FOREST PRODUCTS AND WOOD SCIENCE

AN INTRODUCTION

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DRAWINGS BY KAREN LILLEY

THE IOWA STATE UNIVERSITY PRESS / AMES

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Composed and printed by The Iowa State University Press, Ames, Iowa 50010

First edition, 1982
Second printing, 1985

Library of Congress Cataloging in Publication Data

Haygreen, John G., 1930-
Forest products and wood science.

Includes bibliographical references and index.
1. Wood. 2. Lumber. I. Bowyer, Jim L., 1942- . II. Title.
TA419.H34 674 81-23668

ISBN 0-8138-1800-1 AACR2

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PREFACE

THIS BOOK was written as a textbook for an introductory study of wood as an industrial raw material. It is intended to assist the student in understanding the physical and chemical nature of wood, important wood properties, and the nature and properties of major wood products.

The text was designed primarily for two specific types of students: those who intend to pursue careers in wood science or forest products and those in forestry who receive exposure to the forest products field through only one or two product-oriented courses. The book was also intended to provide an appropriate introduction to wood products for students of materials science and construction materials. It was prepared for the student with no previous knowledge of the wood science/forest products field. In all sections the objective is to present pertinent information in a concise manner, avoiding detail and technical terminology wherever possible.

The book is divided into four parts. Part 1 introduces the nature of wood and bark and the trees that produce them. Part 2 deals with the physical properties of wood, relating these properties to the chemical and structural characteristics covered in part 1. The subject of part 3 is major forest products; basic manufacturing processes and product properties are discussed. The book is concluded in part 4 with a look at probable uses and markets for wood in the future and at wood for energy.

Although it was recognized that most students beginning an introductory forest products course will have a knowledge of basic botany, part 1 was written to permit understanding by those without a botany background. Throughout part 1, features of wood that are useful in identification of timbers are highlighted. The subject of wood identification is not addressed, however, since several good texts are available that deal with this subject.

Throughout this text a mixture of English and metric units of measurement is used to conform to general practice. In wood science research, metric units are recommended. However, much research being reported in the literature today remains in the English system. In forest products manufacturing and wood engineering there is little use as yet of the metric system. Forest products industry committees are active, however, in plan-

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Fiber products 16

WOOD FIBER PRODUCTS include paper, paperboard, hardboard, insulation board, and medium-density fiberboard. All these products are manufactured from wood that has been reduced to individual fibers, small fiber bundles, or fiber parts, which are subsequently formed into a mat.

Paper

In early times man wrote messages on the walls of caves or clay tablets. The Egyptians, however, discovered that it was easier to write on the flattened stems of native papyrus plants (from which the word "paper" was derived). Other people developed writing parchment from split and dried animal skins. About 105 A.D. a Chinese scholar, T'sai Lun, became dissatisfied with the silk and bamboo writing materials then used in China. He experimented with bamboo and then the inner bark of mulberry trees. He pounded the material into pulp and added water. This was then formed into flat sheets and dried. It was the first real paper as we know it.

Although Lun's revolutionary new product was made from woody fiber, subsequent improvement in the manufacturing process involved replacement of wood raw material by linen rags. For almost a thousand years, rags were used as a source of papermaking fiber. Hundreds of substitute materials, the most notable of which was straw, were tried, but it was not until 1844 that wood gained importance as a fiber source. In that year a method of grinding wood to pulp was developed in Germany, and the process was soon adopted in the United States. Today, wood is clearly the dominant raw material for paper manufacture, with wood fiber providing 98+ % of the fiber needs in the United States and 94+ % of fiber used in paper worldwide. Nonwood fibers in use include cereal and seed flax straws, bamboo, sugarcane bagasse, reeds, abaca, esparto and Sabai grasses, cotton linters, cuttings and rags, sisal, and kenaf (Auchter 1976).

Paper has assumed a position of almost incredible importance, especially in highly developed countries. It serves as a primary packaging product, communications medium, disposable products base, and industrial sheet material. In the United States the pulp and paper industry is the second largest consumer of wood, producing in 1978 a volume of paper and paperboard equivalent to 604 pounds for every man, woman, and child in the population (Haas et al. 1979).

THE MANUFACTURING PROCESS. In simple terms, the process of paper manufacture involves (1) reduction of wood to constituent fiber (pulp), (2) suspension of fibers in water, (3) beating or refining the pulp, (4) introduction of additives (fillers, sizing materials, wet-strength binders, etc.), (5) formation of a fiber mat, (6) drainage of water, and (7) drying of the sheet. For many types of paper, surface treatment may follow sheet preparation.

Pulp production. The primary difference among various paper manufacturing processes is the method used to accomplish the first step—pulping. Mechanical, chemical, or heat energy or combinations of these are employed in producing pulp. The forms of energy used determine to a large extent both yield and pulp properties.

Mechanical pulping. Two commonly used methods of producing mechanical pulp are the stone groundwood and the refiner groundwood processes. The grindstone is exactly that—a large stone that is rotated while the tangential surfaces of wood bolts are pressed against the surface (Fig. 16.1). A mechanical rending action tears individual fibers, fiber parts, or fiber bundles from the wood surface, after which a stream of water carries away the accumulated fiber. Groundwood pulp made from spruce is pictured in Figure 16.2; note the pieces of fiber and bundles of unseparated fiber in the mixture. A newer and more popular method of manufacturing mechanical pulp involves the use of a refining machine (called a double-disk refiner) composed of two fluted metal disks that can be closely spaced and rotated in opposite directions. (A variation of this arrangement is to have one fixed disk and one that rotates; a machine configured in this way is called a single-disk refiner.) In both types of refiners, wood chips are moved by a screw-feed mechanism into the center of the machine where they must pass between the two closely positioned disks; the resulting mechanical action reduces the chips to fiber (see Fig. 15.8).

Because the separation of fiber is achieved by merely pulling apart or rending wood chips, little material is lost in the pulping process as long as the fibers are flexible enough to avoid shattering and production of fines. (Because of the fiber-shattering problem when pulping dense woods, species

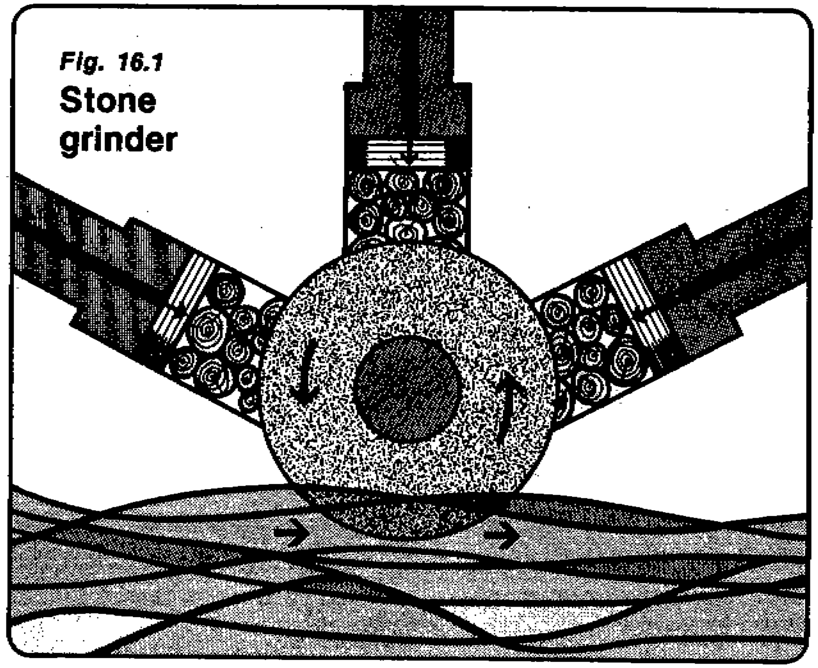


Fig. 16.1
Stone grinder

(Scanning electron micrograph by Crist and Teclaw)

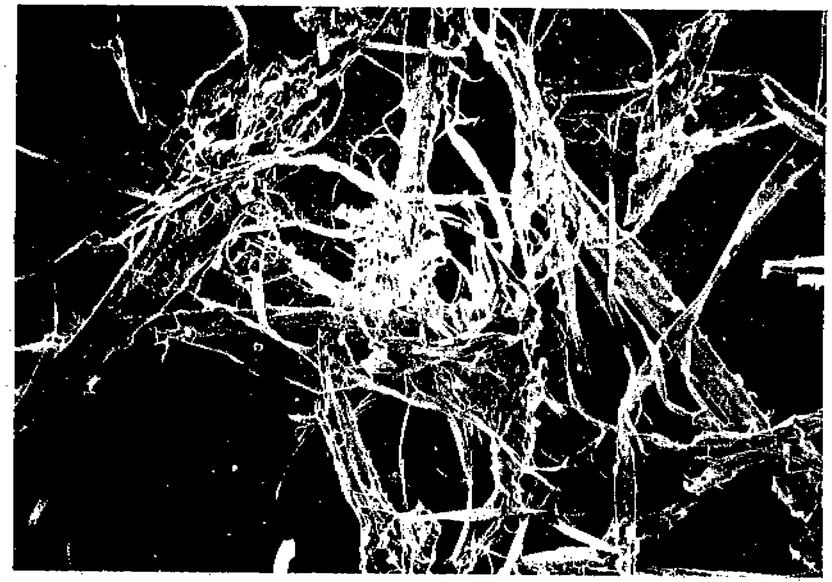


Fig. 16.2
Unbeaten groundwood pulp
(Spruce) ×125

that are typically quite dense are not pulped by mechanical processes.) In mechanical separation, the proportion of wood raw material that becomes usable fiber is commonly on the order of 95–99%, a fact translating to relatively low-cost pulp. Unfortunately, high yield also results in low-strength pulp unsuitable for many uses. As little is lost in separation, the cellulose, hemicellulose, and lignin that make up the wood are all part of the resulting pulp. The lignin, which serves to strengthen solid wood through stiffening of fibers, continues to give rigidity to the fibers of mechanical pulp. These rigid fibers have little fiber-to-fiber bond potential and form a coarse and bulky mat. The paper thus formed has low strength and relatively poor surface quality. The presence of lignin in mechanical pulp contributes to yet another problem, one related to long-term durability. Lignin and certain carbohydrates yellow with age, particularly when exposed to ultraviolet rays of sunlight; this is the reason for the yellowing commonly seen in old newspapers.

A variation of the mechanical pulping technique is the thermomechanical process. Here chips are subjected to superheated steam at a temperature of 120–135°C as they pass through the refiner (meaning that refining is done under pressure). The heat serves to soften lignin, allowing fiber separation with less fiber damage than that realized in manufacture of purely mechanical pulps. Both strength and absorbency are improved. Thermomechanical pulp is commonly referred to as TMP.

Chemical pulping. A technique used to achieve fiber separation, which at the same time removes troublesome lignin, involves the use of chemical and heat energy. Wood chips are placed in a chemical solution (called a cooking liquor) and heated in a pressurized vat (called a digester). Fiber separation occurs as cell-to-cell cementing lignin is dissolved.

Two different chemical pulping processes are used, and they differ in the types of chemical comprising the cooking liquor; these are the sulfite and sulfate processes. The sulfite process makes use of a mixture of sulfurous acid and ammonium, magnesium, calcium, or sodium bisulfites. Established in 1874–75, the sulfite process was found to yield high-quality pulp of the type desired for fine writing papers. The calcium-based bisulfite came to be the most commonly used companion to sulfurous acid. The calcium compound was cheap and worked quite well in pulping of long-fibered species such as spruce, hemlock, and true fir. There were, however, several problems associated with the use of the calcium bisulfite–based process. The most serious was that recovery of cooking chemicals and process heat was technically difficult and economically unfavorable. The result was that sulfite mills constantly had a used cooking liquor disposal problem (in a volume approximating 1500 gal/ton of pulp produced), which all too often was resolved by dumping the residue in a nearby waterway. Another problem was that the process did not work well in the pulping of highly resinous

Table 16.1. Estimated annual wood pulp production in the United States (thousands of short tons)

	Chemical Pulping												
Year	Sulfite	% of total	Kraft	% of total	Soda	% of total	Semi-chemical pulping	% of total	Mechanical pulping	% of total	Total pulp from raw wood	Recycled paper	% of raw wood total
1977	3507	7.1	34,862	70.2	...	0.0	3876	7.8	7417	14.9	49,662	14,015	28.2
1970	4024	9.4	28,670	67.3	218	0.5	3297	7.7	6379	15.0	42,588	11,803	27.7
1960	3711	14.8	14,516	57.9	420	1.7	1970	7.9	4469	17.9	25,086	9,032	36.0
1950	2848	19.4	7,501	51.0	522	3.5	686	4.7	3151	21.4	14,708	7,956	54.1
1940	2608	29.3	3,748	42.1	532	6.0	165	1.9	1843	20.7	8,896	4,668	52.5
1930	2517	*	950	*	474	*	...	*	*	*	*	*	*

Source: Libby (1962), Evans (1978), Lowe (1978), Haas et al. (1979).
* Figure not available.

softwoods such as pine. Therefore, growth of the calcium bisulfite–sulfurous acid system ceased about 1940 and new sulfite installations were designed to use ammonium or magnesium bisulfites. Since the early 1960s there has been only limited expansion of all forms of sulfite pulp mill capacity, while use of the sulfate process has grown rapidly (Table 16.1).

The sulfate process is said to date back to 1884, a year in which a German patent was awarded for development of a new high pH (or alkaline) chemical pulping technique. The process was based upon use of a cooking liquor made primarily of sodium hydroxide and sodium sulfide and obtained its name from the use of sodium sulfate as a make-up chemical in a spent-liquor recovery process. An interesting part of the story is the explanation of how this technique was modified to become known as the kraft process. Historical records tell that in the course of operating a Swedish mill, a digester full of partially cooked pulp was accidentally blown (or dumped). The material was about to be thrown away when the mill manager decided to use it in making some low-quality paper; the surprising result was that the paper produced was far stronger than any previously made. The Swedish (and German) word kraft, meaning strong, soon became an alternate name for the technique.

The recoverability of cooking liquors (as well as process heat) means that the sulfate process is comparatively free of residue disposal problems. This process, furthermore, is effective in pulping any species, including those that are highly resinous. These factors, when added to the result that high-strength pulp is produced, explain the overwhelming popularity of the kraft or sulfate process. One negative aspect is a characteristic rotten cabbage smell caused by volatile reduced sulfur compounds. Costs of eliminating this smell are high. Because the human olfactory system can detect even minute concentrations, virtually 100% of the sulfur compounds must be removed from stack gases to completely solve the odor problem.

Because no mechanical action is needed to achieve cell separation, chemically produced pulp is composed of smooth and largely undamaged fibers (compare Figs. 16.2, 16.3A). Moreover, since a high proportion of the lignin is removed in the process, thus eliminating fiber stiffness and an important component of age-induced yellowing in bleached finished paper, pulp quality is high. The penalty paid for high quality is low yield (and therefore high pulp cost). The yield (expressed as the dry weight equivalent of usable fiber divided by the dry weight of chips placed in the digester) ranges from 44 to 55% for both sulfite and sulfate processes, which is lower than the lignin content might indicate. The reason for these very low yield levels is that the conditions that solubilize lignin also degrade both cellulose and the low-molecular weight hemicelluloses.

Semichemical pulping. Wood can also be pulped in a way that combines the high-yield advantages of mechanical processing and some of the high-quality features of chemical processing. Using techniques known as semichemical or chemimechanical pulping, wood chips are given short-term exposure to a chemical pulping liquor and then passed through a mechanical refiner to separate constituent fibers. The cooking liquor causes partial degradation of the ligneous bonds and serves basically the same function as heat in the thermomechanical process. Mechanical energy needed for fiber separation is greatly reduced and damage to fibers is decreased. The chemimechanical process permits pulping of hardwoods that are too dense to be suitably pulped by strictly mechanical means. Yields of 65–75% are common and may occasionally be higher.

Washing and bleaching. It is necessary to clean pulp after it is formed to remove cooking liquor and/or impurities. After chemical pulping, the wood fiber–cooking liquor mixture is released from the digester into what is known as a blow pit. Here fiber is collected and initially separated from spent cooking liquor and the gases that may have been produced. Fiber is next cleaned in a multistage washing process to remove any residual liquor.

Untreated, wood pulp is brown to tan in color, due mainly to the presence of lignin or extractives from heartwood. Thus when manufacturing writing or book papers or other products where whiteness is important, fiber must be bleached. This is usually done by exposure to strong chlorine-based compounds. Oxygen-bleaching techniques have also been developed. Bleaching attacks residual lignin and can be carried to the point where lignin is either totally removed (as with the highest quality writing and printing papers) or simply lightened in color (as in the manufacture of newspaper or catalog quality stock). The latter degree of treatment is least expensive, having little effect upon yield, but it results in only temporary whiteness.

Bleaching to achieve removal of essentially all lignin gives virtually permanent whiteness, but it is expensive. In this case, water use is high and pulp yield is significantly reduced.

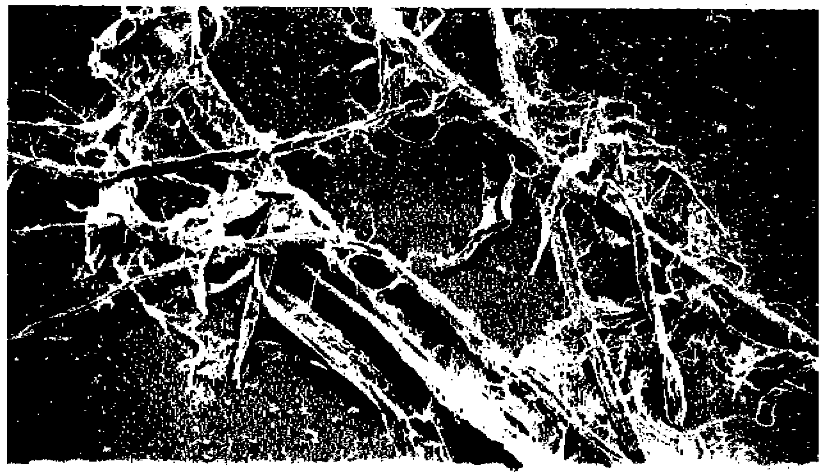
Beating and refining. Much of the strength of paper results from hydrogen bonding of cellulose molecules that make up adjacent fibers. To provide the maximum potential for bonding, fibers are pounded or ground to flatten them and to partially unravel microfibrils from the cell walls; the surface area of fibers (and thus the area available for bonding) is greatly increased by even a small degree of such flattening and unraveling (Fig. 16.3).

Fig. 16.3

Beating flattens and partially unravels fiber walls (chemically pulped southern yellow pine).

A. Before beating (745 CSF)

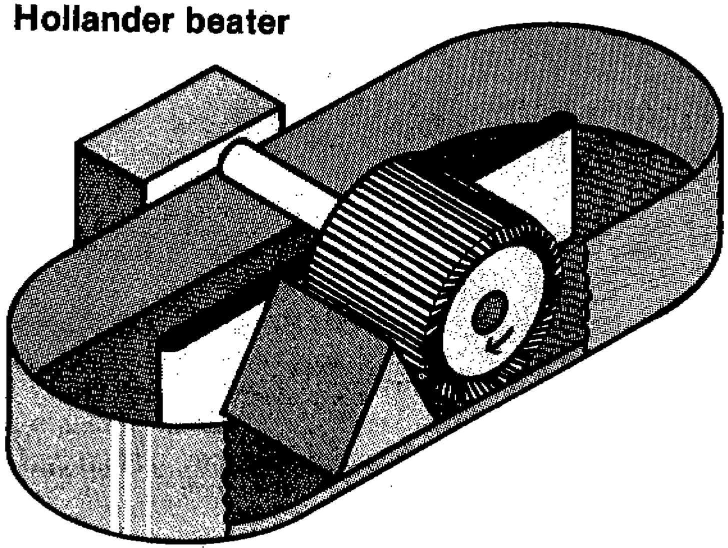
B. After beating (145 CSF)



(Scanning electron micrographs by Crist and Teclaw—x125)

The mechanical flattening and unraveling of fibers is called beating and is accomplished in various types of refining machines. The principle is perhaps best illustrated by examination of an older but sometimes still used type of refiner known as a Hollander beater (Fig. 16.4). In this machine a rotating paddle wheel moves a pulp slurry around a tub, forcing it to pass between the blades of the wheel and a lower bedplate. When the space between the blades and bedplate is small, fibers are subjected to a mechanical rubbing action as they pass through this opening.

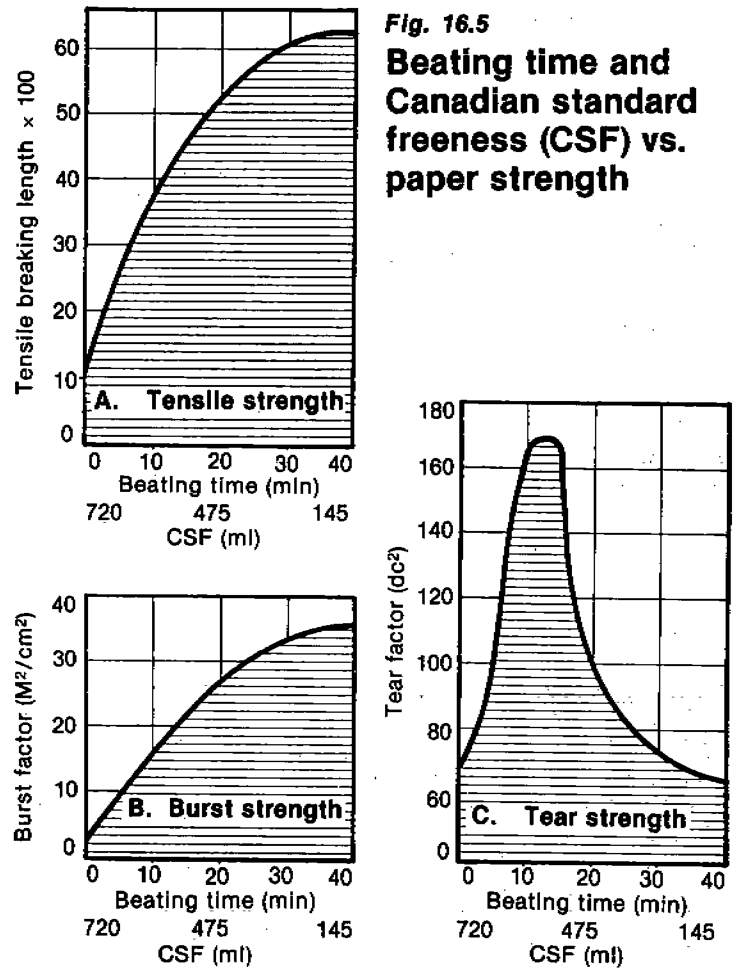
Fig. 16.4
Hollander beater



Because fiber-to-fiber bonding has a great deal to do with paper properties, it is desirable to have a quantitative measure of the bond potential of a pulp. In North America, bond potential is usually expressed in terms of Canadian Standard freeness (CSF). This is measured by suspending a given amount of fiber in water and then determining the rate at which water drains through a wire onto which the fiber has been allowed to settle. Since the rate of drainage is inversely related to surface area of fiber and surface area is directly related to the amount of beating or refining, a mat of well-beaten fiber is quite resistant to drainage of water. The freeness of well-beaten fiber is thus low.

The relationship between beating time, freeness, and various strength properties is illustrated in Figure 16.5. Note that freeness is in all cases decreased by extended beating. Burst and tensile strengths tend to be higher the longer the beating time. As will be explained in more detail later, burst and tensile properties are closely related to interfiber bonding and are thus directly affected by any treatment (such as beating) that increases bond

Fig. 16.5
Beating time and Canadian standard freeness (CSF) vs. paper strength



potential (Fig. 16.5A,B). Figure 16.5C shows that tear strength is significantly increased as beating is begun but is reduced rapidly thereafter. The explanation for this is that tear is somewhat influenced by interfiber bonding but is much more influenced by integrity of individual fibers. With the first few minutes of beating, flattening of cells and some unraveling of microfibrils occurs, which greatly increases surface area while causing little reduction in either length or strength of fibers; the increased surface area resulting from further beating is offset by the damaging effect upon individual fibers.

