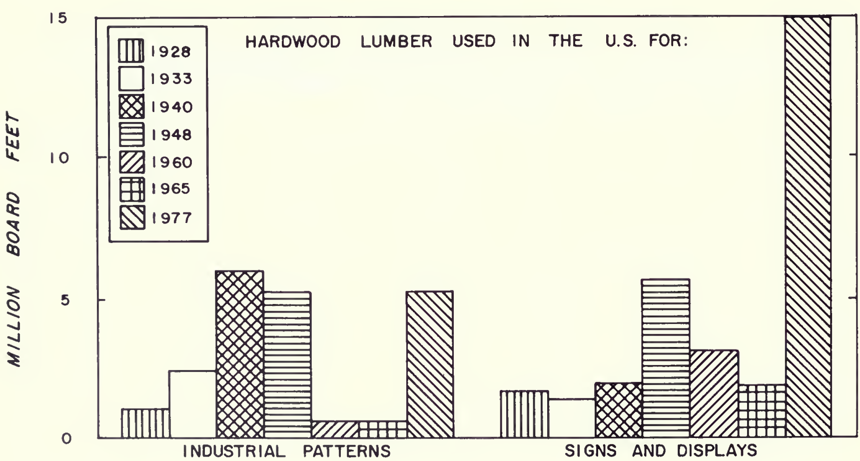


Figure 29-31.—Hardwood lumber consumed in the United States for industrial patterns, and for signs and displays, 1928-1977. (Data from McKeever and Hatfield.[1])

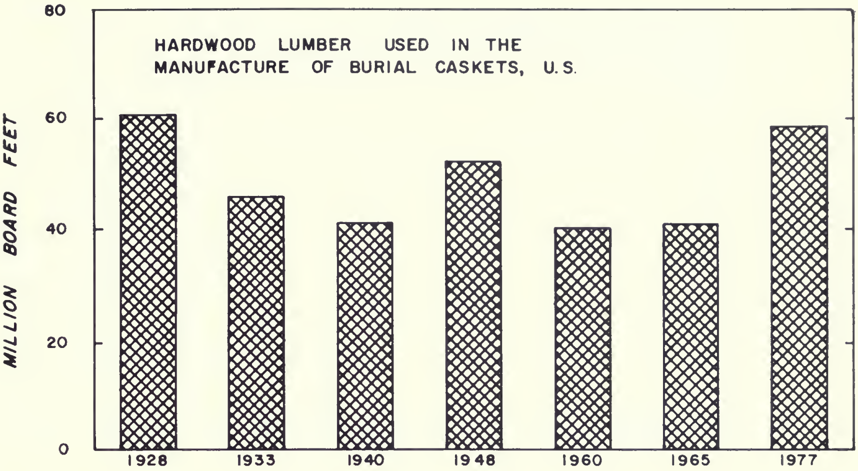


Figure 29-32.—Hardwood lumber consumed in the United States for manufacture of burial caskets, 1928-1977; census category 3995. (Data from McKeever and Hatfield.[1])

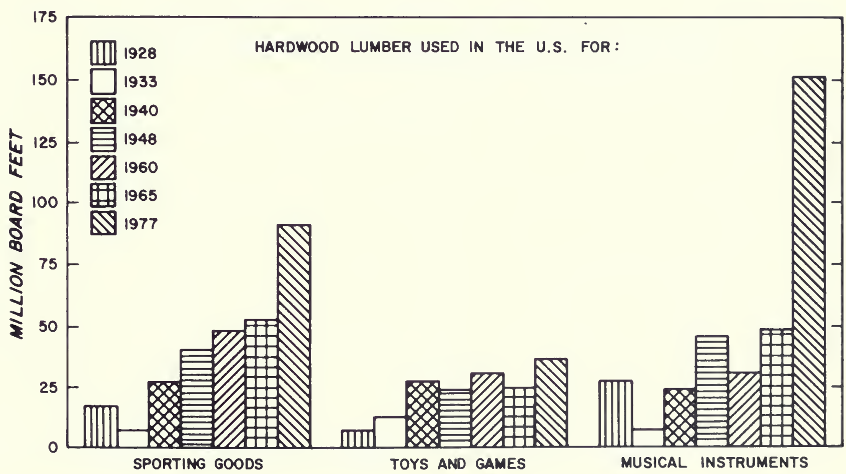


Figure 29-33.—Hardwood lumber consumed in the United States for manufacture of sporting goods, toys and games, and musical instruments, 1928-1977. (Drawing after McKeever and Hatfield.[1])

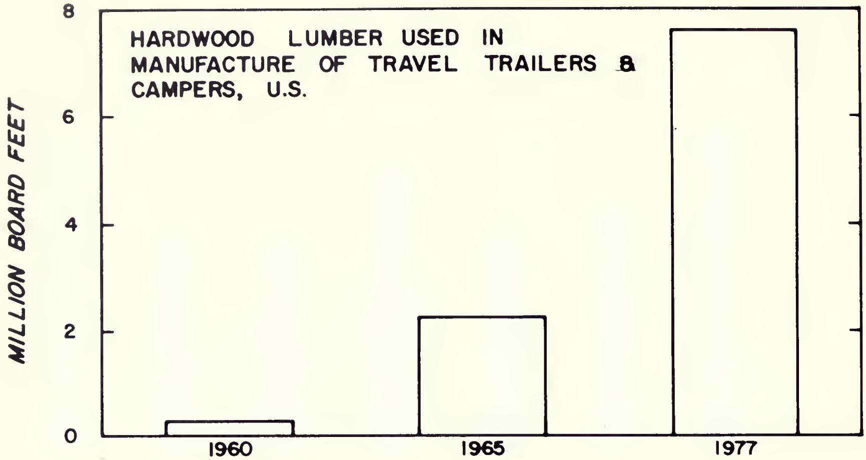


Figure 29-34.—Hardwood lumber consumed in the United States for manufacture of travel trailers and campers, 1960-1977; census category 3792. (Data from McKeever and Hatfield.[1])

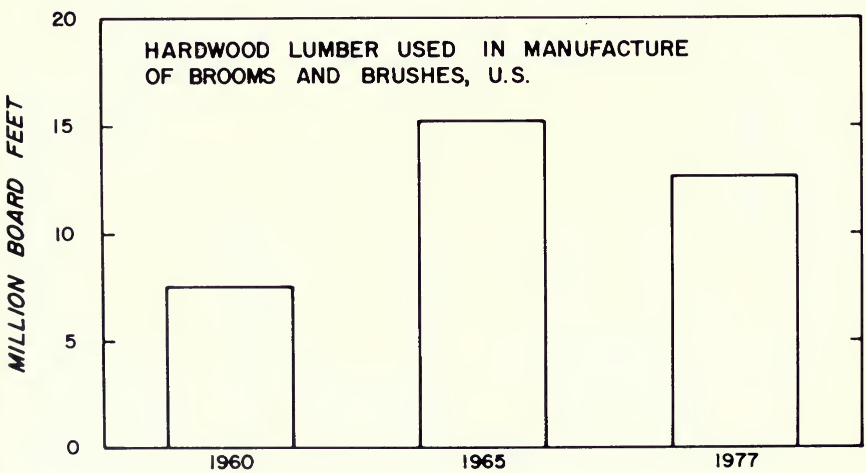


Figure 29-35A.—Hardwood lumber consumed in the United States for manufacture of brooms and brushes, 1960-1977; census category 3991. (Data from McKeever and Hatfield.[1])

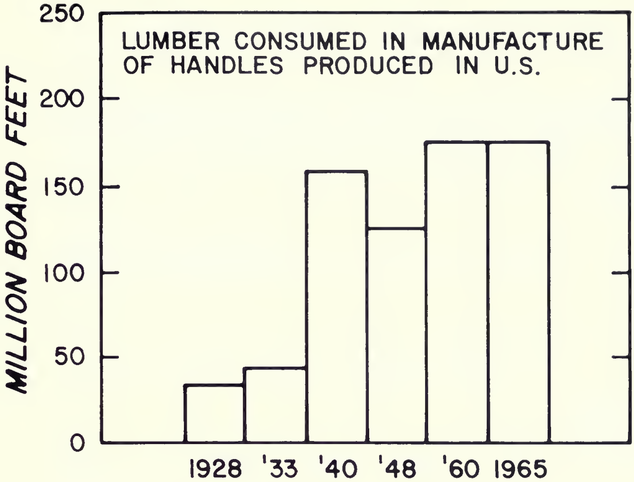


Figure 29-35B.—Lumber consumed in the manufacture of handles in the United States, 1928-1965. (Drawing after McKeever and Hatfield.[1])

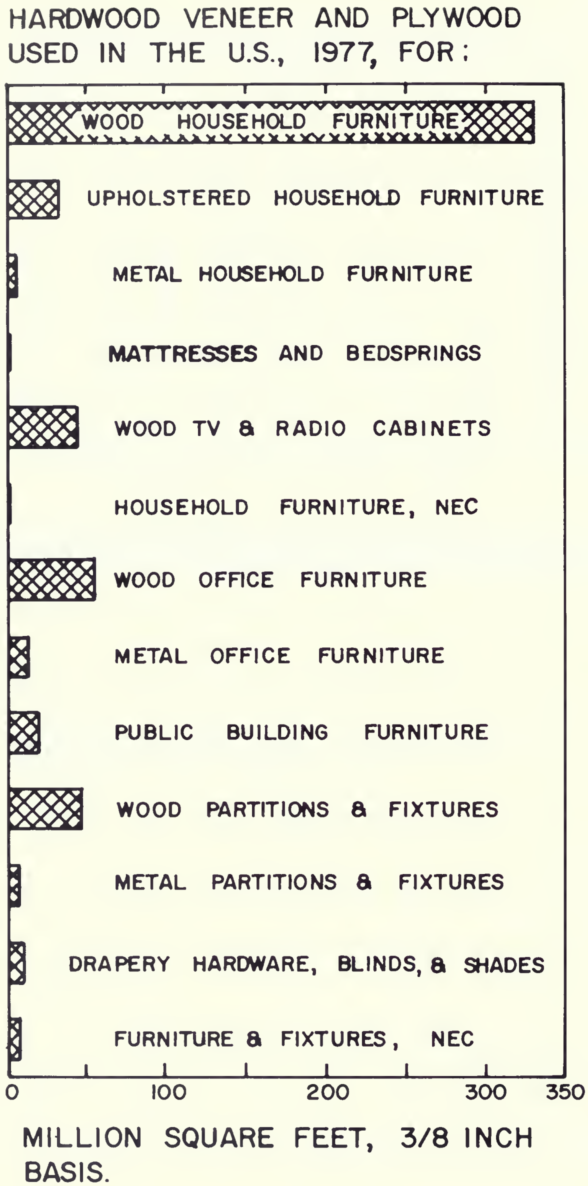


Figure 29-36A.—Hardwood veneer and plywood used by the furniture and fixtures industries in the United States, 1977. NEC = Not elsewhere classified. (Drawing after McKeever and Hatfield.[1])

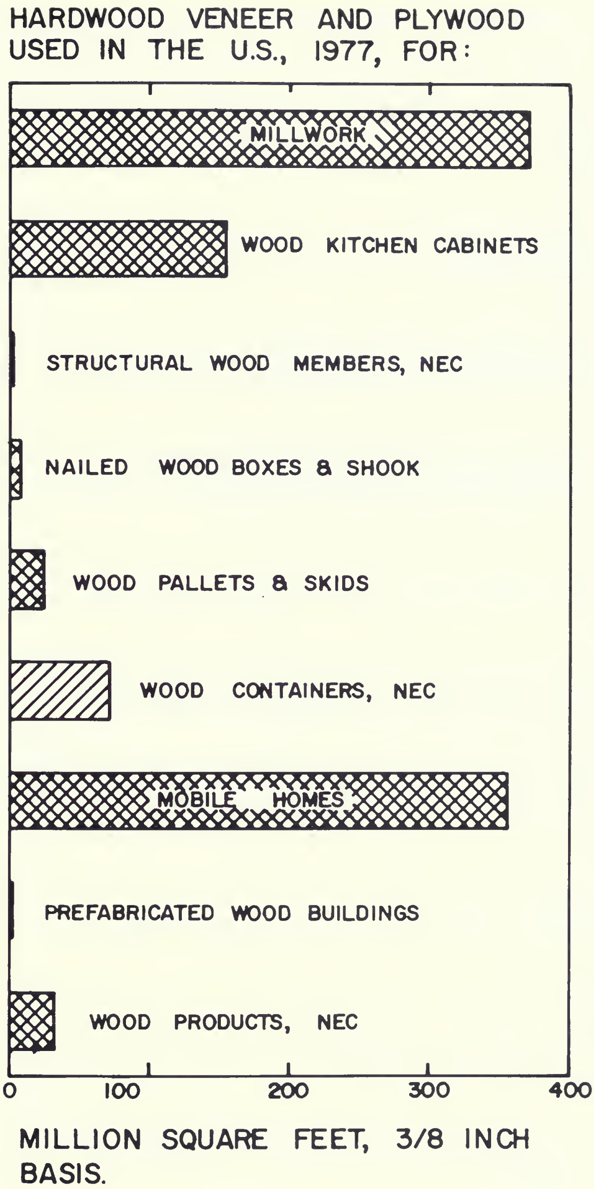


Figure 29-36B.—Hardwood veneer and plywood used by the lumber and wood products industries in the United States, 1977. NEC = Not elsewhere classified. (Drawing after McKeever and Hatfield.[1])