Sheet formation. Following beating, and in some cases secondary refining, fiber is mixed with water to a consistency of about 1% fiber by weight. It is quite common to mix different types of pulp (i.e., mechanical and chemical) at this stage, with the proportion of each dependent upon the kind of paper to be manufactured. Additives such as starch (for increased bond strength) or wet-strength resin are often added to the mixture at this point as well, as are clays (for brightness and opacity) and rosin size (for decreased liquid absorbtion). This mixture is then formed into a thin mat. The most commonly used machine to form the fiber mat is called a Fourdrinier. It is basically a rapidly moving horizontal screen fitted with a device to accurately meter a pulp mixture onto it. Other types of paper machines form a paper mat on rotating wire cylinders. As pulp flows onto the screen, water drains away with the aid of suction boxes or other drainage-enhancing devices mounted under the wire, leaving a mat of fibers. The mat is then wet pressed, passed over a series of steam-heated drums, pressed again to desired thickness, and wound into large rolls. Application of coatings, sheet polishing operations (known as super calendering), and splitting of large rolls into smaller sheets are operations that might follow. The entire process is summarized in Figure 16.6.

PAPER PROPERTIES

Common measures of quality. There are many ways to define paper quality. When making grocery bags, for instance, strength is quite important. As with solid wood, there are many measures of strength. A bag to be filled with heavy bottles or canned goods, which might be picked up by the sides, must have a high tensile strength. Similarly, a bag that may contain an exceptionally heavy item such as a large soft drink bottle should be able to resist this kind of concentrated load (measured by burst strength). High resistance to tear is another property obviously needed in an all-purpose bag. Moreover, the bag should retain its strength when wet.

If a book paper is being manufactured, tear strength is obviously critical. But other factors are quite significant as well. The sheet must accept ink but must have low absorbency to prevent ink diffusion and development of

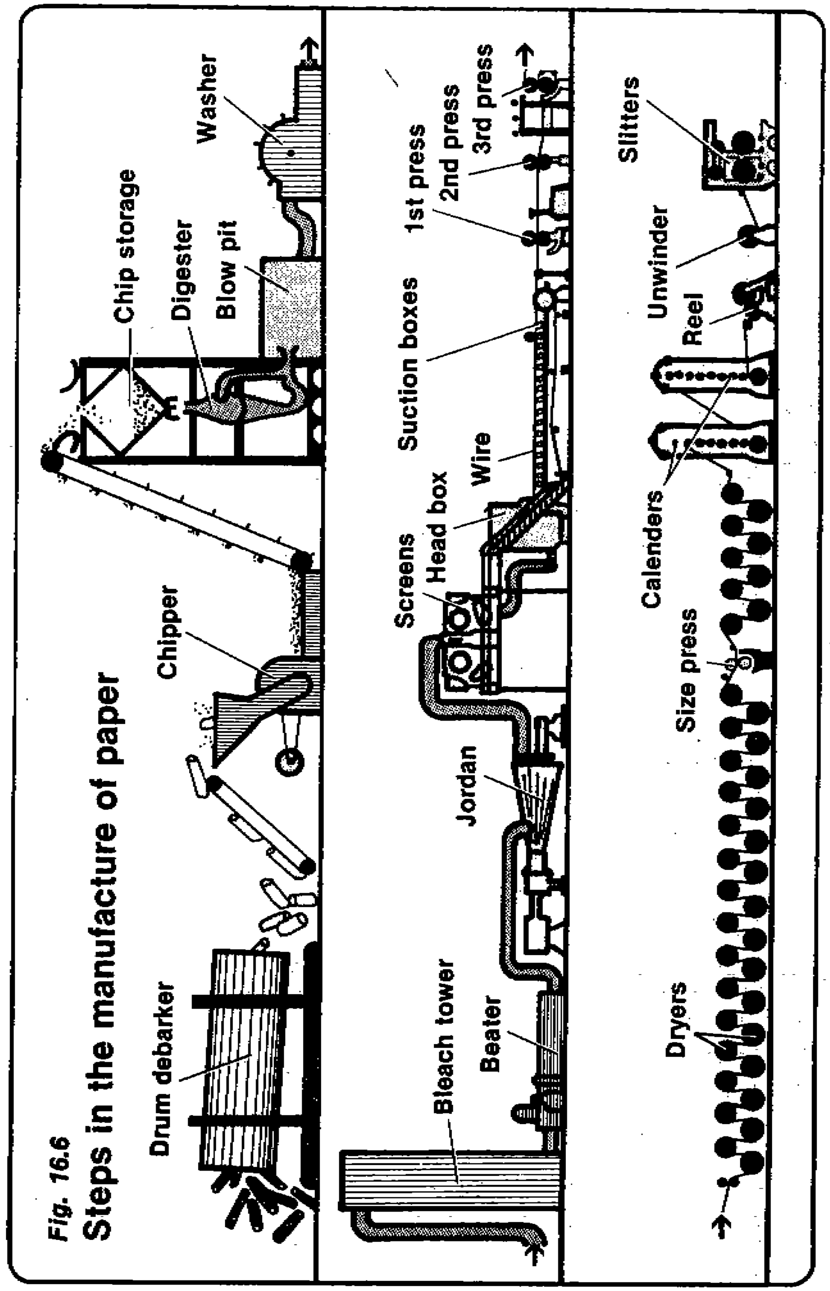


Fig. 16.6
Steps in the manufacture of paper

fuzziness around printed characters. High opacity is also necessary so that printing does not show through the other side. Other important properties might be brightness, permanent whiteness, and surface smoothness. If the paper is to be used in making a product like restaurant menus rather than books, all the properties outlined above would be needed as well as another property—folding endurance.

Paper used for toweling should have an entirely different set of properties. Strength, particularly wet strength, is important in a towel, and such paper should also be highly absorbent. And so it goes. For each of the thousands of paper products a similar list of properties might be enumerated. The point is that there are many kinds of paper, each with individual and often quite different requirements. Various measures of quality have been developed to permit evaluation of the suitability of different pulps for manufacture of these various kinds of paper.

Paper properties and fiber characteristics. Knowledge of only one characteristic of wood, i.e., density, allows prediction of the yield of pulp per unit volume of wood as well as a number of paper properties. Density is directly related to cell wall thickness. The general rule is that the lower the density and thus the lower the proportion of thick-walled latewood cells, the better the wood as a papermaking raw material. It should be noted that this rule does not hold if high tear strength is desired.

Thick-walled fibers result in paper with low burst and tensile strengths but a high degree of resistance to tear. Paper made primarily of thick-walled cells also tends to have very low folding endurance. The relationship of burst and tensile strengths to cell wall thickness is explained by the fact that these properties are very dependent upon a high degree of fiber-to-fiber bonding, which is affected by cell wall thickness. These facts might lead to the conclusion that thick-walled fibers are difficult to beat to a low freeness level as compared to thin-walled fibers. Actually the reverse has been found (Ellwood et al. 1965). The primary reason for low apparent bond potential of thick fibers is that paper is manufactured on a weight basis, meaning that the number of fibers in a sheet is inversely related to the density of fiber walls. Second, thick-walled fibers have less surface area per unit weight than thinner walled fibers. These two factors translate very simply to lessened opportunities for interfiber bonding. Tear strength, like burst and tensile strengths, is influenced by the extent of interfiber bonding. More important, however, is the effect that individual fiber strength has upon tear resistance. Thick-walled fibers are obviously stronger than those having thin walls.

A second characteristic of wood that has an effect upon paper properties is fiber length. Tear strength is the property most affected and the relationship is direct (i.e., the greater the fiber length the higher the tear resistance) up to a length of 4–5 mm. Some reference can be found in the

literature to direct relationships between fiber length and other important strength factors such as burst and tensile. Other investigators, however, discount fiber length as a significant influence on these properties.

In a study of the effect of chemical constituents on papermaking potential, Ellwood et al. (1965) found cell wall thickness to be closely correlated with chemical composition of the wall, making it difficult to separate chemical and other structural effects. It was nonetheless found that thick-walled cells that provided high tear strength were composed of a high proportion of cellulose and were correspondingly low in hemicellulose and lignin. Burst and tear strengths were thus highly correlated to a high proportion of hemicellulose. High levels of hemicellulose are evidently related to rapid hydration of pulp, formation of more and better interfiber bonds, and development of dense mats.

The proportion of various cell types making up a wood can affect the quality and quantity of pulp. This is particularly true of hardwoods and the portion of their volume accounted for by vessels. Because of their shape, vessels do not bond readily to fibers, thereby contributing little to strength (Dadswell and Watson 1962). Vessels may separate from the surface of the finished sheet in subsequent printing (Allchin 1960). Vessels are also more likely to break up during processing, and therefore woods containing a high proportion of these cells are likely to give lower pulp yields than those with a higher fiber content.

MEASUREMENT AND SOURCES OF RAW MATERIAL. In the United States, about half the wood used for the manufacture of paper is in the form of small-diameter and crooked bolts (Fig. 16.7). Because of the large

(Courtesy S. Sinclair)

Fig. 16.7
A load of pulpwood begins the trip to the paper mill.

volume of pulpwood handled at a mill and irregular shapes of individual pieces, pulpwood is measured by calculating the volume of large stacks of roundwood or by determining weight.

A standard unit of measure for pulpwood in the United States is the cord, which is defined in Chapter 13. It is important to remember that a cord does not contain 128 ft^3 of wood but 128 ft^3 of space. A cord of 7- to 10-in. (18–25 cm) diameter, 4-ft (1.2 m) length, and undebarked bolts contains, for example, only about 80 ft^3 (2.3 m^3) of wood and another 10 ft^3 (0.3 m^3) or so of bark. A greater amount of wood is contained in cords composed of larger diameter and/or shorter bolts. In addition to being bought and sold by the cord, pulpwood is also purchased by weight. Payment for this wood is made either directly by weight ($/ton), or weight is converted to cords, with payment then made on a cord basis. Elsewhere in the world, pulpwood volume is commonly expressed in cubic meters.

Almost one-third of the raw material used annually for pulp manufacture in the United States is in the form of wood chips produced as by-products in sawmills, plywood mills, and other wood products operations. Pulp chips are often purchased on a weight basis (by the green or dry ton), volume basis (by the 200 ft^3 unit), or combination weight/volume basis (by converting weight measurement to cords).

In 1977 the equivalent of some 66 million short tons of wood pulp were consumed in the United States in making a variety of paper and paperboard products. About 30 million tons were obtained from roundwood, while some 20 million tons were produced from wood in chip form. The remaining 16 million tons, or almost 25% of production, were obtained from wastepaper (Fig. 16.8).

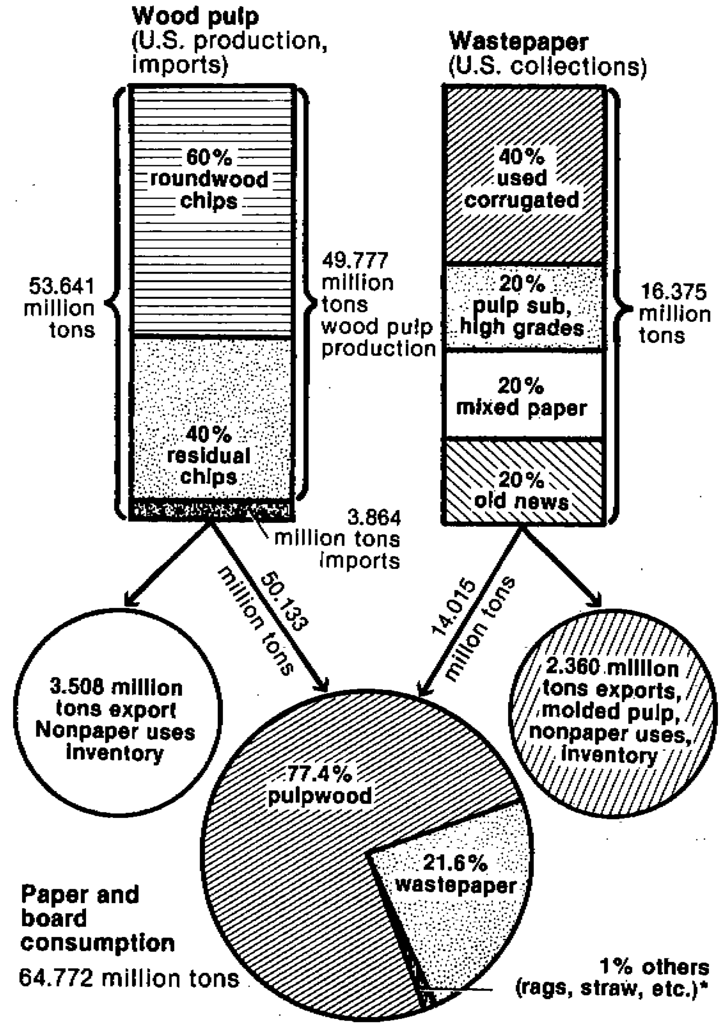
Approximately two-thirds of the nonrecycled pulpwood produced annually in the United States comes from the Southeast. The rest comes from the West (about one-fifth) and the North and Northeast (approximately one-sixth).

Hardboard

Hardboard is a medium- to high-density wood fiber product that is most commonly manufactured to a specific gravity near 1.0. The product is made in the form of flat sheets ranging from 1/16 to ½ in. (0.16–1.27 cm) in thickness and can also be molded to a variety of shapes. It is reported that hardboard was developed accidentally in 1924 by a William H. Mason, who had developed a quick explosion process for transforming chips to pulp and was attempting to make a low-density insulation-type product from it. Having placed a wet fiber mat in a steam-heated press for the purpose of drying the fiber, Mason left his laboratory to eat lunch. When he returned, he found that a small steam valve had failed, causing high and prolonged

Fig. 16.8

Sources and uses of fiber for pulp, paper, and paperboard



From Evans (1978)

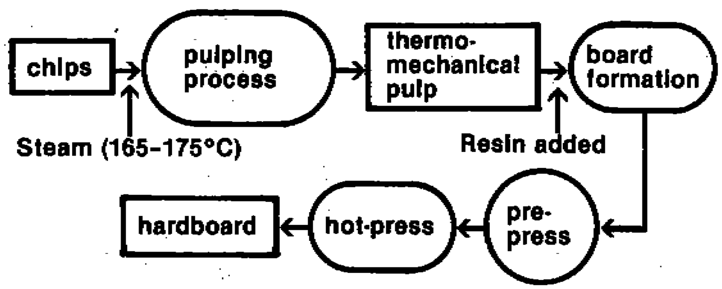
*Consumption of 0.625 million tons not included in above figures pressure on the fiber mat, resulting in a hard, dense panel. The product, dubbed pressed wood by its discoverer, soon came to be known as hardboard. The invention led to immediate formation of the Mason Fiber Company, a name later changed to Masonite Corporation. The name Masonite is still sometimes used interchangeably with the term hardboard.

MANUFACTURING. An important distinction between hardboard and other fiber products is that in hardboard, lignin plays a role in fiber-to-fiber bonding. Ligneous bonding is the primary force holding the finished product together. Because of this, the only kind of pulp suitable for making hardboard is the mechanically produced variety (made by the thermomechanical process or a variation involving presteaming of chips) in which the lignin of wood is retained.

The basic procedure employed in commercial hardboard manufacture is shown in Figure 16.9. Note that resin and wax are added during drying or just after the pulping process. Water-compatible resins such as phenol formaldehyde are normally used, with the concentration generally on the order of 1–2% of dry board weight. These small amounts improve board strength, and the resin as well as the wax increases water resistance.

Following production of pulp, fibers are formed into a mat and prepressed. This step can be accomplished using either water or air as a forming medium. The difference in these techniques, known as the wet and the dry processes, is explained below. The manufacturing sequence is concluded with a hot-press operation in which high temperature (190–235°C) and pressure (500–1500 psi) are employed to bring the lignin to a thermoplastic condition and densify the fiber mat.

Fig. 16.9
Hardboard manufacturing process



Wet process. As the names suggests, the wet process of mat formation makes use of water. In this technique, pulp is mixed with water much as when making paper and this water-fiber mixture is then metered onto a wire screen. Water is drained away with the aid of suction applied to the underside of the wire, and the fiber mat along with the supporting wire is moved to a prepress where excess water is squeezed out. The prepress operation is an important part of the wet process, since the subsequent step involves pressing at high temperatures; unnecessary vaporization of water and resulting waste of heat would result from omission of this step. Following prepressing, the compressed mat is moved into the hot-press along with the wire screen on which it was formed. High levels of pressure and heat serve to re-form ligneous bonds, squeeze out additional water, and dry the mat. The screen is retained in the hot-pressing operation to allow escape of water vapor.

Wet-process hardboard is typified by evenly distributed density (because water is an efficient forming medium) and one rough side (caused by the screen used in the hot-press).

Dry process. Dry-process hardboard is made using air rather than water as a forming medium. Following production of pulp, the fiber is dried and introduced into a forming device in which is created a "snowstorm" of the dry fluffy fiber. The fiber blanket formed in this way is quite thick (perhaps 4–5 in. for what will eventually be a ¼-in. panel), so a press roll is placed downstream of the former to compress the loosely piled fibers. Hot-pressing completes the sequence. Since fiber is dry when it enters the hot-press, no screen is needed beneath the mat; thus the panels are smooth on both sides (S-2-S).

Dry-process hardboard tends to have less evenly distributed density than the wet-process variety, and strength is often slightly lower if similar amounts of resin are used; therefore more resin (about 2% resin solids based on dry weight) is normally used in making dry-process panels.

Tempering. Hardboard is sensitive to moisture, particularly liquid moisture; therefore, unless specially treated, it is intended as an interior product. Moisture can cause linear expansion of panels, thickness swelling, and formation of surface blisters. Hardboard intended for exterior use is thus treated by one of several processes to meet commercial standards for reduced sensitivity to moisture. The resulting product is known as tempered hardboard.

Traditionally, tempering was achieved by soaking finished panels in various oils, followed by baking at high temperature to flash off the volatile fractions. The result was greatly improved water resistance, increased abrasion resistance, improved hardness, and better overall strength. Another process for tempering involves high-temperature treatment without a preliminary oil soak; the purpose of exposure to heat, which may be as great as 200°C, is to increase cross-linking between cellulose and other polymers. Performance under wet conditions can also be improved by simply using more resin in board manufacture. The latter mentioned methods for tempering have become more popular in recent years because air pollution problems associated with baking of oil-soaked panels are avoided.

APPLICATIONS. Hardboard is used in furniture in the form of flat panels for television and radio cabinet backing, drawer bottoms, dust stops, sliding doors, general purpose backing, and table tops (Fig. 16.10). It is also commonly used for wall paneling, cabinet doors and tops, interior door faces, garage door panels, and store fixture components. Unfinished panels are perforated with holes and used as pegboard for decoration of

Fig. 16.10
Hardboard panels have a variety of uses.

Fig. 16.11
Hardboard can be molded to different shapes.

workshop, laundry room, and garage walls. Smooth-faced hardboard sheets are also often painted or covered with vinyl or other material for use as exterior siding or as decorative paneling for interior use. Appearance grade panels can be made with contoured or sculptured surfaces by using sculptured platens (or dies) in the hot-press. This technique allows lifelike reproduction of rough-sawn surfaces, simulated brick, or other textures. Another family of hardboard products is based upon the fact that finished panels can be steamed and molded to various shapes (Fig. 16.11). Molded hardboard products are particularly evident in the auto industry, where they are used as door and roof panels, back window decks, dashboards, and occasionally even heating system ductwork.

Insulation board

A group of fiber panel products is manufactured to specific gravities ranging from about 0.25 to 0.45. These range from low-density acoustical ceiling tile (Fig. 16.12) to relatively high-density structural insulation board that is used under siding in frame construction (Fig. 16.13). The structural insulation product provides added insulation to a wall construction, eliminates the need for corner bracing in the frame wall, and serves to reduce noise transmission through exterior walls.

MANUFACTURING PROCESS. The process used to produce insulation board is quite similar to that employed in making hardboard but with one important difference. As with hardboard, the insulation board sequence involves thermomechanical pulping of chips, subsequent refining of fiber, and board formation (normally using water as a forming medium). The difference is in the pressing and drying of the mat. A hot-press is not used in making insulation board. Instead, the mat is simply brought to desired thickness using a press roll and then dried. The omission of hot-pressing

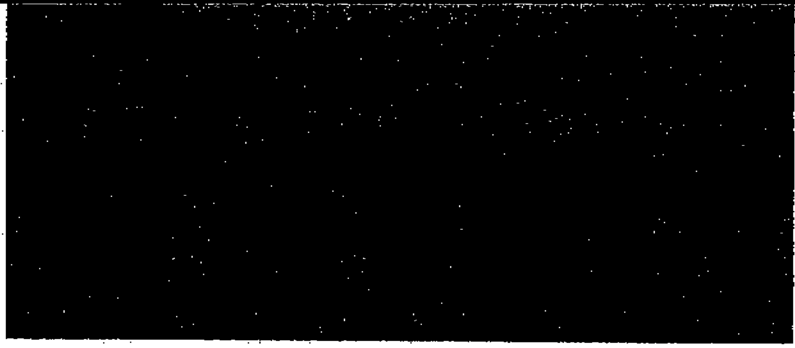


Fig. 16.12
Acoustical ceiling tile is commonly made of wood fiber.

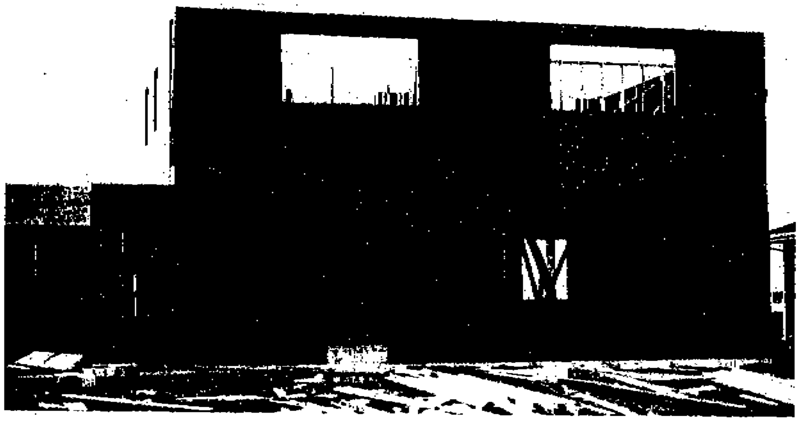


Fig. 16.13
Structural insulation board is applied prior to siding.

means that ligneous bonding is not achieved in insulation board. Fiber-to-fiber linkages are provided primarily by hydrogen bonding, although additives such as starch or asphalt are often used for bond enhancement.

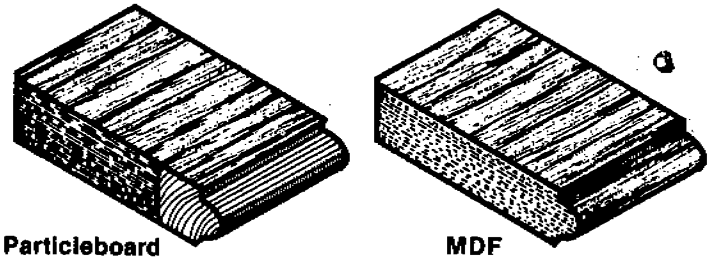
Medium-density fiberboard

A new type of wood panel developed in the 1960s is similar to both hardboard and particleboard yet distinctly different from either. The new product, which is manufactured to a density of 31–50 lb/ft^3 (500–800 kg/m^3), is known as medium-density fiberboard (MDF). Like hardboard, MDF is made from wood that has been reduced to individual fibers and fiber bundles. Bonding of fiber in the finished product is, however, achieved through the use of synthetic resin or other synthetic binder rather

than through redevelopment of ligneous bonds; in this respect MDF resembles particleboard.