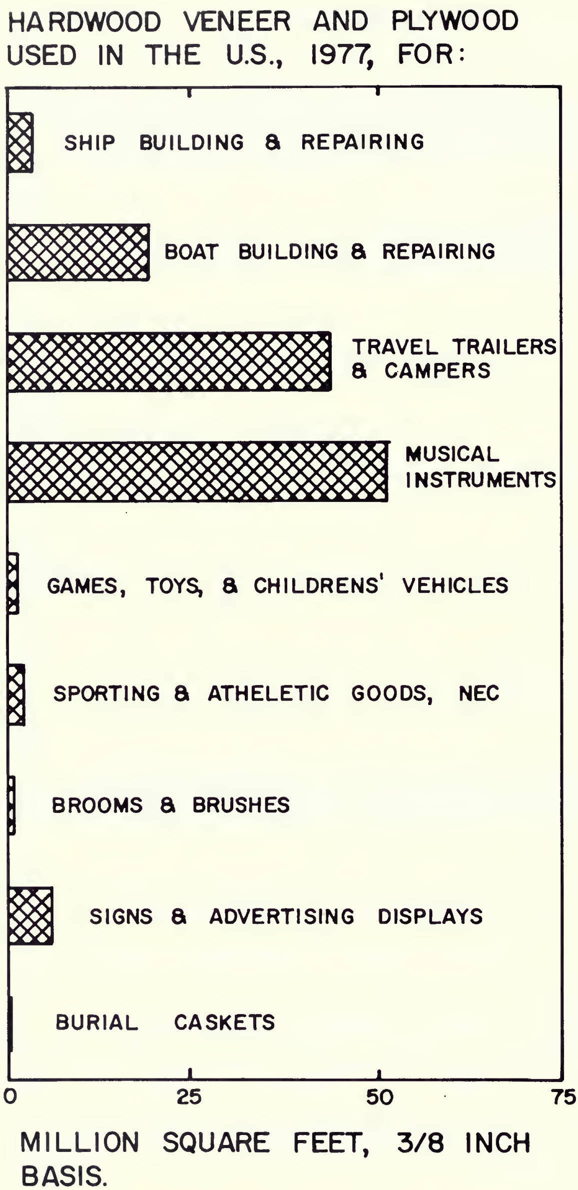


Figure 29-36C.—Hardwood veneer and plywood used by selected wood-using industries in the United States, 1977. NEC = Not elsewhere classified. (Drawing after McKeever and Hatfield.[1])

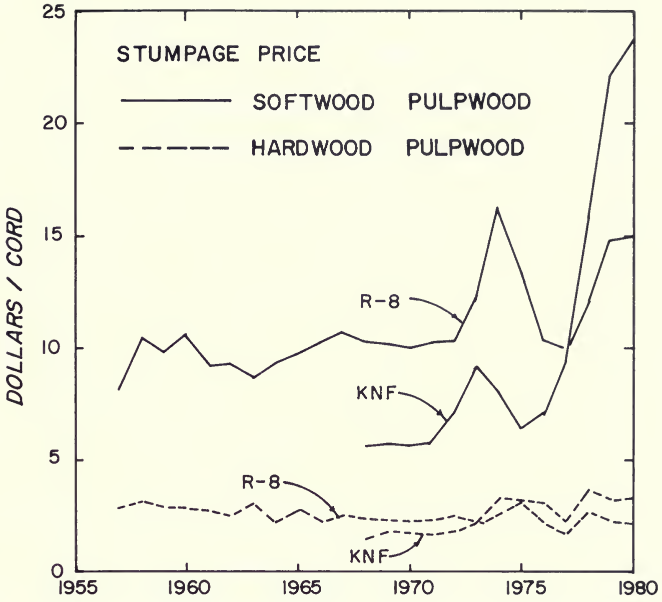


Figure 29-37.—Average price per cord at which hardwood and softwood pulpwood stumpage was sold from lands of the National Forest System of the South (R-8, i.e., North Carolina, Tennessee, Arkansas, Oklahoma, and states south of them), and from the Kisatchie National Forest (KNF) in Louisiana. Data plotted for R-8 are bid prices less allowances for certain road building costs; data for KNF are prices bid with no allowances. (Data from Region 8 of the National Forest System.)

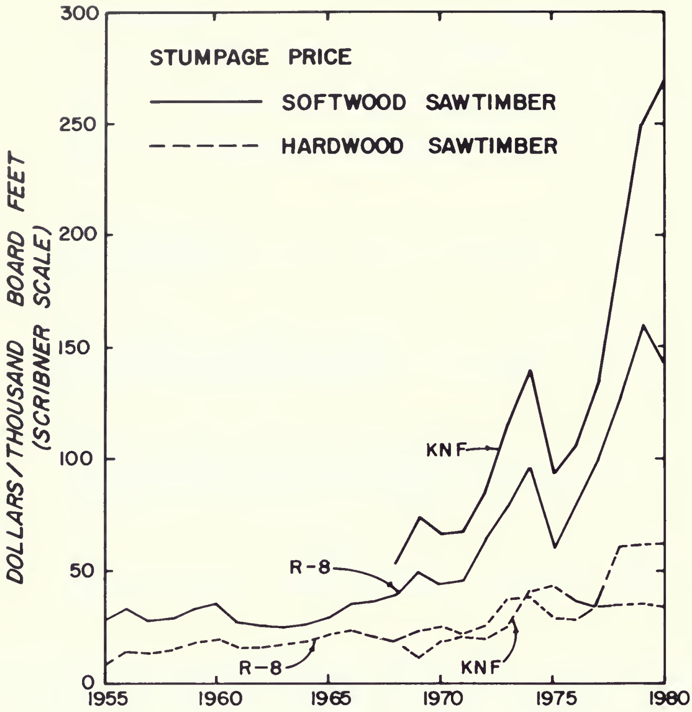


Figure 29-38.—Average price per thousand board feet, Scribner scale, at which hardwood and softwood sawtimber stumpage was sold from lands of the National Forest System of the South (R-8, i.e., North Carolina, Tennessee, Arkansas, and Oklahoma, and states south of them), and from the Kisatchie National Forest (KNF) in Louisiana. Data plotted for R-8 are bid prices less allowances for certain road building costs; data for KNF are prices bid with no allowances. (Data from Region 8 of the National Forest System.)