The most significant use of MDF is in furniture manufacture, where it is used in much the same way as particleboard is. Particleboard is generally preferred where square-edged panels are needed because it is less expensive. However, use of particleboard where edge-profiling of panels is required, such as in table tops, requires special and expensive treatment. The edges are too porous to be shaped and finished directly and are thus commonly edge-banded with solid wood (Fig. 16.14). MDF, on the other hand, has a more uniform density and smooth, tight edges that can be machined almost like solid wood, eliminating the need for edge-banding. MDF can also be finished to a smooth surface and grain-printed, thus eliminating the need for surface veneers or laminates. For these reasons there is a well-defined market for MDF furniture panels.

Fig. 16.14
In contrast to particleboard, MDF requires no edge-banding prior to shaping



MANUFACTURING PROCESS. The first steps in making MDF are very similar to those employed in manufacturing hardboard. Logs are reduced to chips, with these then subjected to a thermomechanical pulping. The process thereafter closely resembles that used in making particleboard (see Chapter 15). Fiber is dried, blended with resin and occasionally wax, and formed into a mat that is subsequently pressed to desired thickness and density. Like particleboard, resin solids compose 6–7% of the dry weight of the product.

8 Wood and water

WATER is a natural constituent of all parts of a living tree. In the xylem portion, water (moisture) commonly makes up over half the total weight; that is, the weight of water in green wood is commonly equal to or greater than the weight of dry wood substance. When the tree dies or a log is processed into lumber, veneer, or chips, the wood immediately begins to lose some of its moisture to the surrounding atmosphere. If drying continues long enough, the dimensions and the physical properties of the wood will begin to undergo change. Some water will remain within the structure of the cell walls even after wood has been manufactured into a lumber, veneer, particle, or fiber product. The physical and mechanical properties, resistance to biological deterioration, and dimensional stability of the product will be affected by the amount of water present and its fluctuation with time. Since almost all properties of wood and wood products are affected by water, it is important to understand the nature of water in wood and how it is associated with the microstructure. Chapter 8 is devoted to this subject and in addition covers some of the practical aspects of wood drying and the proper use of wood products to assure satisfactory performance under a variety of service conditions.

Location of water in wood

Water in green or freshly harvested wood is located within the cell wall and in the cell lumen. The amount of water within the cell wall structure of a living tree remains essentially constant from season to season, although the amount of water in the lumen may vary. The water in the lumen may contain dissolved food materials produced by photosynthesis as well as inorganic compounds. This solution is commonly referred to as sap.

When wood is dried during manufacture, all the liquid water in the cell lumen is removed. The cell lumen of wood in use will, however, always contain some water vapor. The amount of water remaining in the cell walls of a finished product depends upon the extent of drying during manufacture and the environment into which the product is later placed. After once being removed by drying, water will recur in the lumen only if the product is exposed to liquid water. This could result from placing wood in the ground or using it where rain may come in contact with it.

Figure 8.1A may help in visualizing the location of water in a wood cell. As long as there is any liquid water remaining in the lumen, the wall of the cell will be saturated; i.e., it will contain as much water as it physically can adsorb. Most physical properties of wood (other than weight) are not affected by differences in the amount of water in the cell lumen. For example, if the lumen is one-fourth full of liquid water, the cell (and the wood) will have the same strength as when one-half full.

When wood is dried to the extent that all the water in the lumen is removed, water begins to leave the cell wall. The green cell is illustrated in Figure 8.1A. Almost all wood products used in buildings, or for other applications where there is no contact with the ground, contain water in the forms shown in Figure 8.1B.

The point at which all the liquid water in the lumen has been removed but the cell wall is still saturated is termed the fiber saturation point (FSP). This is a critical point, since below this the properties of wood are altered

Fig. 8.1A
Water in a cell of green wood

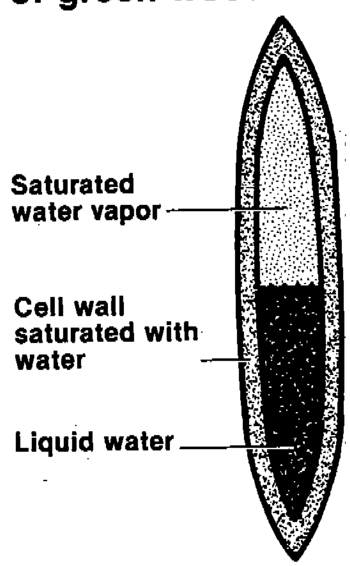
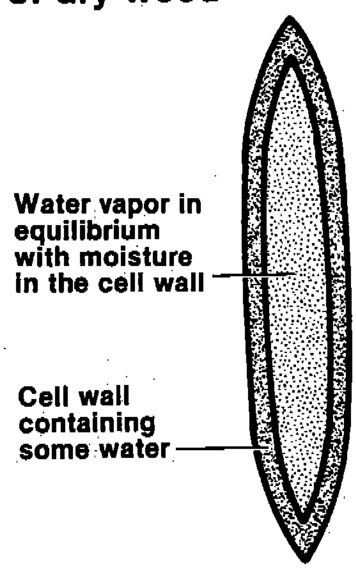


Fig. 8.1B
Water in a cell of dry wood



by changes in moisture content. The amount of moisture present in wood when used in environments providing no contact with liquid water will always be less than the FSP.

Nature of water in wood

To simplify discussion, the liquid water found in the lumen of wood is often referred to as free water and the water within the cell wall is called bound water. This is an appropriate description, since the free water is relatively easy to remove and so is the first to be lost in the drying process. Bound water is held more tightly because of surface adsorption within the wood structure. The lower the moisture content below the FSP the more tightly bound is the remaining water.

The water within the cell wall, bound water, is held by *ad*sorption forces, which are physicochemical in nature. This is not to be confused with the *ab*sorption that takes place, for example, when a noncellulose sponge soaks up water. Aborption results from surface tension forces. Adsorption, in contrast, involves the attraction of water molecules to hydrogen-bonding sites present in cellulose, hemicellulose, and lignin. This hydrogen bonding occurs on the hydrogen side of the OH or hydroxyl group found throughout the chemical elements of wood. Figure 8.2 illustrates where water molecules are held by hydrogen bonding to a segment of a cellulose molecule. The left-hand side of this figure illustrates monomolecular adsorption of water onto the cellulose; the right-hand side shows polymolecular adsorption. In saturated green wood as many as five or six water molecules may be attracted to each accessible sorption site.

In Chapter 3 the submicroscopic structure of wood was discussed. Recall that the groupings of long-chain molecules in the cell wall contain crystalline and amorphous regions. In the crystalline regions, it is believed that the OH groups of adjacent cellulose molecules are mutually bonded, or cross-linked. Therefore, there are no sites to hold water within the crystallites. Within the amorphous or disordered regions, however, the hydroxyl groups are accessible for adsorption of water. The location of water molecules in relation to the cellulose molecules is illustrated in Figure 8.3.

Calculating moisture content

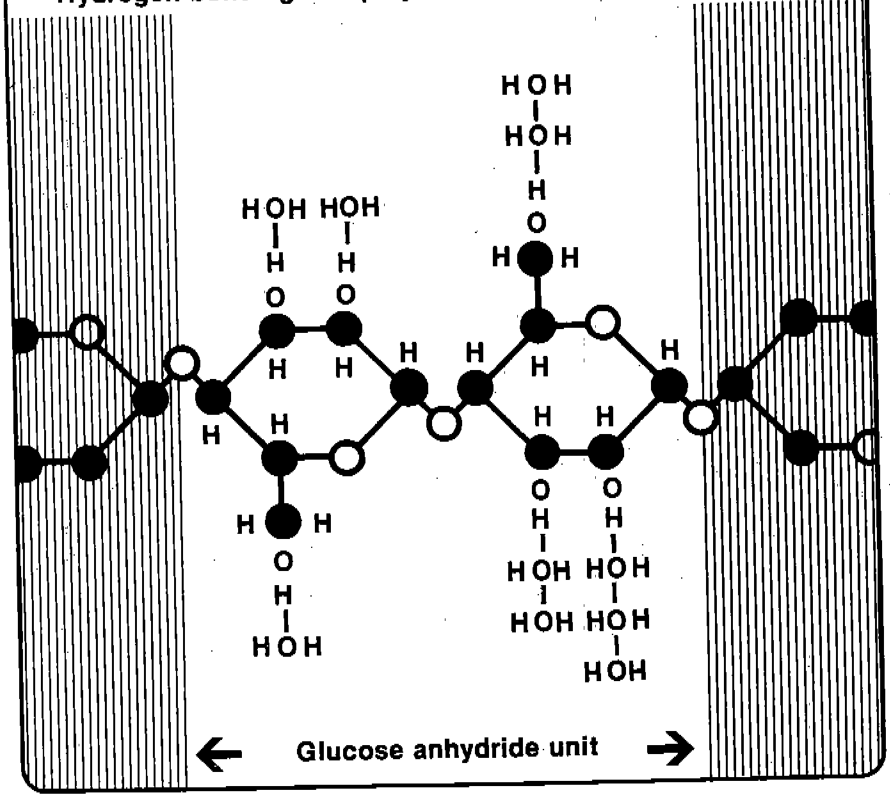
The amount of water in wood or a wood product is usually expressed as the moisture content. The moisture content (MC) is defined as the weight of the water expressed as a percentage of the moisture-free or ovendry (OD) weight of the wood. (The term weight is used rather than mass throughout this book to conform to general practice.) Thus:

$$\%\ MC = \frac{\text{weight of water}}{\text{OD weight}} \times 100$$

Fig. 8.2

Attraction of water to cellulose

Hydrogen bonding and polymolecular absorption



Because the denominator is the dry weight, not the total weight, the moisture content calculated in this way can be over 100%. One of the most common methods of determining the moisture content is to weigh the wet sample, dry it in an oven at 103 ± 2°C to drive off all water, and then reweigh. The details of this ovendry method are described in American Society for Testing and Materials (ASTM) Standard D 2016. When using the ovendry method, the moisture content is computed as follows:

$$\%\ MC = \frac{\text{weight with water} - \text{OD weight}}{\text{OD weight}} \times 100$$

An example may help illustrate how moisture content is calculated. A block of green redwood has a total weight of 970 g. After oven-drying, the weight is 390 g. What was the moisture content when the weight was 970 g?

$$\%\ MC = \frac{970 - 390}{390} \times 100 = 149\%$$

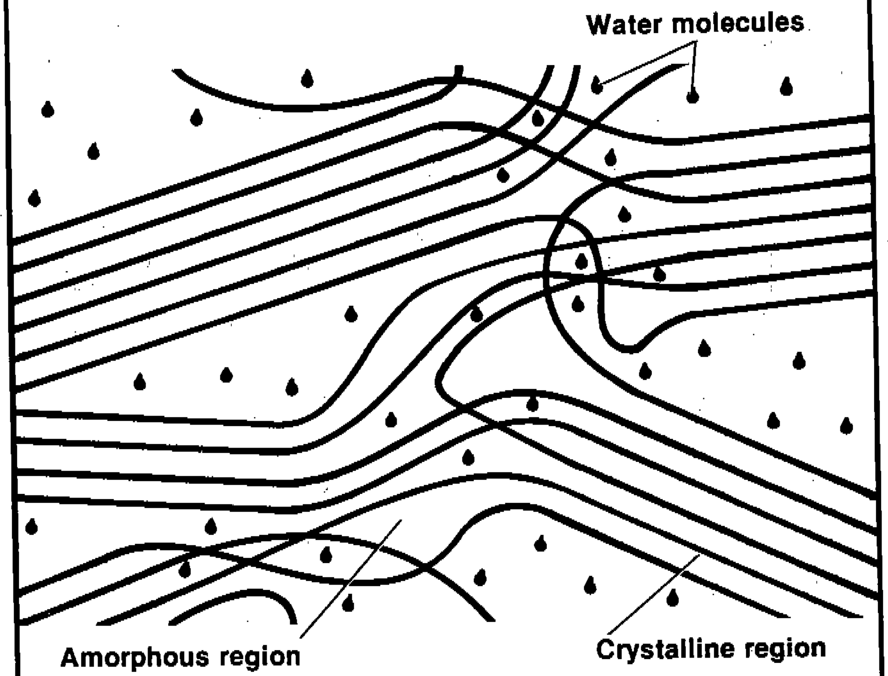
If a similar block of wood with the same ovendry weight is partially dried until the weight drops to 540 g, what is the moisture content?

$$\% \text{ MC} = \frac{540 - 390}{390} \times 100 = 38\%$$

Note that when calculating the moisture content, the amount of water is expressed as a percent of the weight of the dry wood. This method of calculating moisture content is the accepted standard for all lumber, plywood, particleboard, and fiberboard products in the United States and in most of the world. In the pulp and paper industry and when wood is used as a fuel, however, the amount of moisture is often expressed as a percent of the total weight, i.e., weight of wood plus water. In general forest products practice and in this book, if the basis for calculating moisture content is not given, it is on the dry weight. When the wet weight basis is used, it is indicated as moisture content (wet basis). Examples of calculating moisture content on a wet basis are given in Chapter 17.

Fig. 8.3

Relationship of water to cellulose molecules



The basic equation for moisture content can be manipulated to forms that are convenient to use in other situations. For instance, solving the equation for ovendry weight yields:

$$\text{OD weight} = \frac{\text{green weight}}{1 + (\%\ \text{MC}/100)}$$

This form is useful for estimating the dry weight of green wood when the green weight is known and moisture content has been obtained from a small sample. Example: A load of pulpwood weighs 32,200 lbs. The moisture content is found to be 90% by oven-drying representative cross sections from several bolts. An estimate of the dry weight of wood is desired so that the yield of pulp can be determined per unit of raw material input.

$$\text{OD weight} = 32{,}200/(1 + 0.90) = 16{,}900\ \text{lb}$$

In another situation, 400 ft^3 of lumber is to be shipped at a moisture content of 19%. The ovendry weight of a cubic foot of this species (volume measured at 19% MC) is known to be 47 lb. The total weight of the shipment is desired.

$$\text{Green weight} = \text{OD weight} \times (1 + \%\ \text{MC}/100)$$

so

$$\text{Green weight} = (47 \times 400)(1 + 0.9) = 22{,}400\ \text{lb}$$

Consider a situation where 40,000 bd ft of lumber, weighing 3800 lb per thousand bd ft (MBF) when green, is to be shipped. The shipping cost is $3 per hundred pounds. The lumber is estimated to average 60% MC when green. How much money would be saved in shipping cost if this lumber were dried to 15% MC prior to shipping?

$$\text{OD weight/MBF} = 3800/1.60 = 2380\ \text{lb}$$
$$\text{Weight at 15\% MC/MBF} = 2380 \times 1.15 = 2730\ \text{lb}$$
$$\text{Weight savings/MBF} = 3800 - 2730 = 1070\ \text{lb}$$
$$\text{Total weight savings} = 40\ \text{MBF} \times 1070\ \text{lb/MBF} = 42{,}800\ \text{lb}$$
$$\text{Savings in shipping cost} = 428 \times 3 = \$1284$$

Measuring moisture content

The determination of moisture content during manufacture and subsequently to verify conformance to commercial standards is generally accomplished by the ovendry method, described in the preceding section, or by the use of electrical moisture meters, which have the advantage of being relatively simple and direct. Other methods of determining moisture content are sometimes used for research purposes where high precision is required. Such methods are outlined in ASTM D 2016.

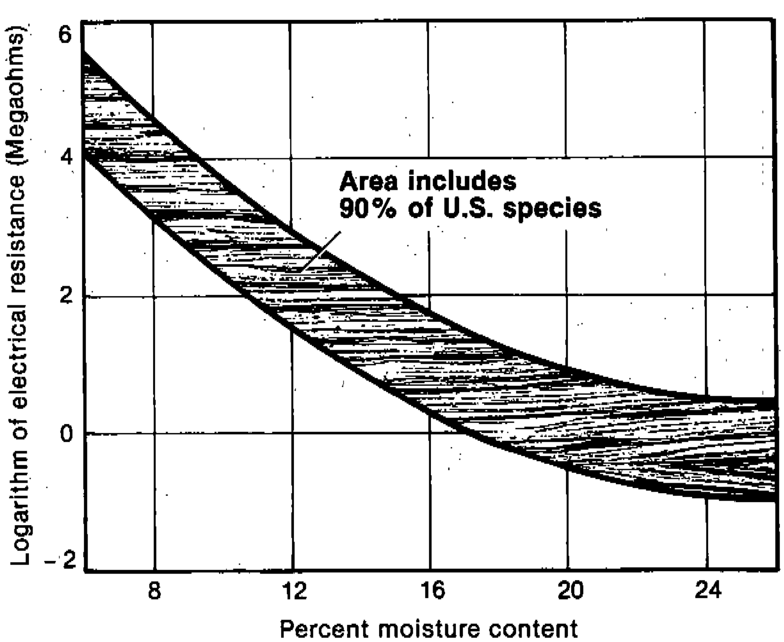
The major disadvantages of the ovendry method are that it is a destructive test; it can take up to several days to complete; and a few species contain volatile components other than water that can be driven off in the drying process, resulting in an incorrectly high moisture indication. However, for most species of lumber and for a wide variety of wood products, the ovendrying method gives an adequately precise and reliable indication of moisture content.

A variety of electrical meters are available to measure the moisture content of lumber, chips, and particles. Although meters are less precise than other moisture determination methods, their instant readout, ease of operation, and nondestructive nature make them well suited for industrial applications.

The most commonly used hand-held meter for lumber is the resistance moisture meter, which measures the electrical resistance between pins driven into the wood. This type of meter indicates the moisture content based upon the relationship shown in Figure 8.4. Insulated pins can be used

Fig. 8.4

Relationship of electrical resistance to moisture content



From USFPL (1987)

to make it possible to measure the resistance between the tips of the pins and therefore to determine the moisture content at different depths. Moisture meters of the resistance type are generally reliable in the 6–30% moisture content range. Since the electrical resistance of wood varies with temperature, corrections must be made if the wood temperature is significantly different from the calibration temperature indicated by the manufacturer. Also, corrections for species are often necessary, since extractives do influence resistance. Above the FSP, electrical resistance meters give a qualitative rather than a precise measure of the moisture content.

Some electric meters are based upon the effect moisture has on the behavior of wood as a capacitor when placed in a high-frequency field. The capacitance of wood varies with the density and moisture content. These meters measure the dielectric constant or power loss of the sample. Such meters must be calibrated for each species to account for density differences. The effective range of 0–30% for capacitance/power-loss meters is only slightly greater than for the resistance-type meters. These meters have electrodes that may contact the surface of the lumber or veneer but no pins need be driven, a particular advantage in valuable woods or when greater speed of measurement is needed. However, the proper use of species corrections is more critical with these meters than with resistance meters. Several types of hand-held meters are shown in Figure 8.5.

The measurement of the moisture in wood particles or fibers that are bulk piled or on conveyors can be accomplished by a combination of a neutron and a gamma gauge. The continuous measurement is accomplished by measuring the water content with a neutron gauge and the total mass with a gamma radiation gauge. Wood moisture can also be measured by a microwave power absorption method.

Moisture systems suitable for automatically controlled production processes are now available. Such systems can provide moisture content information to a data file monitoring output of a production line or provide input to a microprocessor used to control the process.

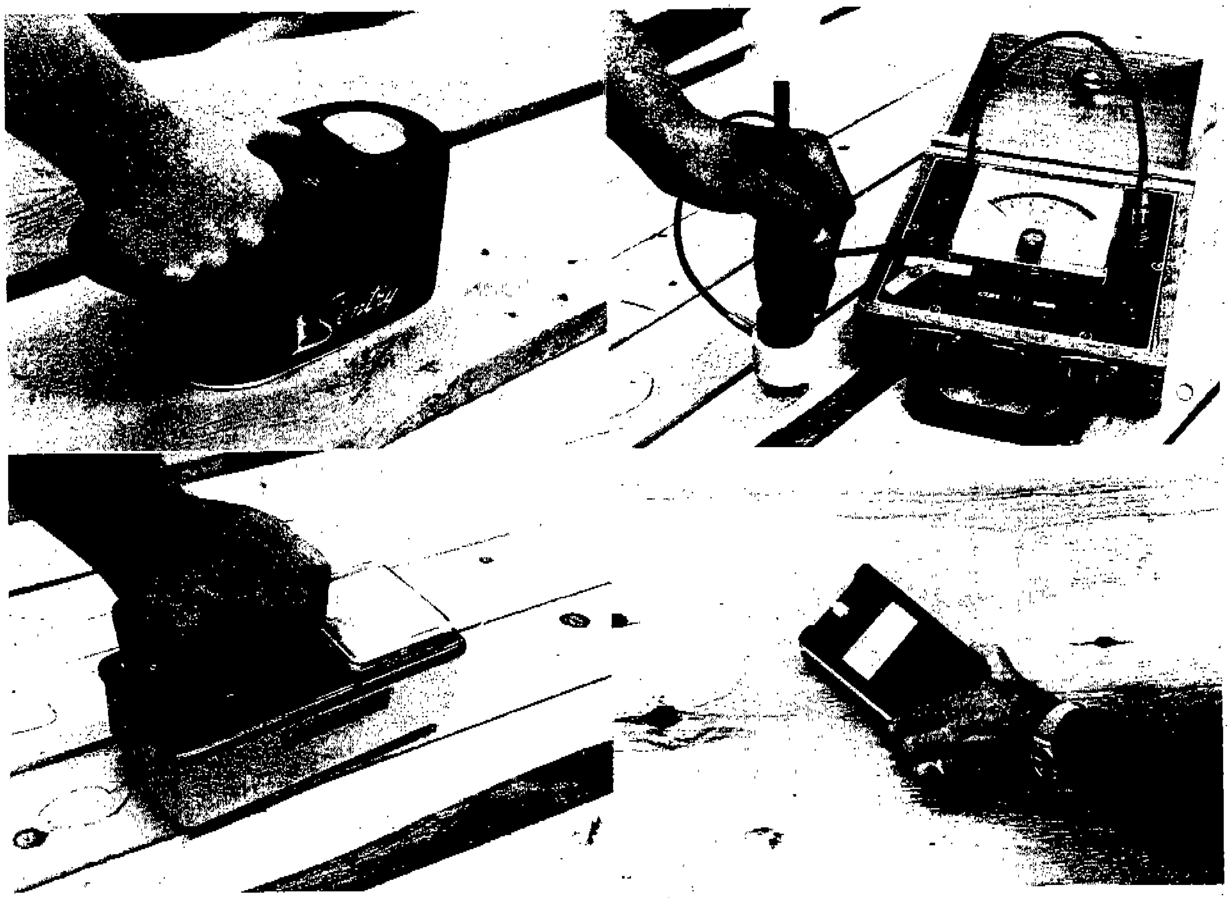
Relation of moisture content to the environment

Because of the adsorptive nature of wood, it has the ability to remove water vapor from the surrounding air until it is in moisture equilibrium with the air. Thus wood is called a hygroscopic material. If wood is in equilibrium with the surrounding environment and the air then becomes drier, the wood will lose water (or desorb) until it again comes into equilibrium. The term sorption is applied to the combined or general phenomena of adsorption and desorption.

The moisture content of wood in equilibrium with a water vapor environment will be less than the FSP. Below the FSP, the forces holding the water to the wood become greater as the moisture content decreases because less polymolecular adsorption and more monomolecular adsorption is involved as the wood approaches the dry condition.

Stamm (1957) stated that monomolecular water is found in wood that

Fig. 8.5
Several types of hand-held moisture meters.