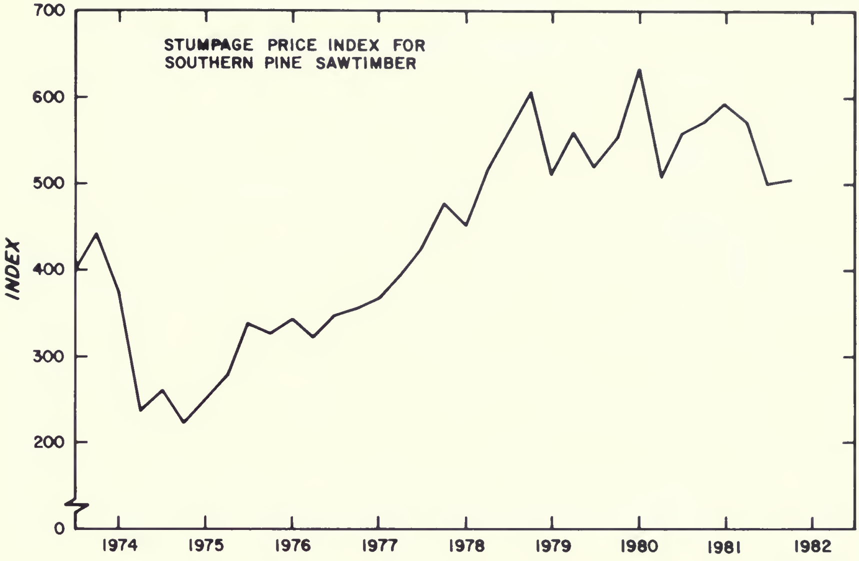


Figure 29-39.—Index proportional to southern pine sawtimber sales price for stumpage, 1974-1981; monthly weighted average for all Vardaman & Co. pine sawtimber sales in 11 southern states. An index of 500 corresponds to a price per thousand board feet, Scribner scale, of $131.86. (Data from James M. Vardaman & Co., Inc.)

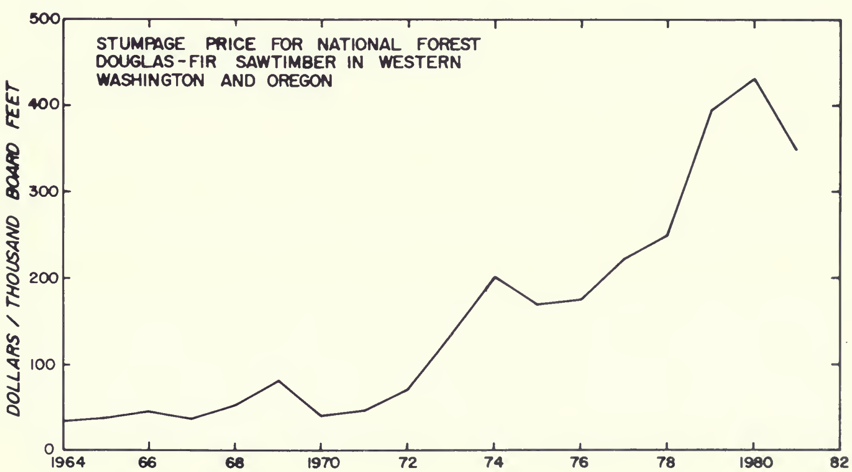


Figure 29-40.—Average stumpage prices for Douglas-fir sawtimber sold on National Forests in western Washington and Oregon, 1964-1981; Scribner Decimal C log scale. (Data extended from Lambert 1977.)

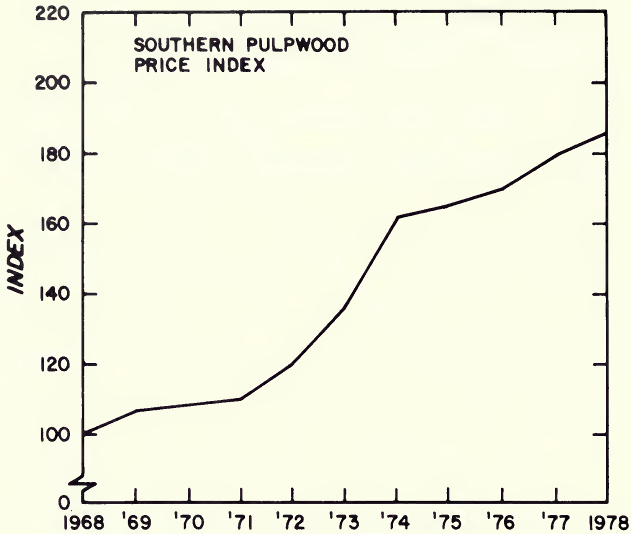


Figure 29-41A.—Index of southern pulpwood prices, delivered basis; 1968 as base year with index of 100. (Drawing after Tufts et al. 1981.)

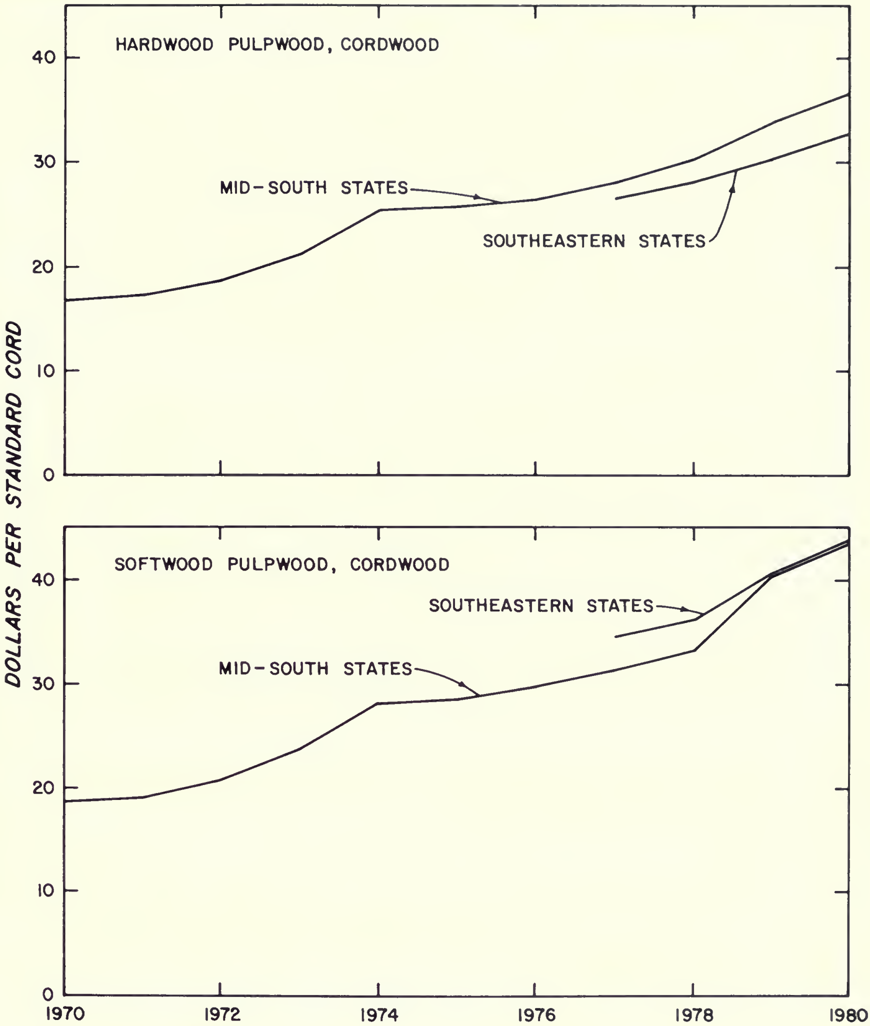


Figure 29-41B.—Prices for hardwood and softwood cordwood delivered to pulpmills (or f.o.b. rail siding) in two regions of the South. Mid-south states are Alabama, Mississippi, Louisiana, Texas, Oklahoma, Arkansas, and Tennessee; southeastern states are Florida, Georgia, South Carolina, North Carolina, and Virginia. (Data from V. A. Rudis of the Southern Forest Experiment Station and C. C. Hutchins, Jr. of the Southeastern Forest Experiment Station, U.S. Department of Agriculture, Forest Service.)

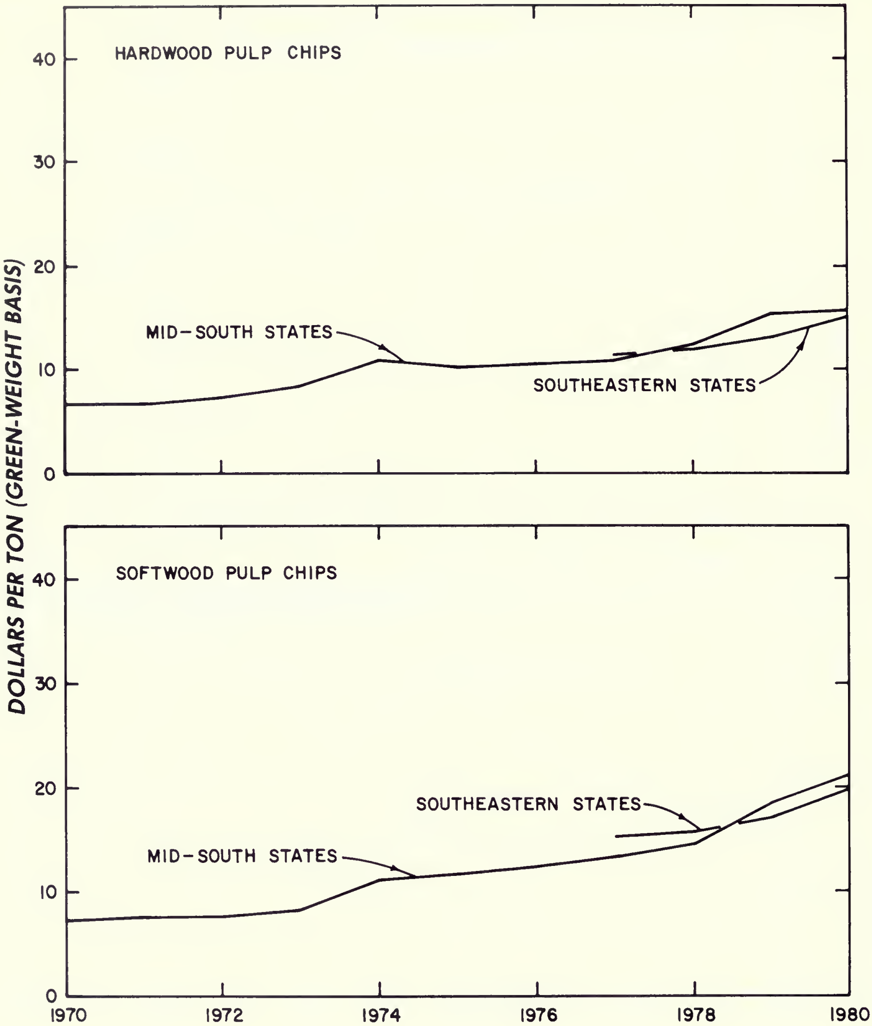


Figure 29-42.—Prices for hardwood and softwood pulp chips delivered to pulpmills (or f.o.b. rail siding) in two regions of the South. See figure 29-41B for names of states. (Data from V. A. Rudis of the Southern Forest Experiment Station and C. C. Hutchins of the Southeastern Forest Experiment Station, U.S. Department of Agriculture, Forest Service.) See also fig. 25-2.