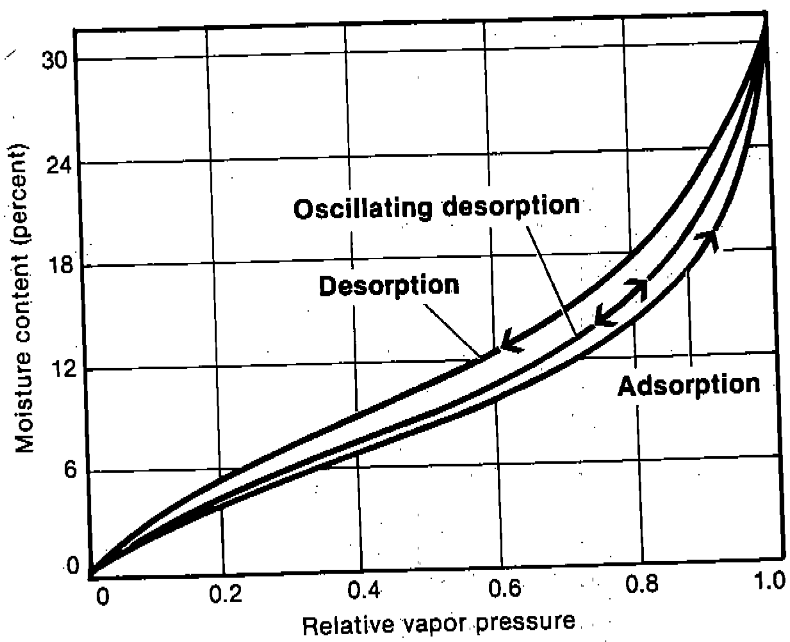


(Courtesy McCarthy Products Co. and Univ. of Minnesota)

is in equilibrium with relative vapor pressures (relative humidities) of 0.2 or less. Between relative vapor pressures of 0.2 and 0.9, most water is held by polymolecular adsorption. Between 0.9 and 0.99, it is believed that some water is held in preexisting capillaries by condensation. Authorities disagree on the extent of capillary-condensed water in wood.

The relationship between the relative vapor pressure in the environment and the moisture content of wood in equilibrium with that environment is not linear. This results from the three different ways in which bound water is held. The graph of this relationship at a constant temperature is called a sorption isotherm. Isotherms developed for white spruce by Seborg and Stamm (1931) (Fig. 8.6) illustrate the shape of the curve that is typical of most species and most wood products. Three curves are shown: desorption, adsorption, and cyclic desorption-adsorption. These show that if a piece of wood has desorbed to an equilibrium point, it may attain a mois-

Fig. 8.6
Sorption isotherms of white spruce at 25°C



From Stamm (1964)

ture content as much as 3% higher than if it had adsorbed at the same relative vapor pressure. Above a relative vapor pressure of about 0.5, the initial desorption curve of green wood is slightly above that of a previously dried piece.

The difference between the desorption and adsorption curves is referred to as hysteresis or lag effect. Hysteresis is common to many types of physicochemical phenomena. A rather simplistic view of this complex phenomenon, but one that may help to visualize the dynamic nature of the water-wood equilibrium process, is as follows. In the green condition, the hydroxyl groups of the cellulosic cell wall are satisfied by water molecules, but as drying occurs these groups move closer together, allowing the formation of weak cellulose-to-cellulose bonds. When adsorption of water then occurs, fewer sorption sites are available for water than was the case originally. Those interested in a thorough discussion of sorption, isotherms, and hysteresis should study Stamm (1964) or Skaar (1972).

In situations where a wood product is subjected to alternating high- and low-humidity conditions, the moisture content will approach the middle curve of Figure 8.6. There is a species effect; some vary markedly from the values indicated. The general shape of the sorption isotherm for all species is similar, however. The FSP indicated in Figure 8.6 is about 31% moisture content. Thirty percent is a value often used as a typical FSP for wood. Higgins (1957) demonstrated that the FSP of some species varies widely from the typical value (Table 8.1). He also found that the hysteresis effect was considerably greater in some species than in others. One cause of variation in the FSP is the presence of extractives. Species generally high in extractives have a relatively low FSP. Presumably, the extractives occupy some sites in the cell wall that would otherwise attract water.

Table 8.1. The fiber saturation point of several species

Species	Fiber saturation point (% *MC*)
Southern yellow pine	29
Sitka spruce	28
Western redcedar	18
Redwood	22
Teak	18
Rosewood	15

Source: Higgins (1957).

Temperature also has an effect on wood-water relationships. The general relationship is illustrated in Figure 8.7. Note that this temperature effect is relatively small. High temperatures also have a permanent effect on the wood itself. Wood that has been subjected to temperatures in excess of 100°C for long periods becomes less hygroscopic; i.e., it equalizes at a lower moisture content than normal wood. This is one of the reasons that products such as fiberboard and particleboard have a lower moisture content in any constant environment than solid wood products. These products are often subjected to temperatures in excess of 150°C during manufacture.

The moisture content that wood or a wood-based product attains when in an environment of constant temperature and humidity is termed the equilibrium moisture content (EMC). Considerable time is required before large pieces of wood will come into equilibrium, i.e., reach their EMC.

Despite the variability in sorption characteristics among species, it is assumed for most purposes that all wood attains the same EMC under the same temperature and relative humidity conditions. A table prepared from data for Sitka spruce is presented in the Wood Handbook (USFPL 1987). It is used throughout much of the world to estimate the EMC and is condensed in Table 8.2.

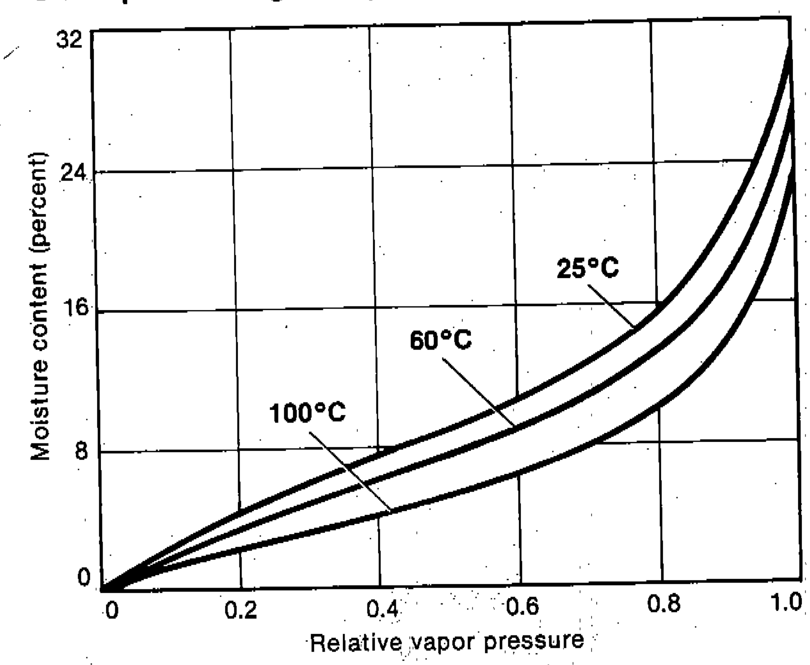
Note that at 70°F the moisture content of wood subjected to relative humidities from 30 to 70% will vary from 6.2 to 13.1%. This is the range of humidity conditions to which most wood is subjected in use. It is therefore the range of moisture content that is normal for wood used indoors where it is protected from contact with water.

Products manufactured from wood tend in most cases to have slightly lower EMCs than the raw wood from which they are produced. This is partially because of the heat-treatment effect mentioned above but also because of the addition of resins, coatings, and sizing materials, which in

Fig. 8.7

Effect of temperature on EMC

Sitka spruce during desorption



From Stamm (1964)

themselves are usually less hygroscopic than wood. Plywood and laminated wood products have EMC characteristics very similar to wood or lumber. Fiber and particle products, however, may exhibit considerably different characteristics. Table 8.3 shows EMC values for softwood plywood, a particleboard, a tempered hardboard, and a decorative laminate as compared to that of solid wood. If accurate EMC information is needed when dealing with a specific forest product, a laboratory determination should be made. Even products of the same type will vary in EMC because of differences in the raw materials used and in the manufacturing process.

Table 8.2. Percent moisture content of wood in equilibrium with dry-bulb temperatures and relative humidity conditions

Dry bulb		Relative humidity							
°F	(°C)	20%	30%	40%	50%	60%	70%	80%	90%
30	(−1)	4.6	6.3	7.9	9.5	11.3	13.5	16.5	21.0
50	(10)	4.6	6.3	7.9	9.5	11.2	13.4	16.4	20.9
70	(21)	4.5	6.2	7.7	9.2	11.0	13.1	16.0	20.5
90	(32)	4.3	5.9	7.4	8.9	10.5	12.6	15.4	19.8
110	(43)	4.0	5.6	7.0	8.4	10.0	12.0	14.7	19.1
130	(54)	3.7	5.2	6.6	7.9	9.4	11.3	14.0	18.2
150	(66)	3.4	4.8	6.1	7.4	8.8	10.6	13.1	17.2
170	(77)	3.0	4.3	5.6	6.8	8.2	9.9	12.3	16.2

Source: Adapted from USFPL 1987.

Table 8.3. Equilibrium moisture content of typical forest products at 70°F (21°C)

Relative humidity	Wood	Softwood plywood	Particle-board	Oil-treated hardboard	High-pressure laminate
(%)			(% *MC*)		
30	6.0	6.0	6.6	4.0	3.0
42	8.0	7.0	7.5	4.6	3.3
65	12.0	11.0	9.3	6.9	5.1
80	16.1	15.0	11.6	9.5	6.6
90	20.6	19.0	16.6	10.8	9.1

Source: Heebink (1966).

Moisture content of green wood

The moisture content of green wood is important because of its direct relation to the weight of logs and green lumber. Therefore, it is of concern to those who design harvesting and transport equipment or purchase wood on a weight basis.

The moisture content of green wood varies considerably among species. Note that among species shown in Table 8.4, the moisture content of heartwood ranges from 33 to 98% and that of sapwood from 44 to 249%. The values in Table 8.4 should be considered as only general indications. Within any species there is considerable variation depending upon the site, age, and volume of the tree. In softwoods the average green moisture content tends to decrease as a tree grows older. There can be a 30% difference in the moisture content of southern pines over 45 years of age compared to trees under 25 years of age (Koch 1972).

Table 8.4. Moisture content of green wood

Species	Moisture content: Heartwood	Moisture content: Sapwood
	(%)	
Hardwoods		
White ash	46	44
Aspen	95	113
Yellow birch	74	72
American elm	95	92
Sugar maple	65	72
Northern red oak	80	69
White oak	64	78
Sweetgum	79	137
Black walnut	90	73
Softwoods		
Western redcedar	58	249
Douglas-fir	37	115
White fir	98	160
Ponderosa pine	40	148
Loblolly pine	33	110
Redwood	86	210
Eastern spruce	34	128
Sitka spruce	41	142

Source: USFPL (1987).

Within a tree there is variation of moisture content. The differences between sapwood and heartwood (Table 8.4) are one source of such variation. When wood in the bole of a tree undergoes change from sapwood to heartwood, the amount of moisture in the cell wall may decrease slightly. This is the result of deposition of extractives, which tend to take the place of water molecules in their association with cellulose and hemicellulose. Some extractives may also be left in solution or suspension in the water found in the lumen of the heartwood cells.

Hardwoods generally have only small differences in moisture content between sapwood and heartwood. This contrasts markedly to softwoods, where the moisture content of sapwood is usually much higher than heartwood, often by a factor of three to four times. Softwoods have a lower overall moisture content as they grow older because the percent of sapwood volume declines. If you are lost in the woods and forced to build a fire from green wood, burn the heartwood of a softwood, not a hardwood!

For most design or total weight estimates, the moisture contents of green wood given in Table 8.4 should be adequate. A more complete listing can be found in Table 2.1. Many trade associations and railroads publish lists of weights, by species, for green and dried products such as lumber and poles. Such information may be useful, but if the actual moisture content can be measured, a more accurate estimate of green weight can be made by using procedures described in Chapter 9.

If green weight is to be used as the basis for purchasing logs or pulpwood, it would be advisable to conduct an on-the-site study of the green moisture content. The effect of the size of the logs or bolts and the season of the year should be determined. The goal of most weight-scaling procedures is to pay a fixed amount per unit of dry wood. Occasionally, however, some adjustments to the price may be made for quality or defects or for the degree of seasoning of the wood.

Little information has been published regarding the seasonal variation of the green moisture content, although many firms and associations have compiled such data. Koch (1972) reported that in southern pine the moisture content of increment cores is higher during midwinter than in summer. In Minnesota, where aspen pulpwood is often purchased by weight, some mills use a weight of 4800 lb during the winter as the equivalent of a cord and 4600 lb as the conversion factor during the summer, reflecting a higher moisture content in the winter. For some other species, a higher moisture content is reported in the summer months.

Shrinking and swelling

As wood loses moisture below the FSP, i.e., loses bound water, it shrinks. Conversely, as water enters the cell wall structure, the wood will swell. Shrinking and swelling is an exactly reversible process in small pieces of stress-free wood. In wood panel products, however, such as fiberboard and particleboard, the process is often not completely reversible. This results in part from the compression that wood fibers or particles undergo during the manufacturing process. In large pieces of solid wood, swelling or shrinking may not be completely reversible as a result of internal drying stresses.

Shrinking of the cell wall, and therefore of the whole wood, occurs as bound-water molecules escape from between long-chain cellulose and hemicellulose molecules. These chain molecules can then move closer together. The amount of shrinkage that occurs is generally proportional to the amount of water removed from the cell wall. Swelling is simply the reverse of this process. Since the S-2 layer of the cell wall is generally thicker than the other layers combined, the molecular orientation in this layer largely determines how shrinking occurs. In the S-2 layer most of the chain molecules are oriented more or less parallel to the long axis of the cell. Thus both transverse dimensions decrease as these molecules move closer together. For the same reason, the length of the cell is not greatly affected as the cell wall substance shrinks or swells.

In reaction wood and other abnormal wood the orientation of the microfibrils in the S-2 layer is often at a significant angle from the cell axis. Therefore, as the wood dries there is a measurable shortening of the cell; consequently, longitudinal shrinking occurs. Longitudinal shrinkage in such abnormal wood can be as great as 3% when going from the FSP to the ovendry condition. A 2 × 4-in. stud 8 ft long for the wall of a home would shrink almost 3 in. in length when drying from its FSP to EMC condition if it were manufactured from such material. Fortunately, such lumber is rarely encountered.

Shrinking and swelling are expressed as a percentage of the dimension before the change occurred. Thus:

$$\%\ \text{shrinkage} = \frac{\text{decrease in dimension or volume}}{\text{original dimension or volume}} \times 100$$

$$\%\ \text{swelling} = \frac{\text{increase in dimension or volume}}{\text{original dimension or volume}} \times 100$$

The longitudinal shrinkage of normal wood is negligible for most practical purposes. This is one of the characteristics that makes lumber and lumber products such usable building materials. If this were not so, the change of moisture content during use would be disastrous. Usually, some longitudinal shrinkage does occur in drying from the green to the ovendry condition, but this amounts to only 0.1–0.2% for most species and rarely exceeds 0.4%.

From an idealized "soda-straw" concept of wood, one might visualize that the radial and tangential dimensions would shrink or swell the same amount. However, tangential shrinkage is greater than radial shrinkage by a factor between one and one-half and three to one. Several anatomical characteristics are believed responsible for this differential, including presence of ray tissue, frequent pitting on radial walls, domination of summerwood in the tangential direction, and differences in the amount of cell wall material radially vs. tangentially. The average transverse shrinkage values of a number of domestic and imported species are shown in Table 8.5. These values are good guidelines to use for estimates; however, the actual shrinkage of individual pieces in service may vary significantly from these averages.

Table 8.5. Shrinkage values of wood from green to ovendry moisture content

Species	Shrinkage* Radial	Tangential	Volumetric
		(%)	
Domestic hardwoods			
White ash	4.9	7.8	13.3
Quaking aspen	3.5	6.7	11.5
Yellow birch	7.3	9.5	16.8
American elm	4.2	9.5	14.6
Sugar maple	4.8	9.9	14.7
Northern red oak	4.0	8.6	13.7
Black walnut	5.5	7.8	12.8
Imported hardwoods			
Apitong	5.2	10.9	...
Balsa	3.0	7.6	...
Mahogany	3.0	4.1	...
Teak	2.5	5.8	...
Khaya (African mahogany)	2.5	4.5	...
Softwoods			
Western redcedar	2.4	5.0	6.8
Coast Douglas-fir	4.8	7.6	12.4
White fir	3.3	7.0	9.8
Western hemlock	4.2	7.8	12.4
Loblolly pine	4.8	7.4	12.3
Sitka spruce	4.3	7.5	11.5

Source: USFPL (1987).

$$* \% \text{ Shrinkage} = \frac{\text{change in dimension}}{\text{green dimension}} \times 100$$

Variation in the shrinkage of different samples of the same species under the same conditions results primarily from three factors:

1. The size and shape of the piece. This affects the grain orientation in the piece and the uniformity of moisture through the thickness.
2. The density of the sample. The higher the density of the sample, the more it will tend to shrink.
3. The rate at which the sample is dried. Under rapid drying conditions, internal stresses are set up because of differential shrinking. This often results in less final shrinkage than would otherwise occur. In contrast, however, some species shrink more than normal when dried rapidly under high-temperature conditions.

Shrinking of lumber during the manufacturing process is significant and must be considered when determining the size of the piece to saw from a log. For example, if a nominal 2 × 10-in. Douglas-fir plank is to be sawn from a log, it must be expected that it will shrink about 0.05 in. in thickness and 0.4 in. in width when it is dried to 15% MC. Since the final dried and surfaced size of that piece must be at least 1.5 × 9.25 in. to meet standard softwood lumber sizes, adequate shrinkage allowance must be provided. Allowance must also be made for sawing variability and surfacing. Some mills use a target sawing size of 1.8 × 9.9 in.

The amount of shrinkage is generally proportional to the amount of water removed from the cell wall. This suggests that higher density species should shrink more per percent moisture content change than lower density species. This is generally the case. Note that high-density woods lose a greater amount of water per percent moisture content change. As an example, sugar pine contains about 0.34 g ovendry wood substance/cm^3, while the same volume of longleaf pine contains about 0.54 g dry wood substance. If each of these woods loses 10% MC, the sugar pine will lose 0.034 g water/cm^3 but longleaf pine will lose 0.054 g/cm^3. The normal volumetric shrinkage, green to ovendry, for sugar pine is 7.9%, while that for longleaf pine is 12.2%. In this example, there is a close relationship between the amount of water lost per unit of moisture content change and the resulting shrinkage.

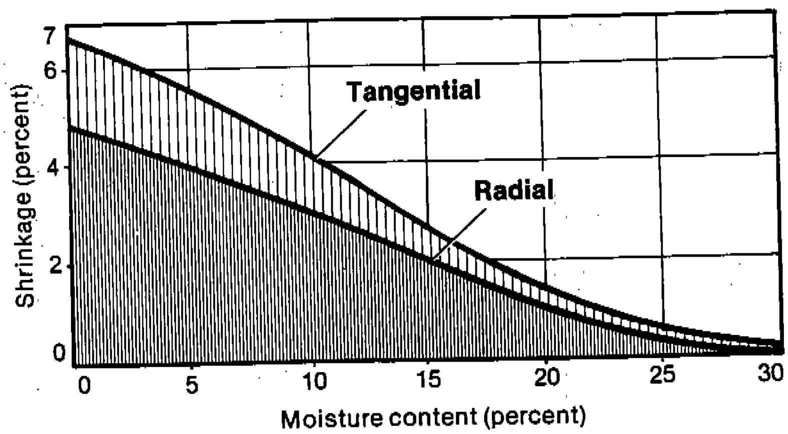
Often, there is a much less direct relationship between the mass of water removed and the resulting shrinkage than in the above example. One would expect, based upon the density difference, that black walnut containing 0.55 g dry wood substance/cm^3 would shrink more than eastern cottonwood containing 0.40 g wood/cm^3. However, the average green to ovendry volumetric shrinkage of walnut is only 12.8% compared to 13.9% for cottonwood. A major factor that tends to mask the effect density has upon shrinking and swelling is the presence of extractives, which tend to lower the FSP and bulk the cell wall. Because of this, the heartwood of some species is more dimensionally stable than the sapwood.

The relationship between shrinkage and moisture content is essentially linear. Figure 8.8 shows the shape of the curve for southern pine. This near linearity makes it relatively simple to estimate shrinkage between any two moisture contents if the green to ovendry shrinkage values for the wood are known. The rationale for such a calculation is illustrated in Figure 8.9, which illustrates the shrinkage that could be expected in the tangential dimension of loblolly pine when dried from 15 to 8% MC. The rate of tangential shrinkage for this species is 7.4/30, or 0.25% shrinkage per percent of moisture content change. These calculations assume that the FSP is 30%, which is a reasonable assumption in most situations. Since the moisture content change is 7%, the total shrinkage expected is about 7 × 0.25, or 1.75%. If the piece were dried from the FSP (30%) to 8% MC, the predicted shrinkage would be 22 × 0.25, or 5.4%. Note that when drying from a higher moisture content, such as 50% to 8%, the predicted shrinkage would also be 5.4%, since it is assumed that shrinkage does not commence until the wood is dried to the FSP. The estimate of radial shrinkage from 15 to 8% MC would equal 4.8/30 × 7, or 1.1%.

In actual practice, the shrinkage of a board may commence before the average moisture content drops below the FSP. This is a result of shrinking in the surface layers of wood that have dried while the core was still wet. However, this need not be considered in general practice when estimating shrinkage as described above.

Fig. 8.8

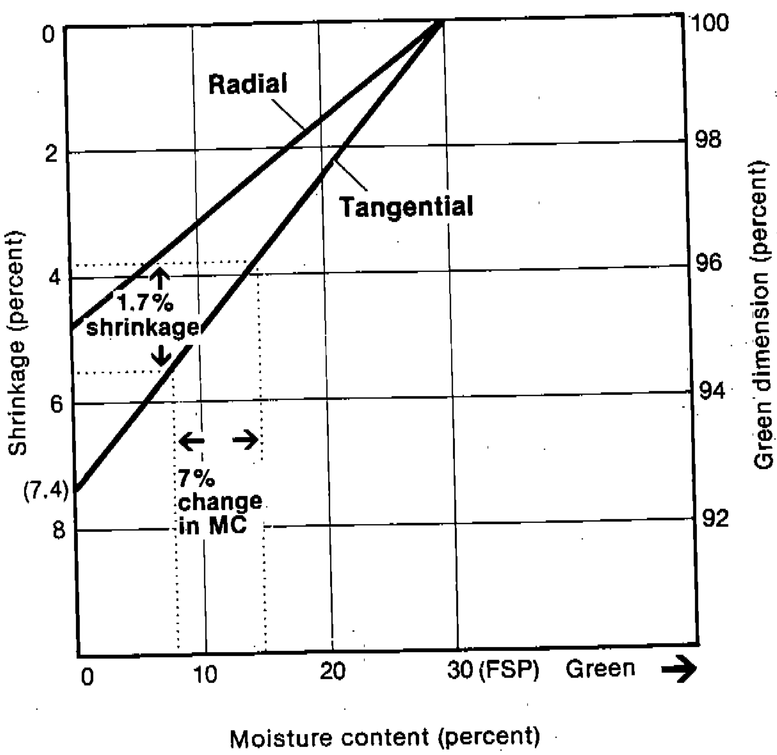
Relationship between MC and shrinkage
(southern pine)



From Peck (1947)

Fig. 8.9

Estimating shrinkage and change in size
for loblolly pine with 4.8% radial and 7.4% tangential shrinkage, green to ovendry



Dimensional changes, environmental conditions

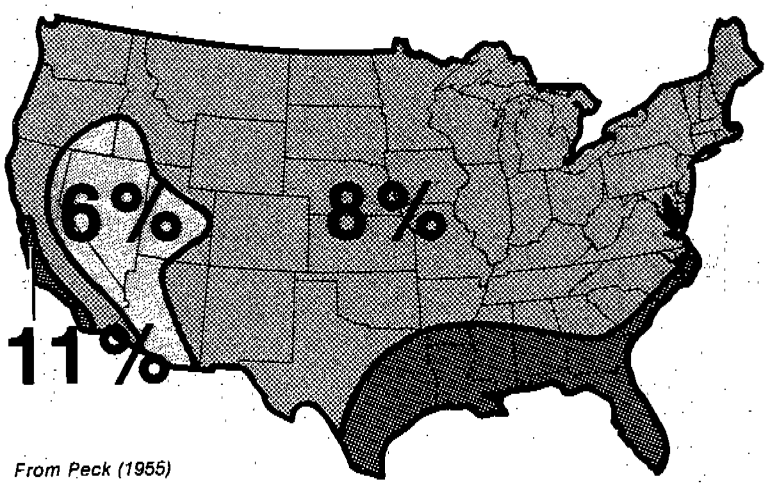
It follows from the previous discussion that wood used where the humidity fluctuates will continually change moisture content and therefore dimension. If humidity changes are small, these dimensional changes will not be noticed and will have no impact on satisfactory use. Even large fluctuations in humidity may have little effect if these conditions last for only short periods (hours or days) and the wood does not have time to come to the new EMC. Problems can arise, however, when a wood product is used under widely varying humidity and temperature conditions if the design and application of that product has not anticipated changes in dimension.