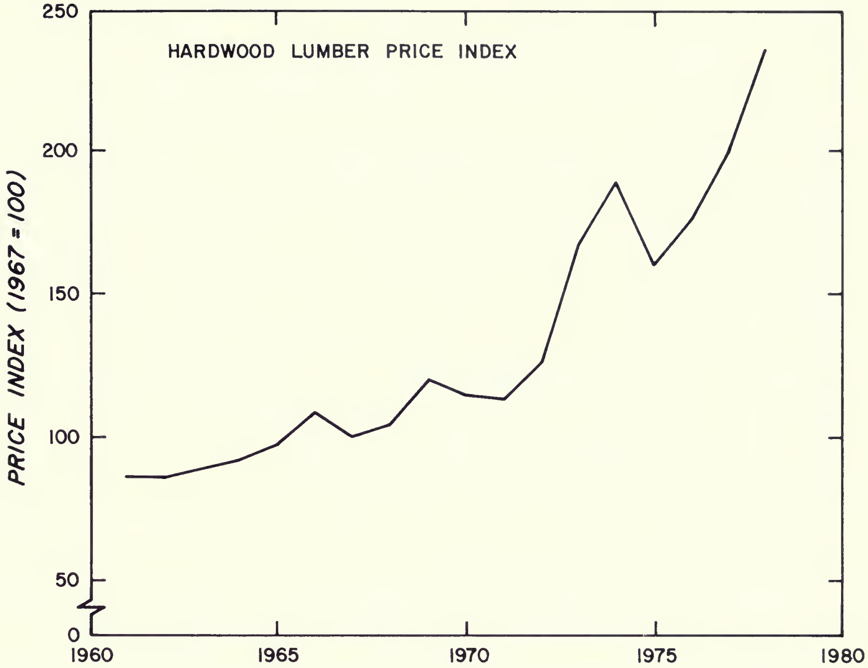


Figure 29-43A.—United States hardwood lumber price index (1967 = 100), 1961-1978. (Data from Luppold 1981, p. 65; derived from hardwood lumber market reports.)

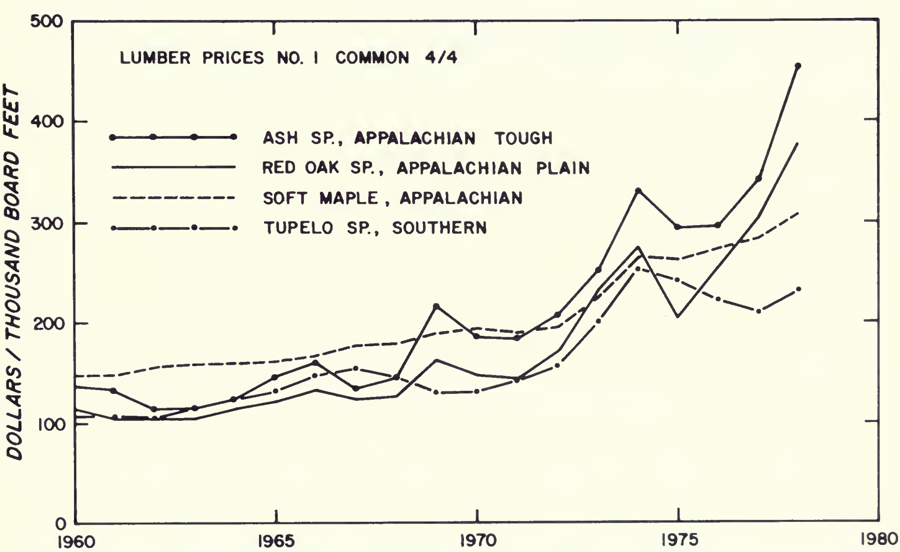


Figure 29-43B.—United States price of No. 1 Common 4/4 hardwood lumber f.o.b. sawmill, 1960-1978. (Data from Luppold 1981, p. 4; derived from hardwood lumber market reports.)

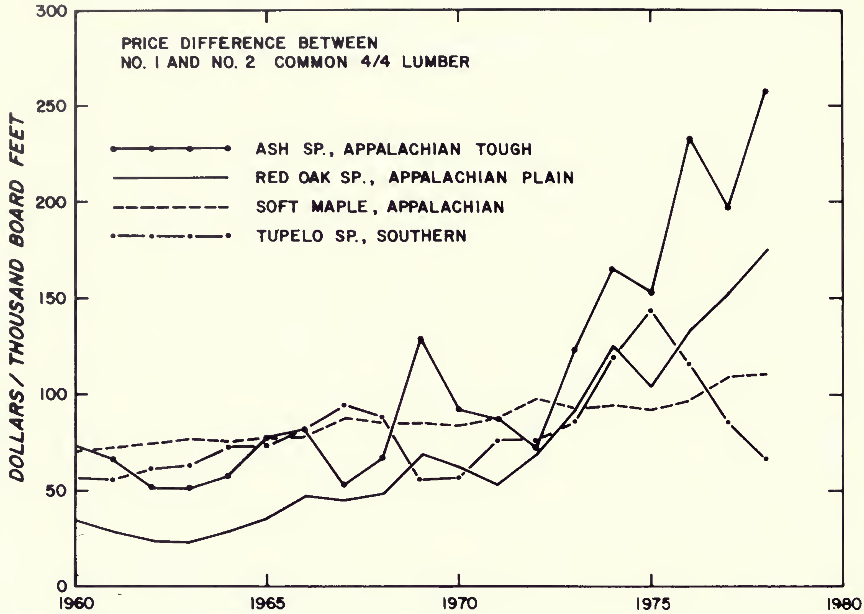


Figure 29-43C.—Price difference between No. 1 and No. 2 Common 4/4 ash, soft maple, red oak sp., and tupelo sp. lumber f.o.b. sawmill, 1960-1978. (Data from Luppold 1981, p. 5; derived from hardwood lumber market reports.)

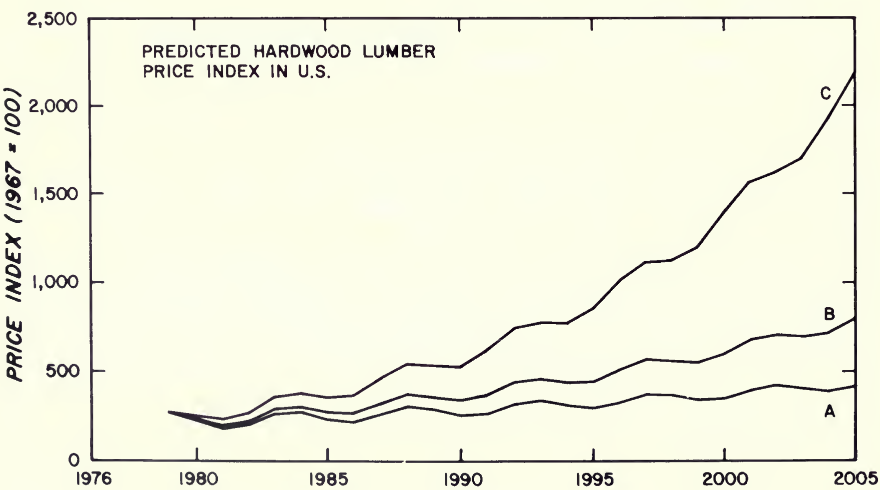


Figure 29-44.—Predicted hardwood lumber price index in the United States, under three sets of assumed conditions; see figure 29-17 for definitions of conditions A, B, and C, 1979-2005. (Drawing after Luppold 1981, p. 93.)