For the most trouble-free use of wood, the goal should be to fabricate it at the moisture content it will average during that application. However, this is not always possible. Framing lumber for light-frame wood buildings, as an example, is commonly manufactured at from 15 to 19% MC, a moisture content that is 5–10% above that to which it will eventually equilibrate in most areas of the United States. This is usually not a problem, because small changes in the dimensions of studs, rafters, and floor joists are not noticeable. If green framing lumber is used, the dimensional changes may be large enough to cause problems such as cracked plaster, nail popping in gypsum walls, and distortion of wall surfaces.

For interior uses such as furniture and millwork, it is much more critical for satisfactory performance to use lumber at the proper moisture content. Figure 8.10 shows the recommended moisture content averages for

Fig. 8.10

Recommended moisture content
(average for interior woodwork)



From Peck (1955)

wood used in the heated interior of buildings in the United States. This provides a good guide for selecting the proper moisture content for wood materials. For demanding situations, where dimensional changes could obviously cause problems, the designer or user should carefully consider the moisture content of the lumber being used, the species, the conditions of use, and the amount of dimensional change that should be expected.

The following examples illustrate the type of cases deserving careful consideration. These will also serve to show procedures that can be used for estimating dimensional changes.

EXAMPLE 1: A gymnasium floor was constructed with wood strip flooring nailed tightly in such a way that essentially no cracks or spaces were left between the strips. The size of the gymnasium was 50 × 120 ft, with the strip floor being laid parallel to the long axis of the gym. The flooring was of hard maple (sugar maple) dried to a uniform 6% MC. The flooring was nailed to 2 × 4-in. wood nailer strips attached by mastic to a concrete slab. Less than 1 in. of space for expansion was left between the wood strip floor and the concrete block wall. Unfortunately, the wood floor was nailed before the concrete floor had completely dried. Under these conditions, the moisture content of the maple increased to about 9%.

Within a short time after the floor was installed, it began to buckle; i.e., ridges began to develop where the strip flooring raised and pulled off the nailers. What was the source of the problem and how could it have been avoided?

The buckling was the result of transverse swelling in the floor restrained at the edges so it could not remain flat. The only way for the flooring to accommodate swelling was to move upward, i.e., to buckle.

The contractor could have anticipated this problem by estimating the amount of swelling that might be involved. Assuming that the wood would swell the average of the radial and tangential values (see sugar maple, Table 8.5), it would swell (4.8% + 9.9%)/2, or 7.4%, in going from an ovendry condition to the FSP. In this situation, the moisture content changed only 3%, so the anticipated swelling would be 3/30%, or 0.1 of the total possible swelling. This then would amount to 0.1 × 7.4, or 0.74%. The total swelling that could be anticipated across the 50-ft-wide (600-in.) gym is 600 × 0.74%, or 4.4 in. Since this potential swelling is considerably greater than the expansion space available, a problem of this type should have been anticipated. The problem could have been avoided by being sure the concrete floor was adequately dry before laying the wood floor, thus avoiding the 3% moisture pickup.

EXAMPLE 2: Rough-sawn western hemlock lumber paneling ¾ in. thick by 7¼ in. wide, with square edges, was used as paneling in an office building. When installed, the pieces were nailed as close together as possible. Cracks between the individual pieces were not over 1/16 in. and were not considered objectionable in view of the rough-natural appearance of the wall. The lumber was stored in the basement of the building for 2½ months during the summer prior to installation. During that time it equilibrated to the 70°F and 70% relative humidity (RH) conditions. After the paneling was installed, the conditions in the heated building during the winter averaged 70°F and 20% RH. If the paneling was flat sawn (the width of the face in the tangential plane), what width of crack could be expected between each piece after shrinking had occurred down to the lower EMC condition?

EMC @ 70°F and 70% RH = 13.1% MC (see Table 8.2)
EMC @ 70°F and 20% RH = 4.5% MC
% MC change = 13.1 − 4.5 = 8.6%
Shrinkage green to OD = 7.8% (see Table 8.5)
% Shrinkage expected = 8.6/30 × 7.8 = 2.2%
Shrinkage per piece (average width of cracks) = 2.2% × 7.25 in. = 0.16 in.

In the actual situation, the cracks averaged about 0.12 in. The difference between the 0.12-in. shrinkage actually encountered and the 0.16-in. estimate was probably because some of the pieces were not flat sawn. Therefore, some radial as well as tangential shrinkage was experienced. These cracks were considered unacceptable, and a large claim was filed against the building materials supplier. The fault lay with the contractor, who stored the material in the humid environment prior to installation.

EXAMPLE 3: A large Douglas-fir timber (8 × 12 in. actual size) was used as a mantle over a fireplace. The timber extended across the entire end wall of the room and the ends of the timber were plastered into the adjacent walls. Solid sawn timbers cannot be purchased dry. In this case, the timber was green (actually about 45% MC) when installed. The radial face of the timber was in the 12-in. dimension, and the 8-in. dimension was the tangential surface of the wood. During a normal year, the conditions in the house averaged 70°F and 30 RH. How much could it be expected that this timber would shrink in use; i.e., how big a gap in the plaster would develop at each end of the mantle?

EMC @ 70°F and 30% RH = 6.2% MC
% MC change through when shrinkage would occur = 30 − 6.2 = 23.8%
% Radial shrinkage green to OD = 4.8%
% Tangential shrinkage green to OD = 7.6%
% Radial shrinkage green to 6.2% MC = 23.8/30 × 4.8 = 3.8%
% Tangential shrinkage green to 6.2% = 23.8/30 × 7.6 = 6.0%
Radial shrinkage = 3.8% × 12 in. = 0.46 in.
Tangential shrinkage = 6.0% × 8 in. = 0.48 in.

Thus a gap about ½ in. wide could be expected to develop at each end of the mantle where it was plastered into the wall. In the actual situation these cracks measured about ⅜ wide. The moisture gradient and drying stresses in this large timber restricted the total shrinkage.

EXAMPLE 4: A wooden dowel manufacturer normally dries the northern red oak dowel blanks to 8% MC prior to turning them to the desired diameter. One purchaser of dowels was very concerned that they be round. Thus specifications called for dowels that were round within 0.02

in. when at 8% MC. This purchaser was less concerned with the actual diameter of the dowels. During the manufacture of a shipment of ¾-in. diameter dowels for this customer, the manufacturer had a problem with the dry kiln, and the blanks were dried only to 11% MC. If the dowels were turned at this moisture content, could the manufacturer be confident that the dowels would meet the out-of-round specification of 0.02 in. when they dried further to 8% MC?

% Radial shrinkage = 4% (green to OD) (see Table 8.5)
% Tangential shrinkage = 8.6% (green to OD)
% MC change = 11 − 8 = 3%
% Actual radial shrinkage expected = 3/30 × 4 = 0.4%
% Actual tangential shrinkage expected = 3/30 × 8.6 = 0.86%
Radial shrinkage = 0.4% × 0.75 in. = 0.003 in.
Tangential shrinkage = 0.86% × 75 in. = 0.0065 in.

Therefore, the dowels will be out-of-round by only about 0.003 in. (0.0065 − 0.0030) after they have redried. Thus there appears to be no problem in meeting this specification if the dowels are round immediately after machining.

These examples illustrate some practical uses for knowledge of the EMC and shrinking behavior of wood. Although these procedures will give only an estimate of what will actually occur, this is often sufficient to avoid costly and wasteful problems in manufacture and use.

Dimensional changes in veneer, fiber, and particle panel products

The shrinking and swelling characteristics of wood shown in Table 8.5 and used in the examples are determined from measurements on small samples 2.5 cm square and 10 cm long. Such samples are cut so that the radial or tangential dimension to be measured is in the 10 cm dimension of the specimen. Because of the small size of the specimen and the fact that it is only 2.5 cm long in the longitudinal direction, drying occurs rapidly and uniformly through the sample. This avoids a large moisture content gradient from surface to center that can cause internal stresses. Therefore the shrinking/swelling values obtained are those exhibited under unrestrained conditions.

The dimensional stability characteristics of most lumber products correspond closely to these unrestrained values for wood. Products such as solid wood furniture, millwork, laminated beams, and construction lumber all behave in a similar way in regard to radial, tangential, and longitudinal shrinking. Forest products produced from veneer, particles, and fiber, in contrast, have unique dimensional behavior under moisture change. These differences from solid wood result basically from three causes: the degree of restraint to swelling provided by one element in the product to other elements in the product; the degree of compression or crushing the wood elements (veneer, particles, or individual fibers) undergo during the manufacture of the product; and the effect adhesives and other additives have on the ability of the elements to respond dimensionally to moisture changes. In some cases these additives bulk the cell walls to some degree, thus lowering the EMC of the wood itself. Each of these factors is discussed below.

Plywood is produced by gluing together veneers, generally ⅙ in. or less in thickness, in such a way that in alternate layers (veneers) the longitudinal direction is at 90° to the adjacent layer. Construction of three-ply plywood is shown in Figure 8.11. If the veneers are not glued together, they can shrink or swell as normal wood. However, when glued into plywood, the face veneers restrain swelling of the core veneer in its transverse direction, while the core restrains the swelling of the faces in their transverse direction. As a result, plywood is a very dimensionally stable product in the plane of the panel. It exhibits much less dimensional change in either direction than normal radial or tangential characteristics of the species. It will shrink or swell slightly more, however, than the normal longitudinal change for the species.

Dimensional changes in plywood do occur, even though small. It is therefore advisable to leave a gap between adjacent 4 × 8-ft sheets when covering a wall or floor. Manufacturers supply specific instructions in this regard.

The second factor affecting the swelling characteristics of wood-based panel products is the amount of compression the product undergoes during manufacture. The thickness swelling or shrinking of plywood with moisture change is about the same as normal solid wood, since little compression occurs. However, in some cases, thickness swelling in plywood may be slightly more than normal wood if excessively high pressures occurred during the pressing process. Wood that is compressed will tend to partially recover its original dimension when rewet.

A dent in wood furniture can often be removed by steaming. The crushed wood tends to recover its original shape. Much the same thing can happen to an entire panel of particleboard. In the manufacture of particleboard, small shavings, flakes, or wafers of wood are sprayed with droplets of a synthetic resin adhesive. These particles are compressed from one and two-tenths to two times their original density, and simultaneously the resin is cured. If such a product is subjected to steaming or other moisture content increases, the wood will swell in the normal way, and in addition the crushed particles will tend to return to their original thickness. For this reason compressed wood-based panel products often exhibit greater thickness swelling than normal wood.

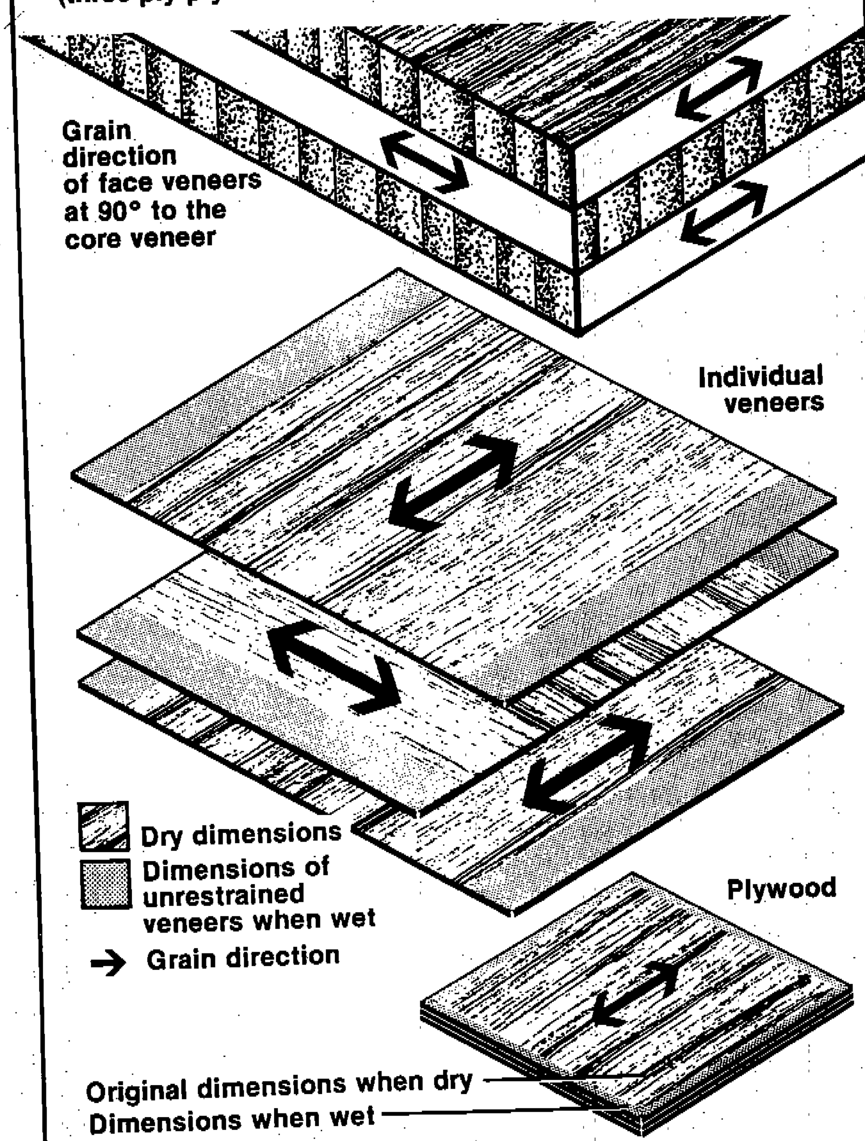
The third factor of concern is the amount of additives in the product. Synthetic resin adhesives and waxes are the most common additives. The wax (or size) is intended to provide resistance to liquid water pickup. Wax does not bulk the cell wall or change the ultimate EMC but rather helps the product shed liquid water, making it water repellent. Synthetic adhesives can, however, alter the recovery of the crushed particles or fibers. Generally, the greater the amount of adhesives used to manufacture a panel product, the less the thickness swelling response to moisture pickup.

Not only are the wood elements in a product held more tightly when more resin is used, but some resin may penetrate into the cell walls and

Fig. 8.11

Comparison of linear swelling characteristics

(three-ply plywood vs. unrestrained veneers)



provide a degree of bulking. Figure 8.12 shows this effect in a wafer-type particleboard. The A board was made with 3% phenolic resin, and boards Band C were made with 10% phenolic resin. In the case of board B, 7% of the total 10% resin was applied to green particles so that the resin could more easily enter the cell wall structure. In board C, all the resin was applied to dry particles. Note the difference in thickness between board types when wet and also how much of the swelling was irreversible, i.e., remaining after the panels were redried.

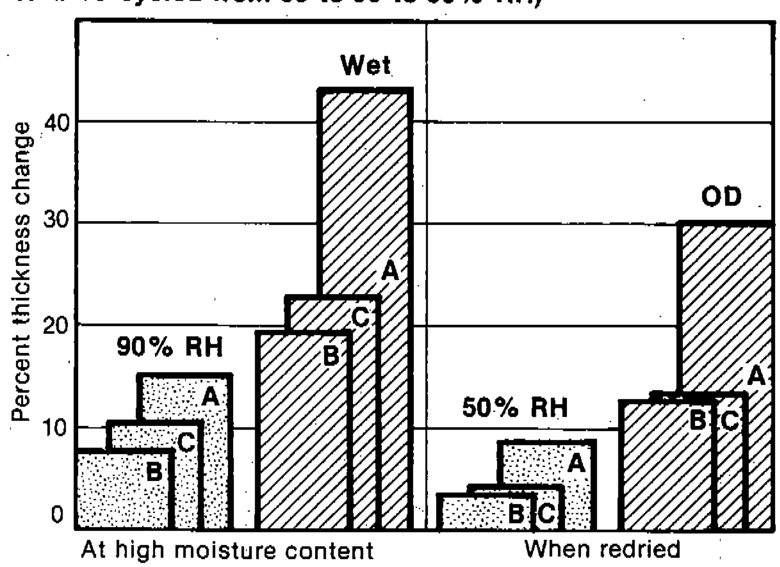
Figure 8.13 shows the dimensional change in the plane of the panel in this same experiment. Note that after moisture cycling, the panel was actually smaller in the plane of the panel than originally. This type of behavior is often found in particle- and fiberboard products. Generally, this effect is so small that it is not noticeable.

Most fiber and particle products are manufactured under commercial or industry standards, which place limits on the swelling properties. Specific property limitations in the standards vary depending upon use of the product. For example, in the commercial standards for particleboard, limits are set on linear swell (in the plane of the panel), ranging from 0.25 to 0.55%. There is no specification as to thickness swell. In the product standard for hardboard (a high-density wood fiber product), there are limits for thickness swell ranging from 8 to 30% but no specification as to

Fig. 8.12

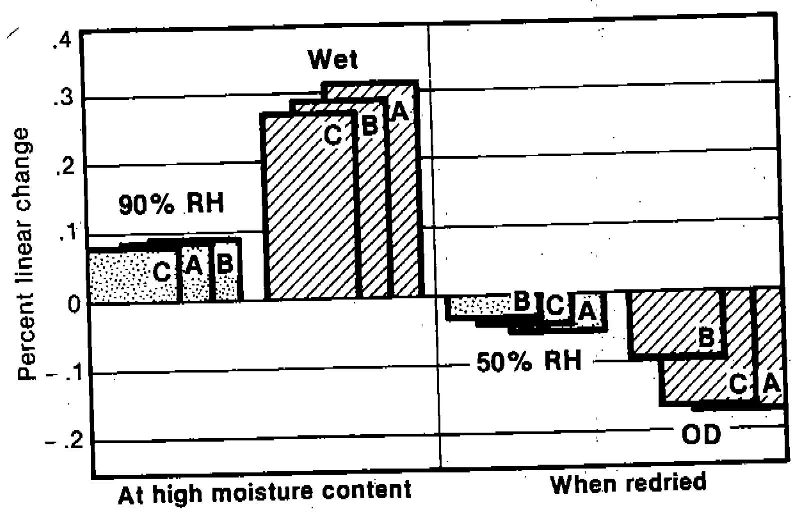
Thickness swelling of a particleboard

(experimental waferboards exposed to wetting-redrying and to EMC cycled from 50 to 90 to 50% RH)



From Haygreen and Gertjeansen (1972)

Fig. 8.13
Shrinking and swelling in the plane of the panel
(same boards as in Fig. 8.12)



linear swelling. Users of wood-based products should obtain data on dimensional characteristics from the manufacturer. Dimensional changes can almost always be accommodated by proper design, whether the product is to be used for furniture, residential construction, or a commercial building. If dimensional changes are not anticipated, however, problems can arise.

Since plywood is a relatively stable product and its dimensional characteristics cannot be easily altered by manufacturing variables, there are no specifications in the plywood product standard as to dimensional stability. However, O'Halloran (1975) provided some helpful guidelines. He pointed out that about 0.2 of shrinking or swelling may occur for each 10% change in the relative humidity. Hygroscopic expansion of plywood consists of a uniform percentage of swelling or shrinking across the width or length of the panel plus an edge effect, which is independent of panel size. For a typical panel the edge effect is about 0.002 in. for each 10% increase in relative humidity.

Means of reducing moisture-induced dimensional change in wood products

There are several means of reducing dimensional change of wood resulting from changes in moisture content. None of these can entirely eliminate dimensional change, but some come very close. Five approaches to reducing dimensional change are:

1. Preventing moisture sorption by coating the product. This is a common but not completely effective method. Coatings include pigmented paints, clear finishes, synthetic resin of other types, and metallic paints. None of these will completely prevent the movement of water vapor but will slow the rate of diffusion. Some are effective in preventing the pickup of liquid water. Proper coatings may be sufficiently effective to prevent dimensional problems in exterior siding and panel materials. Wood, regardless of the coating, can eventually attain the same EMC as uncoated wood.

2. Preventing dimensional change by restraint that makes movement difficult or impossible. The problem with this approach is that internal pressures are built up if wood attempts to swell but is prevented from doing so. These pressures may result in distortion of shape. The buckling of plywood on a roof or wall, which can occur if panels are not properly spaced, is an example of a response to swelling pressure. The restraint method can be used successfully, however, in some situations. For example, particleboard underlayment will exhibit little linear dimensional change if glued to the plywood subfloor beneath it. In this case, the swelling stresses in the particleboard are much less than the strength of the plywood.

3. Treating wood with material that replaces all or part of the bound water in the cell wall is a commercial means of stabilization. Such treatments are applied to wood when it is still green. The treating material remains within the cell wall as the wood is dried. This bulks the cell wall, retaining it in a partially swollen condition. The reduction in shrinkage from such treatments varies from about 30 to 90%. These treatments add up to 35% to the weight of the product, are generally expensive, and may adversely affect finishes applied to the final product. Thus they are used only for special products.

Several effective methods of treatment based upon this principle of bulking, i.e., replacing water molecules in the cell wall with other materials, have been developed. One of the first successful applications of this approach utilized phenol formaldehyde resin, which impregnated the cell wall. The resulting product was termed Impreg. Another product, polyethylene glycol (PEG), is used to stabilize a wide variety of wood products—from wood carvings to gunstocks. PEG is a waxy substance that, when dissolved in water, can impregnate the wood. A simple soak is ordinarily used to treat with PEG.

4. Treating wood to produce mutual cross-linking of the hydroxyl groups in the cell wall has been used experimentally with success. Cross-linking reduces the hygroscopicity of wood by reducing the bonding sites for water in the cell wall. This method has promise for the future. Although

not being used commercially today, means of accomplishing cross-linking are being studied.

5. Impregnation with plastic monomers such as methyl methacrylate and styrene acrylonitrile can improve the stability of wood and increase hardness and wear resistance. These monomers can be polymerized in the wood by radiation or by heating with appropriate catalysts. This technique has been used to produce products such as decorative flooring, novelties, and knife handles. The monomers are generally not as efficient as PEG in eliminating dimensional change, since they have only limited access to the cell wall. The appearance of the wood is not significantly changed.

Moisture movement during the drying process

The movement of water in wood during drying takes place as mass movement of liquid water or diffusion of individual water molecules. Diffusion involves both bound water in the cell walls and vapor in the lumen.

Diffusion is a phenomenon that occurs as water moves from an area of higher concentration to one of lower concentration. Thus, to have diffusion occur, there must be a moisture gradient or a vapor pressure gradient across the cell walls. The rate of diffusion is related to the temperature, the steepness of the moisture gradient across the cells, and the characteristics of the species that determine the ease with which diffusion can occur. The rate of diffusion in a species can be expressed as the diffusion coefficient. Diffusion through individual cells occurs only below the FSP, since above that level the cell walls are saturated and thus no moisture concentration gradient exists as a driving force. Above the FSP, free water moves out of wood as a result of surface drying and capillary forces. At that stage of drying, wood can be thought of as a series of partially filled tubes, with water evaporating from one side.

The rate at which lumber dries is determined by the rate at which water is removed from the surfaces and the rate of mass movement to the surface, or diffusion. In the initial stages the rate of drying is often controlled by surface evaporation and in later stages by the diffusion characteristics of the species.

In some species the structure of the wood inhibits the mass movement of liquid water. Such woods are referred to as impermeable. Tyloses, aspirated pits, and deposition of extractives on pit membranes are examples of wood characteristics that inhibit movement of water. In woods with these structures, the movement of water must be principally by diffusion; thus drying is an extremely slow process. Redwood, white oak, and walnut are a few of the species having relatively impermeable heartwood. Sapwood is generally permeable in all species. Other species such as western hemlock and aspen contain pockets or localized zones that are impermeable. After drying, these latter woods may still contain wet spots. These impermeable wet areas are subject to drying defects if care is not exercised in the drying process.

Using an analogy between electrical conduction and diffusion, Stamm (1964) developed the theoretical transverse drying diffusion coefficients shown in Figure 8.14. Note the over tenfold increase in the rate of diffusion by increasing the temperature from 50 to 120°C.

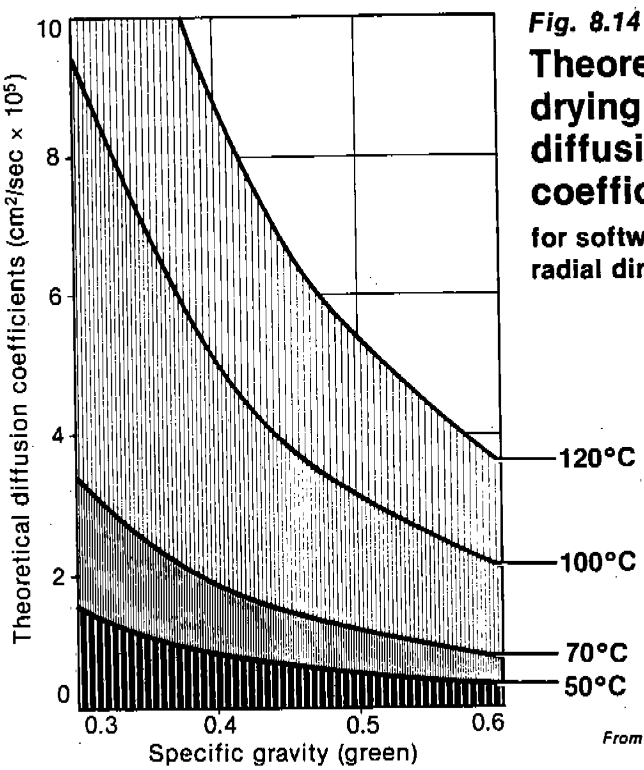


Fig. 8.14 **Theoretical drying diffusion coefficients** for softwoods in radial direction

From Stamm (1964)

A variety of treatments to increase the movement of water through wood, i.e., increase permeability or diffusion, have been developed, but none has found wide commercial application. Erickson et al. (1966) found that freezing redwood lumber prior to drying improved drying performance. Application of hygroscopic chemicals such as urea, sodium chloride, and calcium chloride alters the moisture gradient and permits an increased rate of drying for some species. However, when so treated, the wood retains a hygroscopic surface layer that can cause problems in use. Presteaming of wood has been found to be beneficial in some cases. Unfortunately, a universally effective means of improving liquid water movement and/or diffusion is yet to be found.

drying process

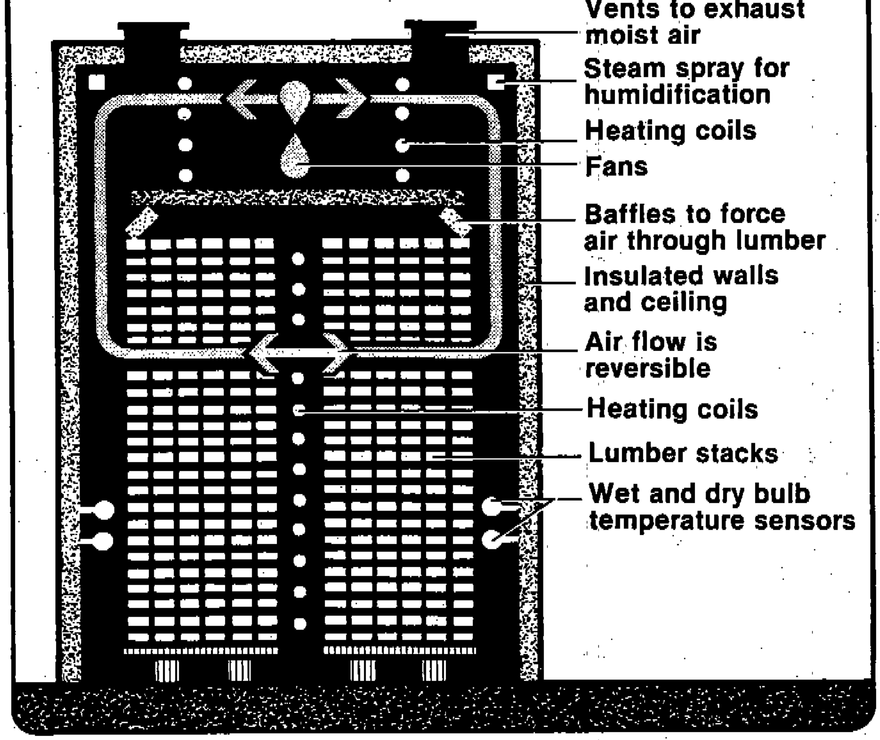
Methods of drying lumber and other solid wood products

Most lumber, whether hardwood or softwood, is dried in some type of dry kiln. Modern kilns have controlled temperature and relative humidity; they are also equipped with fans to force air circulation and ventilation. Conventional kilns operate at temperatures from ambient up to about 100°C. High-temperature kilns designed to provide more rapid drying operate above the boiling point of water. The lumber in a kiln is dried in air that has been heated by steam coils or directly by the addition of combustion gases from a gas-, oil-, or wood residue-fired burner. Figure 8.15 illustrates the main elements in a typical cross-ventilated kiln.

Drying in a conventional kiln progresses through a series of temperature and relative humidity steps designed to dry the wood gently while it is at a high moisture content. After the free water has been removed, more severe drying conditions are imposed to maintain an adequate rate of dry-

Fig. 8.15

The main components of a modern steam-heated dry kiln
(cross-sectional view)



ing. The series of temperature and humidity conditions imposed on the lumber during drying is referred to as a kiln schedule. Most hardwood schedules are controlled according to the moisture content of the lumber; i.e., changes in the drying conditions are made when the moisture content drops to predetermined levels. Softwoods are more frequently dried by a time schedule; i.e., drying conditions are changed at predetermined times. Two contrasting moisture content schedules for drying 1-in. hardwood lumber are shown in Table 8.6. Note the differences in temperatures and relative humidities at each moisture content level for the difficult-to-dry white oak and the easily dried basswood. These schedules are from recommendations in the Dry Kiln Operator's Manual (USDA 1961), which is widely used as the guide to kiln drying. A more recent publication, Drying Eastern Hardwood Lumber (McMillen and Wengert 1978), is also available. After gaining experience with certain species, many firms develop their own drying schedules. However, since an entire kiln load of lumber can be destroyed by drying it too aggressively, caution is usually employed.

Table 8.6. Kiln drying schedules for drying 1-in. basswood and white oak lumber

Basswood			White oak		
	Kiln conditions			Kiln conditions	
Moisture content	Temperature	Relative humidity	Moisture content	Temperature	Relative humidity
(%)	(°F) (°C)	(%)	(%)	(°F) (°C)	(%)
Above 60	160 (71)	58			
60	160 (71)	43	Above 40	110 (43)	87
50	160 (71)	31	40	110 (43)	84
40	160 (71)	21	35	110 (43)	75
35	160 (71)	21	30	120 (49)	62
30	170 (77)	24	25	130 (54)	35
25	170 (77)	24	20	140 (60)	25
20	180 (82)	26	15	180 (82)	26
15	180 (82)	26			

Source: USDA For. Serv. (1961).

Some lumber is still air dried, but more commonly, air drying is used as a preliminary step to kiln drying. This can greatly lower drying costs, particularly for difficult-to-dry species. The energy cost of drying lumber is high; thus economies such as air drying may be advantageous. For refractory species of hardwoods, i.e., those that are difficult to dry without degrade, drying may require over 6.5 million Btus of energy per thousand bd ft of lumber. This amounts to about 70% of all the energy used in the manufacture of lumber.

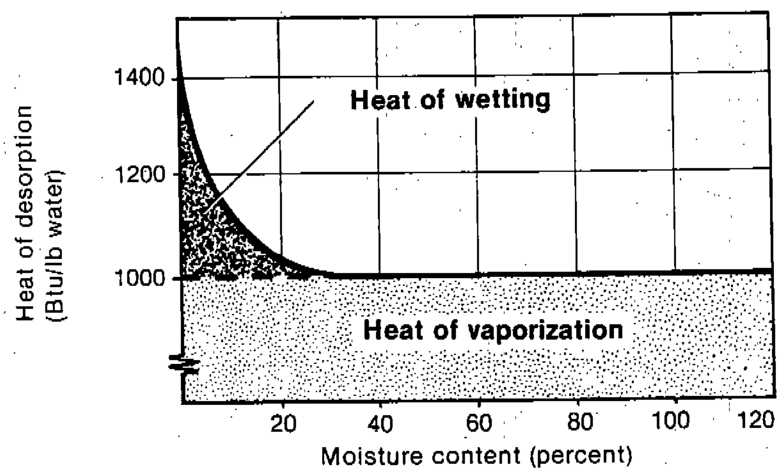
Lumber may be air dried without subsequent kiln drying at small mills not possessing kilns and in regions of the United States where the ambient humidity is normally very low, such as the Southwest and the Rocky Mountain states. Air drying may be satisfactory if adequate time is taken and if the drying specifications to be met are not too rigorous. From the user's standpoint, a disadvantage of air drying is that it may not be possible to reach the lower moisture content required for some applications. From the manufacturer's standpoint, air drying has the disadvantage of requiring a large and costly inventory in the drying yard. Also, degrade is more difficult to control than in a kiln. Air-drying times vary from a month under ideal conditions for easy-to-dry woods to a year or more for refractory woods dried under more difficult conditions.

The amount of energy required to evaporate water from wood is shown in Figure 8.16. Although the heat of vaporization varies slightly with the temperature, in the range of normal drying temperatures it is about 1000 Btu/lb water evaporated. To accomplish drying below the FSP, the heat of wetting must be supplied as well as the heat of vaporization. The total actual energy required to dry wood is much greater than the sum of the heats of wetting and vaporization. Heat loss in the kiln resulting from venting of water vapor, air leakage, radiation and conduction losses through the kiln wall, and the use of steam to provide humidity control are also involved. The total amount of energy consumed in conventional kilns generally varies between 1600 and 3000 Btu/lb water evaporated.

A new drying system, dehumidification drying, is gaining wide use in North America. It was first used commercially in Europe; to date it has been used principally for the drying of hardwoods. The primary difference between this and a conventional kiln is that water is removed as condensate on refrigerated coils rather than by venting the moist air to the atmosphere. Since energy loss from venting is eliminated and heat from the compressor

Fig. 8.16

Energy required to evaporate water from wood



From Comstock (1975)

of the refrigeration unit is used to heat the kiln, the dehumidification drying method appears to offer some economies in energy use. Early installations of this type of kiln had the disadvantage of being slower than conventional kiln drying, but improvements are reducing this limitation. Since the energy used is in the form of electricity, this drying system does not adapt itself easily to the utilization of heat generated from mill residues.

A number of other methods have been used experimentally, and in a few instances commercially, for drying solid wood products. These may have advantages for special situations but are generally more expensive and less predictable than kiln drying. Wood scientists and industry engineers are actively engaged in work to improve drying practices. Some nonconventional drying methods have been studied. They include:

1. Immersing wood in a heated organic liquid. Liquids such as fuel oil or perchloroethylene are heated, raising the temperature of the wood above the boiling point of water, thus driving off the moisture.

2. Vapor drying. This method uses an organic liquid with a boiling point above 100°C. The drying chamber contains the wood and the organic vapor. The condensation of these vapors on the wood heats the wood rapidly, driving out the water, which is then separated from the solvent vapor in a condenser and separator.

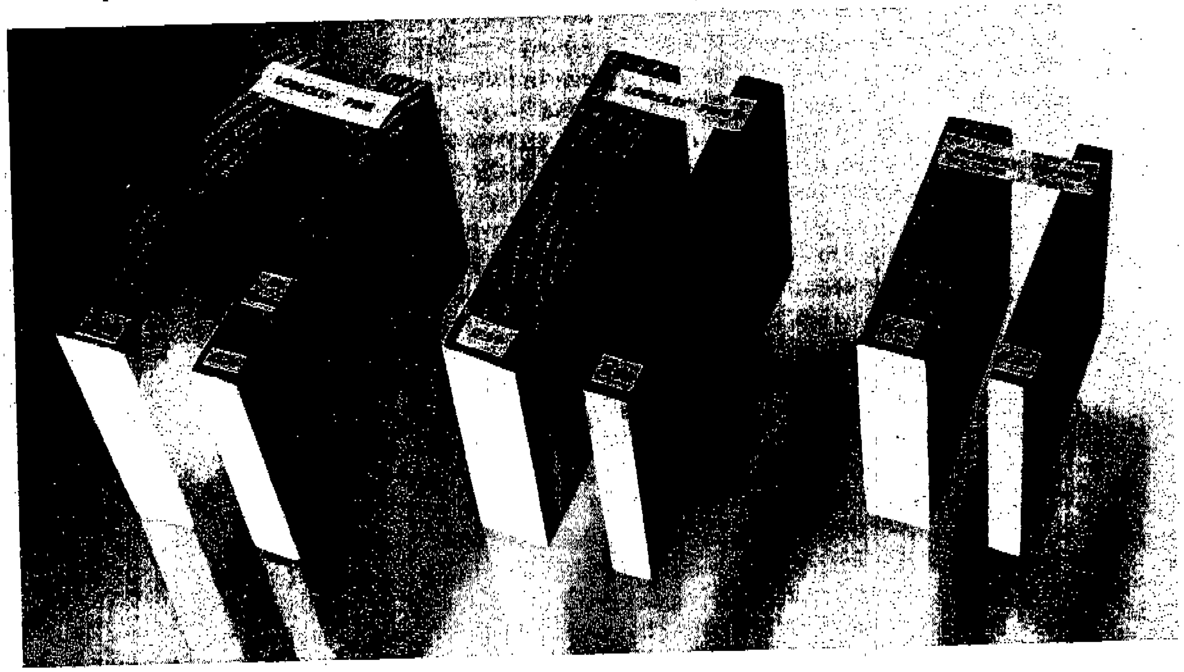
3. Radiofrequency dielectric heating. This approach to drying involves placing wood between two electrodes and subjecting the material to an electric field oscillating at high frequency. Being polar, water molecules in wood rotate in the alternating field, thus generating heat. In woods that dry easily, the internal temperature tends to rise only slightly above the boiling point until the free water is gone. However, in impermeable woods, the temperature may rise to destructive levels. A variation of this process is the combination of microwave energy with hot air impingement drying.

4. Combination of radio frequency heating and vacuum drying. Lumber is heated dielectrically at 7–9 MHz while it is in a chamber in which a partial vacuum can be created. Thus water will boil at a lower pressure, speeding the drying process. Such kilns, capable of drying 10,000 bd ft of lumber, have been built and good results reported (Wengert and Lamb 1982).

5. Press drying. Wood is press dried by placing it between two heated platens. Heat transfer is by conduction from metal to wood and thus is very rapid. This technique works well on easy-to-dry species. It is used commercially for high-quality veneer, but only one commercial application for lumber has been reported. This drying method can be combined with high pressures to produce a densified product. Figure 8.17 shows experimental results of simultaneously drying and densifying two species of pine. In one sample shown, phenolic resin was added to increase dimensional stability.

Fig. 8.17

Normal and densified loblolly and Norway pine. Specific gravity of the samples is indicated.



Drying of veneer, particles, and fibers

The major difference in principle between drying veneer and lumber is that veneer, being very thin, develops a limited moisture gradient. Therefore, the drying stresses and impermeable zones that cause problems in the drying of lumber are not the limiting factor in veneer drying. Other considerations, such as the glueability of the surface, may dictate how fast veneer can be satisfactorily dried.

Veneer driers consist of a means of conveying the veneer through a heated chamber where temperatures range from 150 to 260°C. In older roller driers, air is circulated in a manner similar to that in a dry kiln. This type of drier is still in wide use for hardwood veneer. Most plants built in recent years utilize jet driers. These are also called impingement driers since a curtain of air at velocities of 2000–4000 fpm is directed against the surface of veneer. The high velocity produces turbulent air on the surface of the veneer. This eliminates the laminar boundary layer that slows down heat and moisture transfer under ordinary drying conditions.

Most wood particle- and fiberboard plants utilize a high-speed drying system of some sort because of the large tonnage of material to be dried; one plant in the United States dries 2 million lb wood/day. In common use are driers of two types: drum driers and tube driers. Rotating drum driers are the most common type used in particleboard plants. The wood particles make one, two, or three passes from one end of the drier to the other and then are discharged. Inlet temperature of such driers can be as high as 870°C when wet furnish is being dried but is reduced to about 260°C or lower if dry planer shavings are involved.

Drying wood particles at temperatures above the burning point of about 230°C is possible as long as moisture is present in the wood. Drier control systems must be designed to insure that dried wood is not present in the preliminary high-temperature stages of the drier. The particle movement through these driers is controlled by air velocity. The finer particles, which dry faster, are blown more rapidly through the drum and therefore are exhausted before reaching the combustion point.

The drying of fibers for dry-process fiberboard production can be accomplished in tube driers. The fibers are introduced into a stream of gas heated from 200 to 320°C. These driers may have a second stage operating at a lower temperature. Moisture is often flashed off in a few seconds; thus effective feed and temperature control systems are critical to avoid fires.

The moisture content to which fiber- or particleboard particles are dried for the manufacture of panel products depends upon the specific product, the amount of water added with the resin and wax size, and the pressing cycle. Generally, the wood furnish is dried to between 4 and 8% MC. Precise control is necessary, since a moisture content 2% higher than desired can cause blows or internal explosions in the panels when the press is opened. A moisture content 2% below the desired level can cause poor bonds and therefore will reduce mechanical properties.

REVIEW

A. Terms to define or explain:
1. Moisture content
2. Fiber saturation point
3. Equilibrium moisture content
4. Resistance-type moisture meter
5. Sorption
6. Adsorption vs. absorption
7. Polymolecular adsorption of water on cellulose
8. Free water
9. Bound water
10. Hysteresis
11. Transverse swelling
12. Longitudinal shrinkage
13. Dry kiln
14. Bulking agent
15. Cross-linking for stabilization
16. Dehumidification drying
17. Press drying
18. Refractory species

B. Questions or concepts to explain:
1. Be able to calculate the moisture content from green and dry weights.
2. Be able to estimate the weight of products at any moisture content, knowing the present weight and moisture content.
3. Be able to estimate the shrinking or swelling in any principal direction when wood changes from one moisture content to another.
4. Be able to estimate the dimensional change that would occur if the environmental conditions change.
5. Be able to estimate the equilibrium moisture content for wood at any temperature and relative humidity.

HAYGREEN & BOWYER (1989)

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HAYGREEN & BOWYER (1989)

Table 9.4. Common non-SI to SI conversions

Non-SI unit	SI unit equivalent
Length	
foot	3.048×10^{-1} m (meters)
inch	2.540×10^{-2} m
mile (U.S. statute)	1.609×10^{3} m
Area	
acre	4.046×10^{3} m^2
hectare	1.000×10^{4} m^2
ft^2	9.290×10^{-2} m^2
in.^{2}	6.452×10^{-4} m^2
Volume	
ft^3	2.832×10^{-2} m^3
in.^{3}	1.639×10^{-5} m^3
board foot	2.360×10^{-3} m^3
Force	
kilogram-force	9.807 N (newtons)
kilopond	9.807 N
lbf	4.445 N
Mass	
pound (avoirdupois)	4.536×10^{-1} kg (kilograms)
ton (short)	9.072×10^{2} kg
ton (metric)	1.000×10^{3} kg
Moment	
lbf·in.	1.130×10^{-1}N·m (newton
lbf·ft	1.356 N·m meters)
Energy and work	
Btu	1.055×10^{3} J (joules)
ft·lbf	1.356 J
Density (mass per unit volume)	
lb/ft^3	1.602×10 kg/m^3
g/cm^3	1.000×10^{3} kg/m^3
Pressure or stress	
lbf/in.^{2} (psi)	6.895×10^{3} Pa (pascals)
kgf/m^2	9.807 Pa

Other SI symbols

s	second
k	kilo or 10^3
M	mega or 10^6

Cord of wood = 128 ft^3 of space

force is indicated, however, the use of the term weight is discouraged by SI. Nonetheless, it will undoubtedly remain in common practice and is used in this text as a unit of mass.

Many wood science references in the European literature use kilogram-force (kgf) or kilopond (kp) as the units of force. These have been replaced in SI with the newton (N). The newton is used for other derived units involving force. For example, stress is expressed as newtons per square meter (N/m^2) and called a pascal (Pa); the unit of energy, a newton meter (N·m), is termed a joule (J); and the unit of power, called a watt (W), is a N·m/s.

For engineering purposes it is generally more convenient to work with kilopascals (kPa = 1000 Pa) than with Pa. It may be helpful to remember than 1 pound per square inch (psi) equals approximately 7 kPa. In some cases the use of megapascals (MPa) is convenient. Note that in SI the prefix M equals 10^6. In the English system M is often used to indicate 10^3, as in MSF (thousand square feet), another source of possible confusion. Also, the use of terms such as billion and trillion should be avoided. In the United States billion means 10^9, but it means 10^{12} in most other countries.

13

Lumber types and technology

[redacted] The process can be accomplished by hand power if necessary, in the way lumber is still being manufactured in some less developed countries of the world. Yet today's modern sawmill has become a highly technical process using electronic scanners and computers to control important steps in the operation. [redacted] using methods capable of high production rates. This does not mean that modern sawmills are larger than the older existing mills; in fact the opposite is tending to be true. New mills have equipment and design appropriate to the smaller logs available today. Some of the old sawmills in the western United States could cut over 1 million board feet (bd ft) of lumber per day. Today's small-log sawmills produce one-third to one-half that amount but process 5–10 times the number of logs.

[redacted]

Although over half of these mills are in the South, this region produces only about one-third of the U.S. total. The West Coast, where there are fewer but larger mills, produces about one-half of U.S. production. In a typical year, about 80% of the lumber produced is softwood, with 70% of the softwood logs from the West, 25% from the South, and 5% from other areas. Production of hardwood lumber is about evenly divided between the North and the South, with only minimal production in the West.