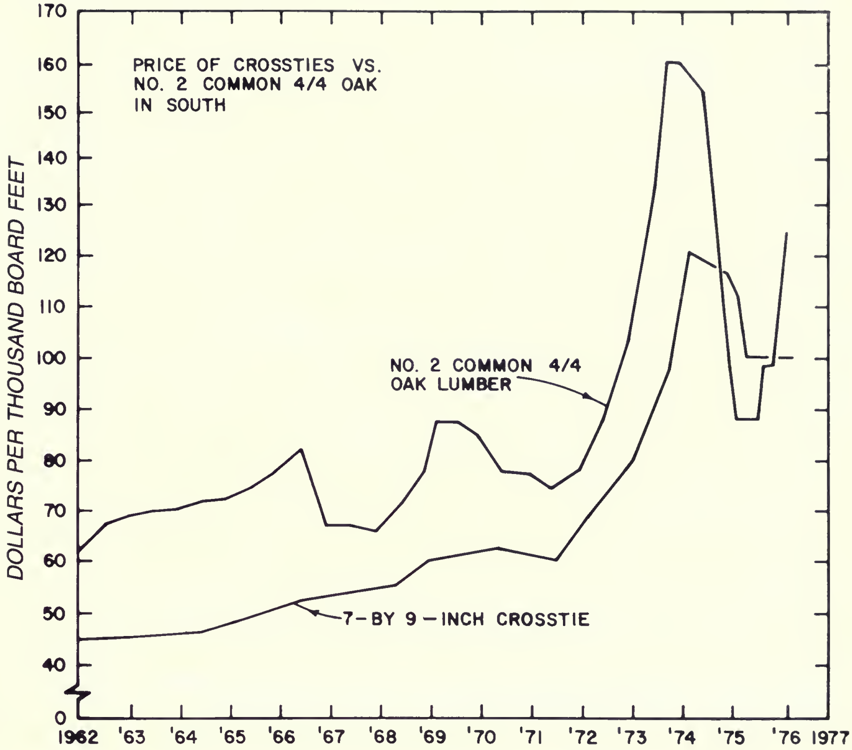


Figure 29-45.—Comparison of sales prices at southern locations for No. 5 7- by 9-inch hardwood crossties delivered to a concentration yard, and No. 2 common 4/4 red oak lumber as quoted in hardwood market reports, 1972-1976. In January 1982, "Timber Mart South" reported average sales price per hardwood 7- by 9-inch crosstie at about $7 f.o.b. sawmill, i.e., about $156/thousand board feet. (Drawing after Reynolds 1977.)

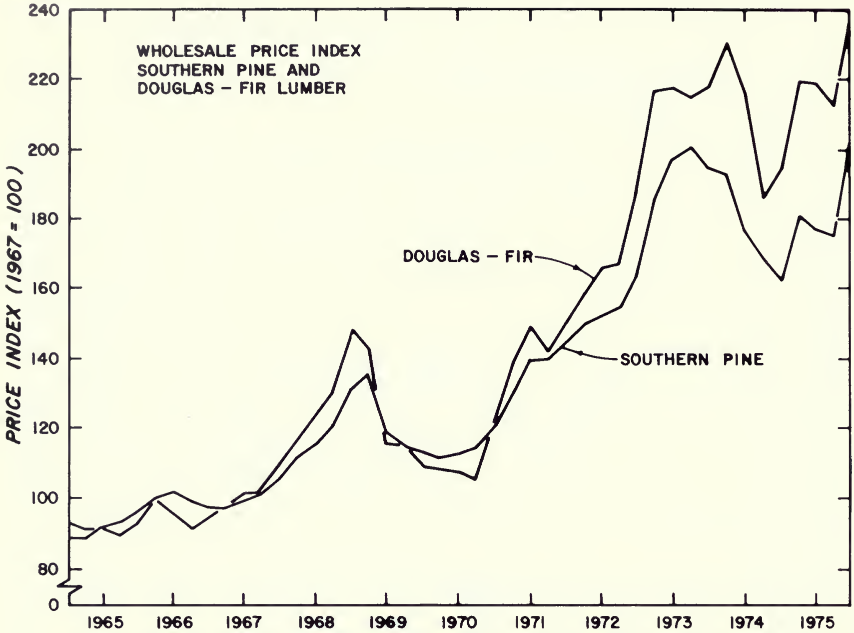


Figure 29-46.—Variation in wholesale price index for southern pine and Douglas-fir lumber, 1965-1975. (Drawing after Nelson and Adrian 1976.)

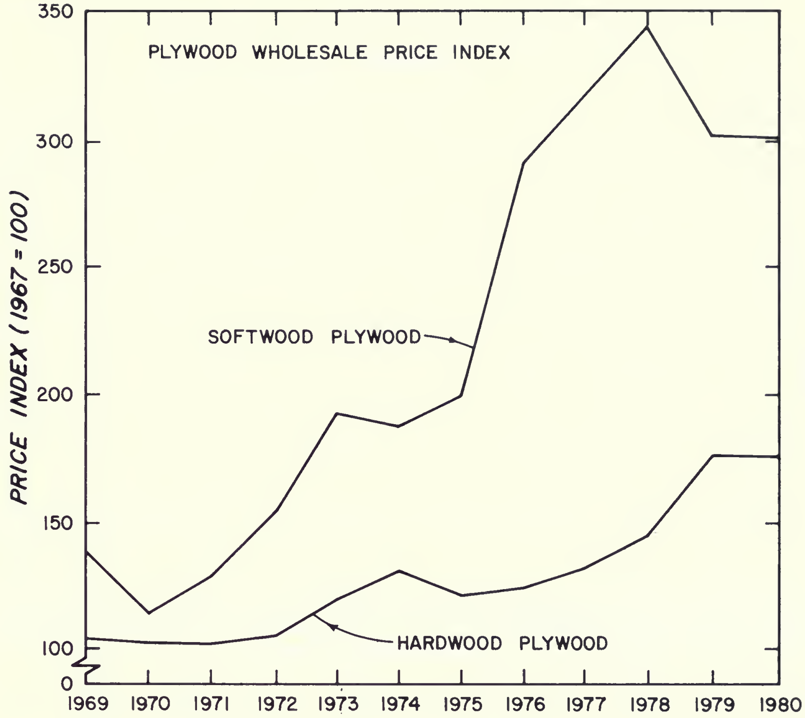


Figure 29-47.—Hardwood and softwood plywood wholesale price index, 1969-June 1980. (Data from Bureau of Labor Statistics.)