[redacted] applied to products sawn to a [redacted] railroad crossties or cants produced by slabbing a log on two or four sides. [redacted]

[redacted] These terms apply to thickness categories. When dealing with softwood lumber, the term boards indicates lumber less than 2 in. thick, dimension is material 2–4 in. thick, and timbers are pieces 5 in. or thicker. Unfortunately, [redacted] in regard to size categories and many other characteristics, [redacted] For example, the term dimension when applied to hardwood refers to material that has been cut to size for furniture or pallet manufacture. One of the interesting challenges when entering the lumber industry or an industry that is a user of lumber is to learn the language.

[redacted] Pallet production in the United States now exceeds 300 milion units per year, averaging about 23 bd ft per unit. In the eastern United States, [redacted] Hardwoods find many miscellaneous industrial uses as timbers for mining, retention walls in construction ditches, local agricultural construction, and dunnage for shipping. [redacted]

[redacted] among the most commonly harvested hardwoods, [redacted] being the single most important species. Black walnut, black cherry, and yellow birch are the most highly sought after fine hardwoods in the United States. However, practically every hardwood found in suitable quantity and size is manufactured into lumber. Some lumber marketing firms specialize in developing uses for relatively little known species such as sassafras, holly, and honey locust.

[redacted] About 85% of all housing units built are of this type.

[redacted] are the most important U.S. softwoods cut for lumber. [redacted] provided about three-fourths of the softwood sawtimber harvested in the United States. Another 15% of softwood sawlogs are obtained from western hemlock, ponderosa pine, and the true firs. Of the softwood construction lumber consumed in the United States, about one-third of it is produced in Canada.

The basis for grading and scaling (measuring the volume) hardwood lumber is very different from softwoods. This results in some variations in the way these two groups of woods are handled in the manufacturing process. [redacted] Grading is based upon the percent of the board that is usable in smaller clear pieces free of defects on one or both sides. These pieces are termed cuttings. For instance, the highest grade, firsts and seconds (FAS), is a board that contains 83% usable cuttings that exceed a certain minimum size. The regular hardwood lumber grades are thus not readily adaptable to applications where the entire board will be used as a single piece.

[redacted] in contrast, [redacted] Therefore, softwood lumber is graded as an [redacted] for a combination of strength and appearance or for appearance only. As explained in Chapter 10, knots and slope of the grain are the main characteristics that determine strength. Softwood grading rules contain specifications intended to assure a minimum level of strength while maintaining a reasonably good appearance.

[redacted] In the sawmill, hardwood boards are cut (edged) to the maximum width possible when removing the bark. [redacted] nominally, 4, 6, 8 in., etc.) [redacted] 2-ft multiples) [redacted] (S4S).

cut

Lumber designation vs. tree species

To simplify the marketing and distribution of [redacted] it [redacted] Appendix Table A.9 lists the standard commercial names for hardwood lumber produced from North American tree species. In most cases [redacted] For example, all oaks are sold commercially as either red oak or white oak. A forester may pay a preferential price when purchasing logs from certain species because of his knowledge of the grade yield that can be expected. For example, he might be willing to pay more per unit volume for northern red oak logs than northern pin oak or for southern red oak than for turkey oak. However, once cut, the lumber becomes simply red oak and its value is determined by the lumber grade.

[redacted] Some hickories are termed pecan when cut to lumber. Sweetgum is termed simply gum or is classed as red gum if it is heartwood. Lumber from yellow poplar is called poplar, which could easily be confused with the true poplars, i.e., aspen and cottonwood.

In softwoods the grouping of species for commercial use is slightly different than for hardwoods. The approved lumber names for the softwood tree species are listed in Appendix Table A.11. These individual lumber species may be combined and sold under a group name. [redacted] Examples of such groupings are Doug Fir-Larch, which is Douglas-fir and western larch; Hem-Fir, which is West Coast hemlock and various true firs; and Northern

Haygreen/Bowyer (1989)

Pine, which is jack pine and Norway pine. Southern yellow pine lumber is produced principally from four tree species: longleaf, slash, shortleaf, and loblolly pine. In some instances slash and longleaf pine are exported under the name pitch pine.

Haygreen/Bowyer (1989)

Measurement and sizes of lumber

In North America and much of the developing world that exports to the United States, [redacted] The number of board feet in a piece of lumber is therefore determined by multiplying the thickness in inches times the width in feet times the length in feet. For example, a 1 × 6-in. piece 10 ft long contains 1 × 6/12 × 10 = 5 bd ft.

Complicating the measurement of lumber when using board feet is the fact that [redacted] A dry, surfaced softwood 2 × 4, for example, measures 1½ × 3½ in. in cross section, while a 2 × 10 measures 1½ × 9¼ in. When pieces of standard size are in the rough green condition, they must be larger in cross section to allow for shrinkage and surfacing. Sizes of hardwood lumber also take this into account. A 1-in.-thick hardwood board has a standard surfaced thickness of 26/32 in. if sold dry but should be a full inch thick if sold dry and rough. If sold green, hardwood lumber should be thick enough to allow for shrinkage to the specified rough size.

softwood

[redacted] Therefore, an 8-ft-long 2 × 4, which actually measures 1½ in. × 3½ in. × 8 ft, contains 2 × 4/12 × 8 = 5⅓ bd ft. Appendix Table A.9 lists nominal and actual sizes for S4S softwood lumber when dry or green.

hardwood

[redacted] For example, a piece of 2-in. lumber that measures 9 in. wide by 10 ft long contains 2 × 9/12 × 10 = 15 bd ft. Hardwood lumber is scaled by hand using a scaling stick, and the footage of each piece is recorded to the nearest board foot. A hardwood inspector simultaneously measures and grades hardwood lumber as it passes on the green chain. If hardwoods are cut to specified widths, as in the case of material to be used to manufacture pallets, the board footage is measured as with softwoods. The thickness of hardwood lumber is often spoken of in quarters of an inch. For example, 1-in. lumber is referred to as four-quarter and 2-in. lumber as eight-quarter.

In Europe and most countries outside the United States, lumber is specified by its actual size. The volume in cubic meters (the unit used for measurement) is based upon the actual volume of the material when dry. Therefore, a dry piece measuring 148 mm × 240 mm × 4 m contains 0.148 × 0.24 × 4 = 0.142 m^3. If the lumber is measured when green, a shrinkage factor must be taken into account. A cubic meter of dry lumber contains 424 bd ft as determined from the actual (not the nominal) lumber size. A conversion factor of 450 bd ft/m^3 is often used in the international trade of green lumber.

In past years, [redacted] The suggested metrication would involve converting to metric equivalents with some rounding to simplify sizes where possible. Under this system the size of a 2 × 6, for example, actually 1½ × 5½ in., would become 38 × 139 mm. The cost of this type of conversion would be small as compared to converting to even modular metric units such as 50 mm × 150 mm. In that case all strength properties, structural designs, sizes of related products, and manufacturing equipment would have to be changed, the cost of which would be staggering.

Basic steps in lumber manufacture

The sequence of processing steps in lumber manufacture is illustrated in Figure 13.1. [redacted] Some will not be remanufactured in any way (resawn or re-edged) but may go directly from the edger to the trimmer. Some sawmills do not dry lumber but sell it green, while still others produce only rough, unsurfaced lumber. Most modern sawmills, however, have equipment to accomplish all the steps shown in the block diagram.

DEBARKING. [redacted] This has several advantages, [redacted] Bark-free wood chips are more valuable and more readily marketable to pulp mills than barky chips (chips with bark). Many pulp mills will not purchase chips containing bark at any price. This situation will change if methods developed to separate bark from chips become economically feasible and are adopted by the pulp industry. Acceptance of barky chips improves when barkfree chips are in short supply.

There are [redacted] important [redacted] and [redacted]

The most widely used type of debarker in medium to large sawmills is the [redacted] (Fig. 13.2). In this machine the log passes through a rotating ring that holds a number of pressure bars. These press against the log and tear off the bark. Large units of this type can debark logs at speeds of up to 200 lineal ft/min. Another type of equipment, a [redacted] looks similar to a ring debarker but centers the log between three rotating cylindrical heads and rotates it as it passes through a revolving ring holding knife-faced pressure arms.

A [redacted] debarker is sometimes used in sawmills where high production rates are not needed. A similar machine is also used for

types

1

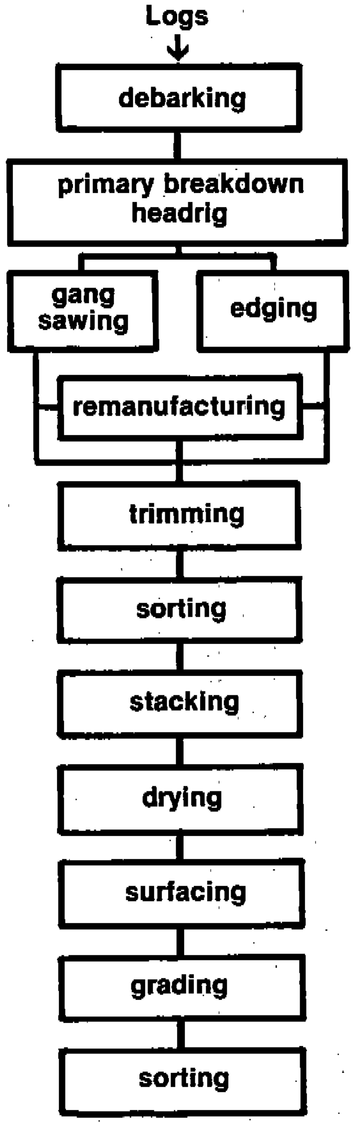
2

Haygreen/Bowyer (1989)

Haygreen/Bowyer (1989)

Fig. 13.1

Processing steps in the production of lumber



(Courtesy Nicholson Manufacture Co.)

Fig. 13.2
A small pine log passing through a ring debarker. The ring is rotating counterclockwise. The ring and the pressure bars appear here as a blur.

peeling posts and poles. The rossing head is a rotating cutterhead, similar to the head on a lumber planer, that rides along the log and cuts off the bark as the log is rotated. This debarker is also suited to situations where crooked or stubby logs must be debarked. Care must be taken with this type of equipment not to remove too much wood with the bark. The high value of lumber and pulp chips makes excessive wood fiber removal an expensive mistake.

[redacted] were well suited to sawmills designed for large, old-growth logs in species with thick, heavy bark. Jets of high-pressure water directed against the log surface blast the bark loose. These debarkers are now used principally in the western United States and Canada for redwood and Douglas-fir. They are also suitable for large tropical hardwoods. However, use is diminishing because of the expensive water treatment needed to meet environmental regulations.

PRIMARY BREAKDOWN. The primary breakdown of the log is accomplished by one of [redacted] One method is [redacted] This is referred to as a carriage rig. One piece is cut from the log with each pass by the saw. The thickness of the lumber is determined by moving the log on the carriage. The mechanism that moves the log forward on the carriage is called the setworks. Until the 1960s almost all lumber was produced on carriage rigs. Since that time, however, [redacted] In new sawmills today, carriage rigs are used principally for larger logs (over about 16 in. in diameter) or in mills that require a great deal of flexibility in regard to log and lumber sizes. Most hardwood mills still use carriage rigs.

[redacted] Figure 13.3 illustrates a typical small carriage rig sawmill utilizing a circular headsaw. In such a mill there are three operators—the head sawyer, the edgerman, and the trimmerman—who are responsible for the decisions that determine the quantity and grade of lumber obtained from each log. Circular headsaws vary in diameter from about 36 to 60 in. and can handle logs up to about 36 in. in diameter. If larger logs are to be cut, a second circular saw located above the main saw can be used.

[redacted] They are much more expensive to maintain than circular saws, and the original capital investment is higher. They are used principally where large logs are to be sawn.

[redacted] varies from about 3/16 to 3/8 in. in circular saws. Bandsaw kerf is somewhat narrower, typically about 3/16 in. As a result, large volumes of sawdust are produced, particularly if boards and dimension are cut on the headsaw. For example, if boards with an actual target green thickness of 1 in. are being cut with a saw kerf of 3/8 in., 1 3/8 in. of the log is removed each time a board is cut. This does not consider the variability in sawing thickness that inevitably

Haygreen/Bowyer (1989)

occurs. About $\frac{3}{8} \div 1\frac{3}{8} \cong 27\%$ of the wood removed in this case becomes sawdust. This does not include the kerf lost in edging the lumber. For this reason, and also to increase the production rate in a mill, [redacted]

[redacted] Williston (1976) points out [redacted] Some of the major advancements in recent years for measuring and positioning logs and controlling the cut will be discussed later.

[redacted] In equipment of this type [redacted] The three most common types of single-pass headrigs in use are chipper canters, scragg mills, and multiple-band headrigs. [redacted] Figure 13.4 shows a twin-band headrig cutting a small log.

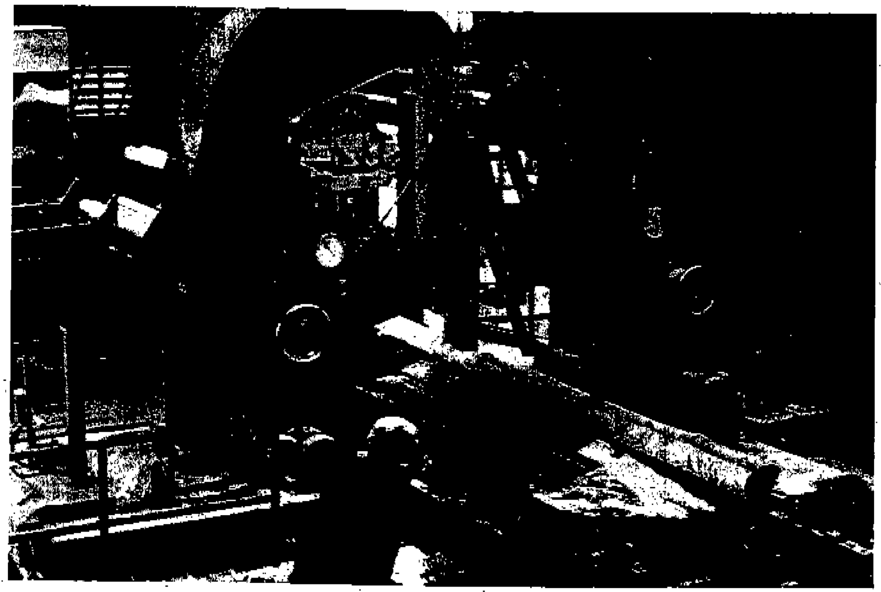


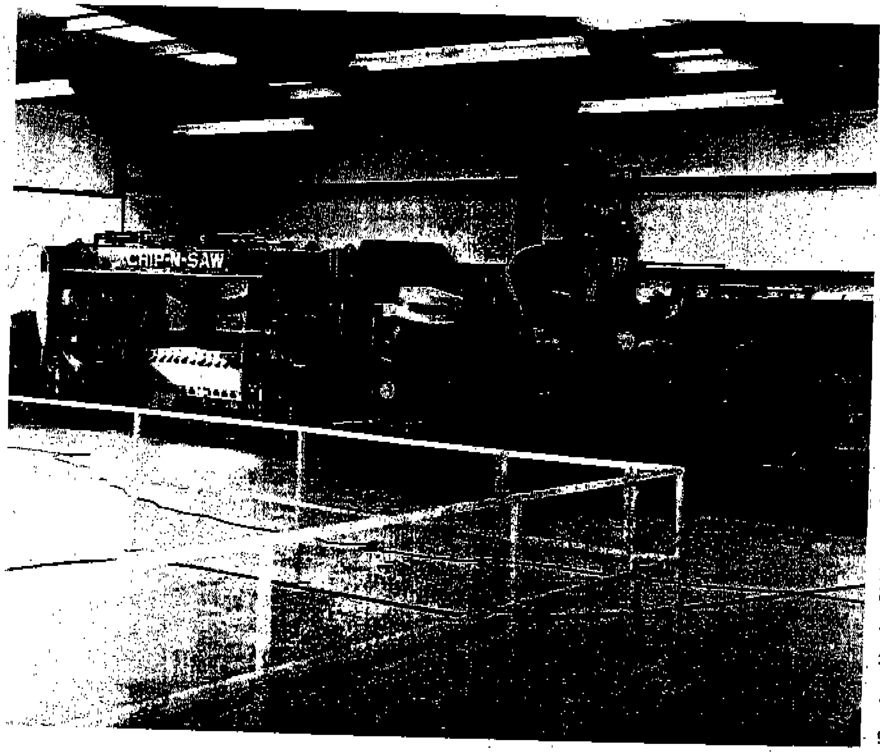
Fig. 13.4

Twin-band headrig cutting a small softwood log. A 4-in. cant and two slabs are produced.

[redacted] The chips are removed with knives mounted on rotating cutterheads, so no sawdust is produced. Typically, these machines operate at from 150 to 200 lineal ft/min. Such a mill can cut over 200 logs/8-hr shift. Theoretical capacity is nearly double this figure.

[redacted] developed in the 1960s, [redacted] Although some models will handle logs up to 24 in. in diameter, most mills using these machines are cutting logs from 6 to 16 in. in diameter. There are several manufacturers of chipper canters of various types. [redacted] Such a machine is shown in Figure 13.5. Some of the possible configurations of lumber that can be produced on chipping headrigs are shown in Figure 13.6. [redacted] such as the rotary gang shown in Figure 13.7.

[redacted] that have the potential of yielding the higher



(Courtesy Hawker Siddeley Canada Inc., Canadian Car Division)

Fig. 13.5
Chipping headrig (Chip-N-Saw) showing the log transport and chipping and sawing sections.

grades of lumber. Chipper canters are also used to convert cores from plywood veneer bolts into 2 × 4s. In this case the veneer bolts are peeled down to a certain size, usually about 5⅝ in., and then the core of the bolt is ejected from the veneer lathe and conveyed to the chipper canter.

[redacted]. The distance between the blades can be adjusted by the operator to produce 4-, 6-, or 8-in. thick cants. Logs make one pass through this rig, producing a two-sided cant plus two slabs (on a two-saw scragg). The cant is then broken down to boards by a gang resaw. If the slabs are thick enough, they can be resawn to produce a 1- or 2-in. board. The logs in most scragg mills are moved through the saws by a conveyor chain. A few scragg mills use an overhead device that clamps the log at both ends and carries it through the saws.

[redacted] As with the other single-pass headrigs, multiple-band headrigs were developed to process small logs. Williston (1976) stated that there is no reason they cannot also be used for larger logs, as long as there is no need to turn the log, as can be done on carriage rigs to recover higher lumber grades. Multiple-band headrigs are adaptable to electronic scanner and computer control applications.

[redacted] The slab chipper has a cutterhead with knives, which chips flat the portion of the log that would ordinarily be removed as a slab. The cutting action of a slab chipper is similar to the cutterheads in some chipper canters. The use of two-slab chippers with a quad band makes it possible to cut the log into four pieces of lumber plus one cant as it passes through the rig.

SECONDARY BREAKDOWN. [redacted] however, [redacted]. [redacted] make a series of cuts and so can reduce a cant to boards in one pass. [redacted] can split a plank into two boards or cut a board from the wider side of a slab. [redacted] can also be used to salvage lumber from slabs. In this case the excess wood is chipped away rather than sawn.

[redacted] requiring operators with a good knowledge of lumber grades. Electronic scanners and control systems are now available that will allow automatic edging and trimming of boards for maximum yield. [redacted] Excessive edging and trimming is costly, of course, as it reduces lumber output.

Figure 13.8 illustrates the importance of properly edging and trimming

(Courtesy Corley Manufacturing Co.)

Stull — 1. the top piece of a set of mine timbers.
2. A timber prop supporting the roof of a mine opening.

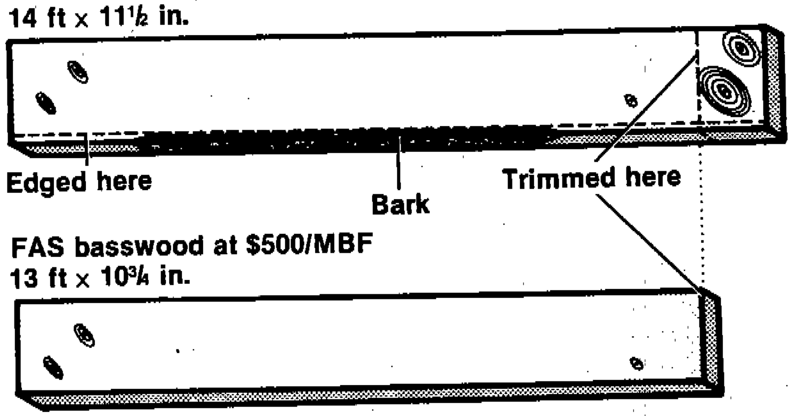
Hangreen/Boyer (1989)

Fig. 13.8

Value is increased by properly edging and trimming

No. 1 Common basswood containing 13 bd ft changed to FAS grade of 12 bd ft

No. 1 Common basswood at $340/MBF
14 ft x 11½ in.



hardwood lumber. This piece of basswood originally contained 13 bd ft of No. 1 Common grade valued at $340/thousand bd ft (MBF) or $0.34/bd ft. If edged and trimmed as shown, the volume of the piece would decrease to 12 bd ft, but the grade would increase to FAS at $500/MBF. The value of the piece in this example is increased from $4.42 to $6, an increase of 36%. There are many opportunities to realize this kind of increase in lumber value by proper manufacture.

DRYING, SORTING, AND FINISHING. The drying process was discussed in Chapter 8. [redacted] To dry lumber uniformly and in a minimum time, it is desirable to dry only one thickness, width, and species per kiln load, although sometimes this is not possible. Semiautomatic equipment is generally used to stack the lumber for drying. [redacted] At the green chain (located following the trim saws in the mill) the lumber is sorted by species, size, and grade. [redacted] A wide variety of lumber-sorting equipment is available for use at the green or dry end of the mill. The simplest system is to have the lumber manually pulled and sorted as it proceeds down a so-called green or dry chain. The manual handling of lumber is eliminated in modern mills by mechanical sorters that can be controlled by a single grader-operator. Sorters are available to automatically sort lumber by length, width, or thickness.

[redacted] In hardwood mills shipping only rough green lumber, obviously no planer mill is required. [redacted]. A surfacer is a machine that planes the lumber on two faces only (S2S). High-speed matchers used for softwood dimension have four or more heads to surface the lumber on four sides (S4S). Some of these machines can operate at lineal speeds in excess of 1000 ft/min. Matchers may have profile heads for running patterns or splitting wide stock into narrower widths. A moulder is similar to a matcher but is designed to run smaller stock to pattern. It usually has both top and bottom profile heads.

Log scaling and measurement practices

The units of measure used in the sale of logs and sawbolts vary widely depending upon the size of the logs, whether the logs are sold tree length or as individual bolts, and upon the local practices in the region. The same basic methods are used to purchase logs for a plywood plant, although some specifications such as the minimum diameter or the amount of acceptable heart rot may differ from that for sawlogs.

The most commonly used methods of measuring logs are:

1. Log scaling, in which the diameter and length of each log is measured. These measurements are converted by use of a log rule to board feet or to actual cubic measure (cubic feet or cubic meters). The procedure for scaling will be described later. Scaling can be done manually or by use of electronic scanners.

2. Weight scaling, in which a load of logs is simply weighed. Weight can then be converted to an equivalent board foot or cord volume, or payment can be made directly on a weight basis. Table 13.1 shows the

Table 13.1. The average weight of 1000 bd ft of logs as scaled by three log rules

Species of southern pine	Log rules: Doyle	Scribner Decimal C	International ¼
		(lb/1000 bd ft)	
Loblolly	17,750	12,800	11,010
Shortleaf	17,920	12,650	10,870
Longleaf	24,230	14,350	12,240
Slash	23,860	14,990	12,730

Source: Page and Bois (1961).