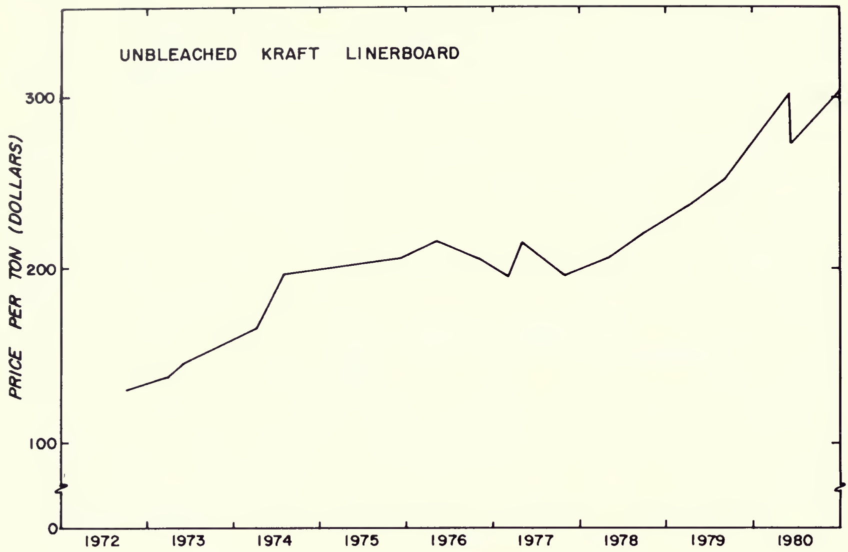


Figure 29-48.—Unbleached kraft linerboard; wholesale price per ton, f.o.b. southern mills, 1972-1980. From 1955 to October 1972 the list price was essentially steady at $127.50/ton. (Data from *Official Board Market* Reports.)

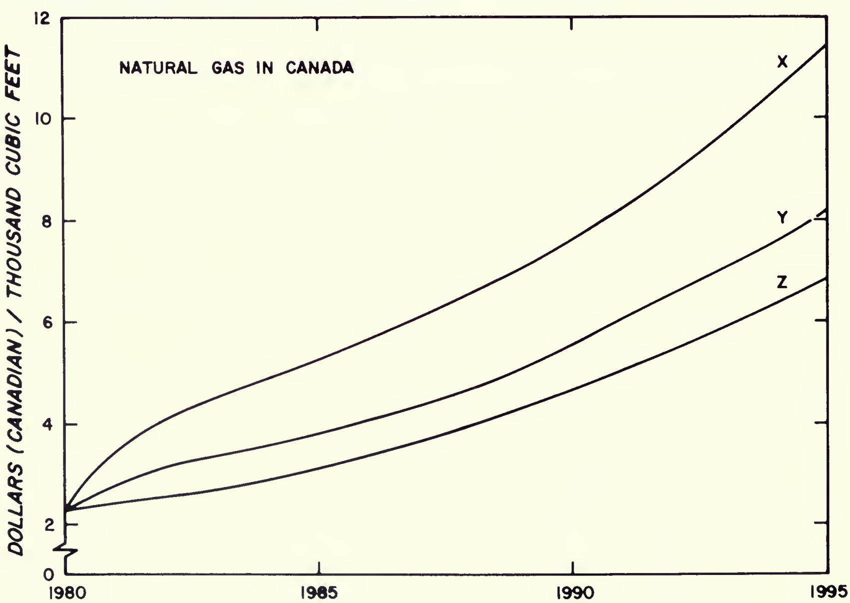


Figure 29-49.—Natural gas prices (Canadian dollars) in Canada, 1980-1995 projected according to three sets of assumptions. In 1982, prices coincided with the highest curve, X. One thousand cubic feet = 1 million Btu. (Data from personal correspondence March 15, 1982 with B. H. Levelton & Assoc., Ltd., Vancouver, B.C., Canada.) Natural gas prices in the southern U.S. vary widely; trend data were not available in 1982.

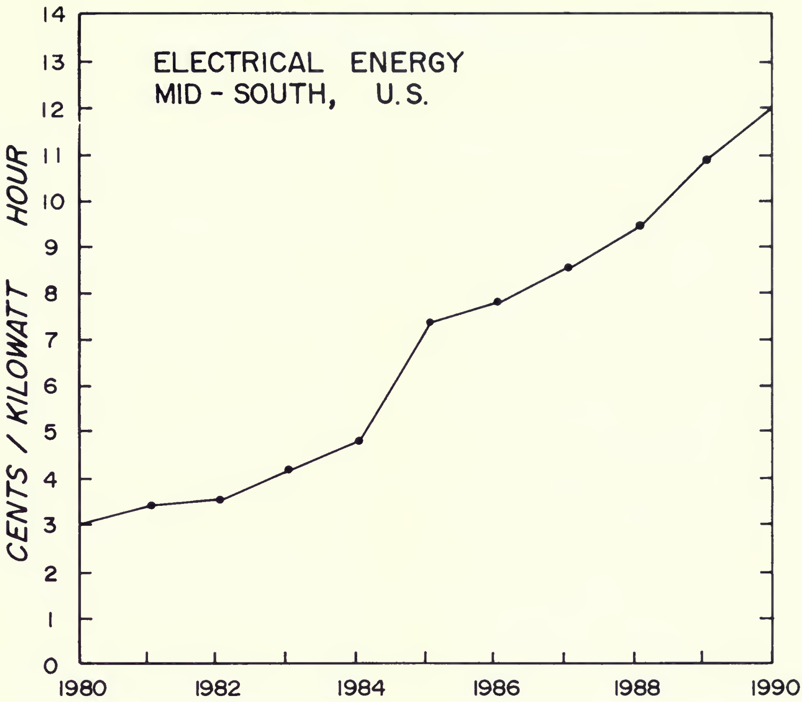


Figure 29-50.—Electrical energy prices in the Mid-South, 1980-1982, with estimates projected to 1990. Prices are for industrial users, e.g., pulpmills, sawmills, and plywood plants. (Data from personal correspondence, Central Louisiana Electric Company, May 1982.)

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GENERAL INDEX

SPECIES INDEX