Haygreen/Bowyer (1989)

average weight of 1000 bd ft of logs for the major southern yellow pines measured using three different log rules. The reason for the differences between the log scales will be explained later. Note that even for these similar species there can be as much as a 35% difference in the weight of an equivalent volume of wood. The effect of variability of moisture content and wood density on weight scaling was discussed in Chapters 8 and 9.

3. Cord scaling is sometimes used in the marketing of sawbolts. This method is more commonly applied to pulpwood. A standard cord is defined as the volume of stacked wood 4 × 4 × 8 ft, i.e., 128 ft^3. There are many variations from this standard. In some regions of the Lake States a cord length of 100 in. is used instead of 8 ft. In areas of the South a unit with a depth of 63 in. is used. The actual volume of wood in a cord, regardless of its definition, varies with the length, diameter, and straightness of the bolts and with the care used in stacking. Table 13.2 illustrates the relationship between bolt diameter and the volume of wood and bark in a cord of 4-ft-long bolts. Note the dramatic increase in the green weight and the volume of wood per cord as the bolt diameter increases. Van Sickle (1966) found for both pine and hardwoods in the South that the average volume of wood being delivered per cord ranged from 79 to 82 ft^3. Other studies have found the solid wood content of a standard cord to vary from 58 to 94 ft^3.

Table 13.2. Volume for stacked standard cords of 4-ft longleaf pine pulpwood

Diameter of average bolt, inside bark	Volume per standard cord: Wood	Volume per standard cord: Bark	Green weight per cord
(in.)	*(ft³)*	*(ft³)*	*(lb)*
5	56	23	4840
7	67	22	5430
9	71	21	5590
11	74	20	5760
13	77	20	5893
15	80	20	6100

Source: Williams and Hopkins (1968).

Log rules provide a conversion that relates the diameter and length of the log to an estimate of the lumber yield. Many factors determine how many board feet of lumber will be obtained from each cubic foot of round logs. These include the width of saw kerf, diameter of the log (and therefore the proportion lost as slabs), taper, and presence of sweep or defects. Various log rules provide estimates of lumber volume based upon different assumptions regarding these factors. Lumber recovery that exceeds the volume estimated by a log rule is called overrun. Three commonly used log rules are briefly described:

1. Doyle rule. This rule is computed from the equation, $V = [(D - 4) \div 4]^2 \times L$, where V = the board foot volume, D = the scaling diameter in

inches, and L = the log length in feet. This rule greatly underestimates the volume of lumber that can be obtained from small logs. Mills purchasing small logs on Doyle may obtain over twice the volume of lumber estimated by the log rule. A mill producing twice as much lumber as the log scale would have a 100% overrun.

2. Scribner rule. This rule was devised on the premise of sawing 1-in.-thick boards with ½-in. kerf from perfectly circular logs and based upon diameter at the small end of the log and no taper taken into account. Therefore, this rule underestimates lumber yield on small logs and on long logs with taper. If the volumes are rounded to the nearest 10 bd ft, this rule is called the Scribner Decimal C.

3. The International ¼ rule. This rule assumes sawing 1-in.-thick lumber with ¼-in. kerf and allowing ½ in. of taper for each 4 ft of length and ⅟₁₆ in. of shrinkage in board thickness. The International rule generally provides the closest estimate to actual lumber production of any of these commonly used rules. Thus it allows less overrun than the Doyle or Scribner rules for all but the largest logs.

The scaling of logs, regardless of the log rule used, involves measuring the length and diameter of the log. Strict specifications for length must be met or the log is considered to be of the next shorter standard length. The scaling diameter is the average diameter of the small end inside the bark. Tables can be used to convert the diameter and length to the desired log scale. When done manually, scaling sticks are used, which read directly in board feet.

When selling or purchasing logs, the basis for measurement is not nearly as important as understanding the relationship between the different rules. Table 13.3 compares the content of 16-ft-long logs as scaled with different log rules. Note that as the logs get larger the differences become smaller.

The overrun that may be obtained in a sawmill will vary greatly depending on the log rule used. Table 13.4 compares typical overrun expecta-

Table 13.3. Comparison of board foot volumes as determined by three log rules for 16-ft logs

Scaling diameter	Cubic volume*	Log rule: Doyle	Log rule: Scribner	Log rule: International ¼
(*in.*)	(*ft*³)		(*bd ft*)	
6	4.30	4	12	19
8	7.10	16	31	39
10	10.59	36	55	65
12	14.78	64	86	97
14	19.66	100	123	136
16	25.25	144	166	181
18	31.53	196	216	232
20	38.53	256	272	290
22	46.19	324	334	354
24	54.57	400	403	424
26	63.64	484	478	501

* Assumes cone with 2-in. taper per log.

Hangreen/Boyer (1989)

Table 13.4. Predicted percent overrun in southern pine sawmills using three log rules

Scaling diameter	Log rule: Doyle	Log rule: Scribner Decimal C	Log rule: International ¼
(*in.*)		(%)	
6	172	21	−3
8	95	19	−4
10	59	16	−5
12	39	14	−5
14	25	11	−6
16	16	9	−6
18	8	6	−7
20	2	4	−8

Source: Williams and Hopkins (1968).

tions in the southern pine region. The overrun when using Doyle is by far the greatest for logs 14 in. and smaller in diameter. The International ¼ rule may actually overestimate the amount of lumber that can be produced and thus a negative overrun (underrun) may result.

The measurement of actual cubic volume of logs, as a replacement for log scales, is becoming more common in the softwood lumber industry. This is the only absolute measure of log volume and allows much better monitoring of the true input to a mill. Cord, weight, and log rule methods are all inferential methods of determining the volume of raw material input. Electronic scanners and computer systems are being used to measure actual log volumes in the softwood lumber industry. Thus, as their use increases, the use of nondirect volume measurement methods will decline. This will make significant improvement in process control procedures possible.

Improving sawmill efficiency

A mill purchasing wood on only one log rule can compare total log volume input with lumber volume output to determine overrun. Done over time, this gives an indication of any change in the performance of the key operators in the mill or in the quality of the logs. A better way to consider the efficiency of a sawmill, however, is to analyze yield in terms of board feet of lumber produced per cubic foot of actual log volume. This ratio is termed the lumber recovery factor (LRF). To determine this, the mill must scale the logs being processed for cubic volume.

If lumber were actually cut to nominal sizes, there were no losses from kerf, and logs were square, the LRF would be 12; i.e., 12 bd ft would be obtained from each cubic foot of log. In the United States the average LRF among the larger sawmills is about 7.8 (Clapp 1982). This average varies by region because of size of timber and the size and sophistication of mills. Regional averages range from 8.3 to 5.7 bd ft/ft^3. Individual mills will vary considerably from these averages, but the LRF gives manufacturers a guideline with which to compare their efficiency of log conversion with others.

There are a number of possible means of improving the LRF of a sawmill. Among the most important are reducing kerf; reducing variability in thickness, which requires that lumber be sawn oversize; and making optimum decisions about how to cut each log and accurately positioning it according to the decison made.

The reduction of kerf losses in a sawmill is accomplished primarily by minimizing the saw cuts made on the headsaw and breaking cants down on smaller secondary saws that have much less kerf. There have been significant advancements in circular saw technology, which has reduced the kerf in saws designed to rip cants. Modern rotary gang saws typically have kerfs of about ⅛ in. and produce smooth, accurately sawn lumber.

An important means of increasing the LRF is by reducing the variability of lumber thickness. If a headrig has a variability in sawing thickness of ¼ in. and this can be reduced in some way to ⅛ in., there can be a saving of $\frac{1}{16}$ in. of wood each time a saw cut is made. This saving results from setting the saw $\frac{1}{16}$ in. over the desired thickness rather than ⅛ in., which would be required with the greater variability. Proper selection and maintenance of equipment is very important in attaining this goal.

The greatest advancement in increasing the efficiency of sawmills in recent years has been in the application of electronic log scanners and computers to the measurement of logs and placement for the first saw cut. The results as applied to chipping headrigs are shown in Figure 13.9; they came from a Canadian study of improved sawing decisions made by computer control over manual control with two different models of a Chip-N-Saw, a chipper canter of the type shown in Figure 13.5. Note in Figure 13.9 that the LRF was increased ½ to 1 bd ft/ft^3 by using the computer-controlled system.

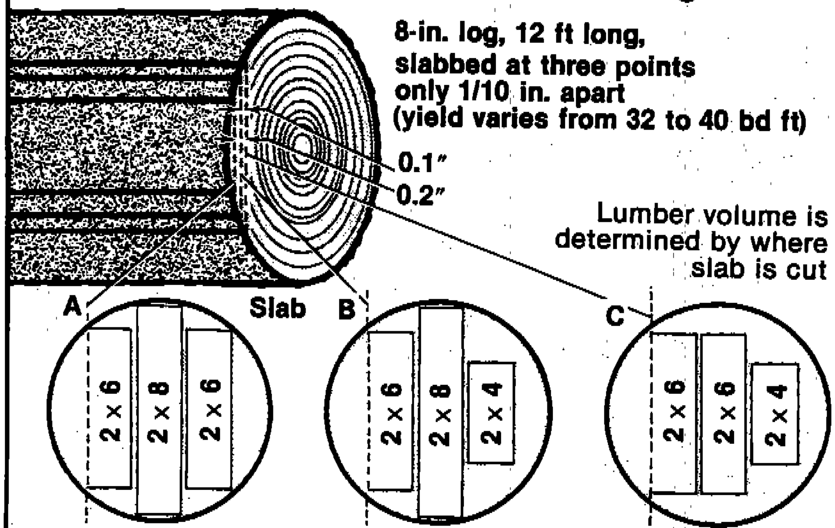
The coupling of an electronic scanner and a computer for operation control has many potential applications within a sawmill (Williston 1976). One computerized optimizing edger scanner measures board geometry, computes the optimum edging decision, positions the board and the saws, and passes the board through the edger to achieve maximum value.

A scanner is a means of measuring the length, diameter, or shape of a log or cant by passing it through a light or laser beam. Some scanners operate with a light receiver that senses the width of the object being placed between the light source and the receiver. Other scanners take measurements from the light reflected from the object being measured, whether it is a log or a cant. Figure 13.10 illustrates the combination of a scanner and a computer to control the relative position of the log and the saw lines. Application of this technique has brought about dramatic increases in lumber recovery.

The importance of making the first cut in a log at the proper position may not be apparent. However, once the first saw cut is made, the location of subsequent cuts is already determined. An illustration of how much difference a shift in the first cut can make in lumber yield is shown in Figure 13.11. On this small log the lumber yield could increase from 32 to 40 bd ft by moving the cut to the right only 0.20 in. The data in this figure is from

Fig. 13.11

Importance of first saw cut in a log



From Hallock (1973)

Hallock (1973), who did much work to demonstrate the importance of properly locating the first cut or chipping line. He referred to this as the best opening face, or the BOF.

[redacted] In Figure 13.8 it is demonstrated that the piece with the highest volume does not necessarily have the highest value. In the next decade further significant advancements will be made in the application of computerized process control to lumber manufacture.

Relationship between grades and uses of lumber

Those involved in the manufacture, sale, or use of lumber for secondary products must understand lumber grades if they are to produce and utilize the material in the most efficient manner. Using the wrong species or grade for a job can be costly to the homebuilder or furniture manufacturer. It can also result in using more lumber than necessary. Becoming knowl-

Haygreen/Bowyer (1989)

edgeable about grades and applications requires considerable study and experience.

The grades used in the United States and Canada for hardwood lumber are written by the National Hardwood Lumber Association (NHLA). These rules are also widely used in other countries exporting lumber to the United States. A number of softwood lumber trade associations are responsible for preparing the grade rules applying to their particular species. The larger of these organizations are the Western Wood Products Association, Southern Pine Inspection Bureau, West Coast Lumber Inspection Bureau, Redwood Inspection Service, Northeastern Lumber Manufacturers Association, and Northern Hardwood and Pine Manufacturers Association. The grade rules they have prepared must conform to PS20-70, a product standard developed under the jurisdiction of the U.S. Department of Commerce and administered by the American Lumber Standards Committee. The grades of dimension lumber for all these softwood associations are similar, conforming to the National Grading Rule for Softwood Dimension Lumber.

HARDWOODS. The standard grades of hardwood lumber as well as some of the major requirements for each are shown in Table 13.5. These grades are based upon the percentage of the total area of the face of the board that is usable as furniture parts. When grading, the lumber inspector first determines the poorest side of the board. Then by visual judgment and occasionally by actual measurement the proportion and size of clear rectangular cuttings from the piece is estimated. These cuttings must meet the minimum size requirements shown in Table 13.5. If over 83% of the area of a piece is in these usable cuttings, the board is an FAS; if it yields between 66 and 83%, it is a No. 1 Common, etc. Experienced inspectors can accurately

Table 13.5. Some characteristics of the NHLA hardwood lumber grades

Grade name	Required yield*	Minimum size of cuttings used in calculating yield	Minimum allowed size of board
	(%)	(*in.* × *ft*)	(*in.* × *ft*)
FAS	83	4 × 5 or 3 × 7	6 × 8
Select†	83	Similar to FAS	4 × 6
No. 1 Common	66	3 × 3 or 4 × 2	3 × 4
No. 2 Common	50	3 × 2	3 × 4
No. 3A Common	33	3 × 2	3 × 4
No. 3B Common‡	25	3 × 2	3 × 4

* Percent of board in cuttings that must be free of defects on one side.

† Differs from FAS in that the minimum board size is smaller and the grading is done from the best side of the board rather than from the poorest. Different basis is used to grade pieces less than 6 in. wide.

‡ Grading from poorest side and yield based upon sound, not clear, areas.

make these estimations at a surprising rate. They are considered to have graded a shipment correctly if upon reinspection the value of the lumber is not found to differ from the original by more than 4%.

When purchasing hardwood lumber, a furniture plant selects the grade based upon the size of pieces (dimension) they must cut from the lumber. The smaller the pieces they require, the lower the grade of lumber that can be used. Generally, a plant will obtain a much higher yield of usable cuttings from the lumber than indicated by the required yield percentages for that grade as shown in Table 13.5. This results from the fact that the plant is not restricted to the size of cutting used in the grading rules and the required yields for the grades are minimums, not averages.

An inexperienced hardwood lumber buyer will tend to buy a higher grade than necessary and as a result will needlessly increase raw material costs. To approach the use of lumber grades scientifically, many private firms and public research agencies have developed tables of expected yield for various size cuttings obtained from different grades and species. With this information, a firm can calculate the grades to purchase to minimize the total cost. Computer programs to accomplish these calculations are available through private consultants and forestry extension personnel of the U.S. Department of Agriculture.

There is no moisture content standard for hardwood lumber; i.e., there is no specific moisture content maximum for lumber sold as dry or kiln dried. A purchaser should specify the moisture content requirement when buying such lumber. Although there are standard surfaced thicknesses for hardwood lumber, it is good practice to specify both moisture content and actual thickness when purchasing hardwood lumber S2S.

Many uses of hardwoods do not involve a cut-up operation like those found in a furniture or flooring plant. Figure 13.12 shows that over one-third of hardwood lumber is used for pallets and containers. Much of this material consists of grades No. 2 or No. 3 Common or is ungraded. This material is often not sold by species but simply in a group of species of

hardwood use

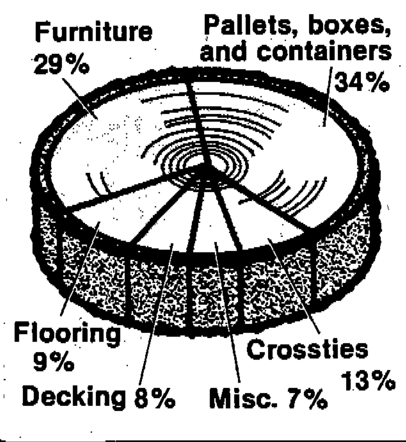


Fig. 13.12
Major uses for sawn hardwoods

From Appalachian Hardwood Manufacturers (1977) similar density. The higher density woods are preferred where strength is critical, and low-density woods are selected where nailability and shipping weight are most important.

Hardwoods are generally not used for construction lumber that competes with softwood dimension. However, some lower density hardwoods may be suitable for this purpose and will find greater use in the future. Aspen is presently being used to produce 2 × 4s graded similarly to softwoods. Poplar also has potential for such utilization.

Haygreen/Bowyer (1989)

softwood use

SOFTWOODS. Most grading of softwood lumber is by visual inspection. Experienced graders can assess in a few seconds the knot size and location, slope-of-grain, freedom from decay, and other characteristics that determine grade. Some dimension lumber to be used in highly engineered structures is also graded by machine. This is termed machine stress–rated (MSR) lumber. The main use of MSR lumber is in trussed rafters. The major components of a machine that stress grades lumber are shown in Figure 13.13. The machine measures the stiffness of lumber passing through it by flexing it in the two flatwise directions and measuring the force required to do so. The stiffness is then related by a computer program to the bending strength, and the piece is stamped accordingly. The variability in strength of a grade of MSR lumber is much less than for visually graded lumber, an advantage when high strength is needed.

[redacted] A few grades that are intended for cut-up operations similar to hardwoods are called shop grades. These are used principally for production of millwork. The largest portion of construction lumber goes into dimension, i.e., lumber 2–4 in. thick. The grades of softwood dimension assigned allowable stresses are shown in Table 13.6, with the highest grade in each category listed at the top. The special grade of Stud is somewhat similar to a No. 3

Fig. 13.13

Main elements of a machine that mechanically stress-grades lumber

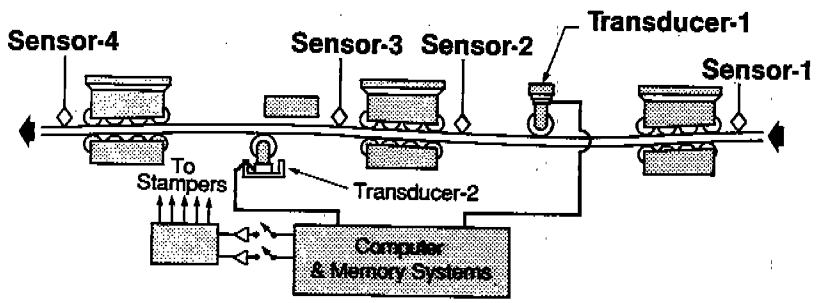


Table 13.6. Grades of softwood dimension lumber assigned allowable stresses

	Grades	
Nominal size	General use	Structural use
2–4 in. thick and 2–4 in. wide	Construction Standard Utility Appearance	Select Structural No. 1 No. 2 No. 3 Stud
2–4 in. thick and 6 in. and wider	Select Structural No. 1 No. 2 No. 3 Appearance	Select Structural No. 1 No. 2 No. 3

but with stricter requirements in regard to warp. The Appearance grade is quite similar to a No. 1 but with greater restrictions as to wane (barky edges) and other appearance factors. Not shown are lower grades usable for blocking, dunnage, etc.

There are many more grades of softwood dimension lumber than are practical for many mills or retail lumber dealers to handle. There are 11 grades of softwood 2 × 4s, so if a mill produces lumber from three species groups, it would have 33 different categories of material to store for just this one size of dimension. Most manufacturers and building materials dealers restrict themselves to a limited number of grades and species. This reduces inventory problems and confusion of the customer/builder. It is common practice to sell mixed grades of dimension, for example, No. 2 and Better or Standard and Better. The percentage of the lower grade allowed in such a mix is often specified to assure that the customer does not receive only the lower grade.

(moisture content)

[redacted] These categories are used for both boards and dimension. Timbers are ordinarily sold only in the green condition. It is not advisable to use green dimension in finished buildings because of the possibility of warp and shrinkage. Nonetheless, green dimension is still used for home construction in some parts of the country. Southern pine is usually manufactured to the 15% MC requirement (KD), but other softwood manufacturers produce principally S-Dry material.

Most softwood lumber, particularly dimension, is grade stamped at the mill after it has been dried and surfaced. A major reason for doing so is that building codes require the use of grade-stamped lumber for framing. Grade stamps for visually graded lumber indicate the grade, the species or species group, the moisture content category, the association under whose supervision the grader works, and also a number that designates the mill at which the lumber was produced. An example of such a grade stamp is shown in Figure 13.14. A grade stamp for MSR lumber is illustrated in Figure 13.15. The elements in this stamp are similar to those of a visually graded piece. However, the classification of MSR lumber is designated by the allowable bending strength and stiffness values.

The sale of species of softwood lumber in various regions follows traditional marketing patterns developed over many years. Builders and building contractors become accustomed to certain species and grades, and sometimes it is difficult to change their preferences unless significant cost savings are possible. Homebuilders may advertise their use of well-known species such as Douglas-fir or southern yellow pine as indications that their homes are superior, implying that builders using other species are produc-ing inferior homes. To an uninformed public this approach sometimes works. Although significant advantages or disadvantages of one species as compared to another do exist, there is no reason that any species of softwood dimension will not do the job for which it is intended if the lumber is properly manufactured and the building is designed with the properties of the species and grade in mind.

In many situations in building construction it is possible to use the next larger size of dimension rather than changing to a higher grade or a stronger species. Such a change may be less costly and result in a better building than using the smaller size of the higher grade.

When using dimension lumber for construction, it is often helpful to be able to compare the strength and stiffness of different lumber sizes. Two rules of thumb can be very useful in this regard: (1) the strength of a beam is proportional to the square of its depth and (2) stiffness of a beam is proportional to the cube of the depth. For example, from Table 13.7, the strength of a 2 × 8 can be compared to a 2 × 10 by comparing 52.6 to 85.6. The 2 × 10 can safely support 85.6/52.6 or 1.6 times as great a load as the 2 × 8. In terms of stiffness the 2 × 10 is 791.5/381.1 or 2.1 times as stiff as the 2 × 8. This means it will deflect 1/2.1 or only 48% as much under a given load. Such comparisons assume that the span and allowable stress values for the sizes being compared are the same. They emphasize the large increases in strength and stiffness often obtained by merely increasing the size of structural members by one increment.

Table 13.7. Factors to compare bending strength and stiffness of different lumber sizes

Nominal size	Depth (*in.*)	Depth squared (*in.*^{2})	Depth cubed (*in.*^{3})
2 × 4	3.5	12.3	42.9
2 × 6	5.5	30.3	166.4
2 × 8	7.25	52.6	381.1
2 × 10	9.25	85.6	791.5
2 × 12	11.25	126.6	1423.8

Haygreen/Boyer (1989)

REVIEW

A. Terms to define or explain:

1. Board foot
2. Hem-Fir
3. Southern yellow pine
4. Log rules
5. Ring debarker
6. Rossing head debarker
7. Chipper canter
8. Scragg mill
9. Band headsaw
10. Log scanner
11. Overrun
12. Lumber recovery factor
13. Gang saw
14. National Hardwood Lumber Association
15. Standard cord
16. Doyle rule
17. Scribner rule
18. Weight scaling
19. Red oak lumber
20. S-Dry
21. MC-15
22. Construction
23. FAS
24. No. 3A Common
25. Cuttings
26. Select Structural
27. Boards
28. Timbers
29. Required cuttings (hardwood) yield
30. Stiffness
31. Nominal size
32. Matcher
33. Planer mill
34. Sticker
35. MSR lumber

B. Questions or concepts to explain:

1. The major processing steps in the manufacture of lumber.
2. Reasons for debarking logs prior to processing.
3. Types of headsaws and characteristics of each.
4. Basis of grading hardwood lumber as compared to softwood lumber.
5. Procedure for scaling logs.
6. Relationship between three major log rules.
7. The difference between overrun and lumber recovery factor.
8. The difference between tree names and lumber species group names.
9. How board footage is calculated for hardwood and softwood lumber.
10. The use of scanners and computers for control systems.
11. The thickness categories of softwood dimension.
12. The moisture content standards for hardwood and softwood lumber.
13. The relationship between the size of a wood beam and its strength and stiffness.
14. Methods of grading softwood lumber.

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HAYGREEN & BOWYER (1989)

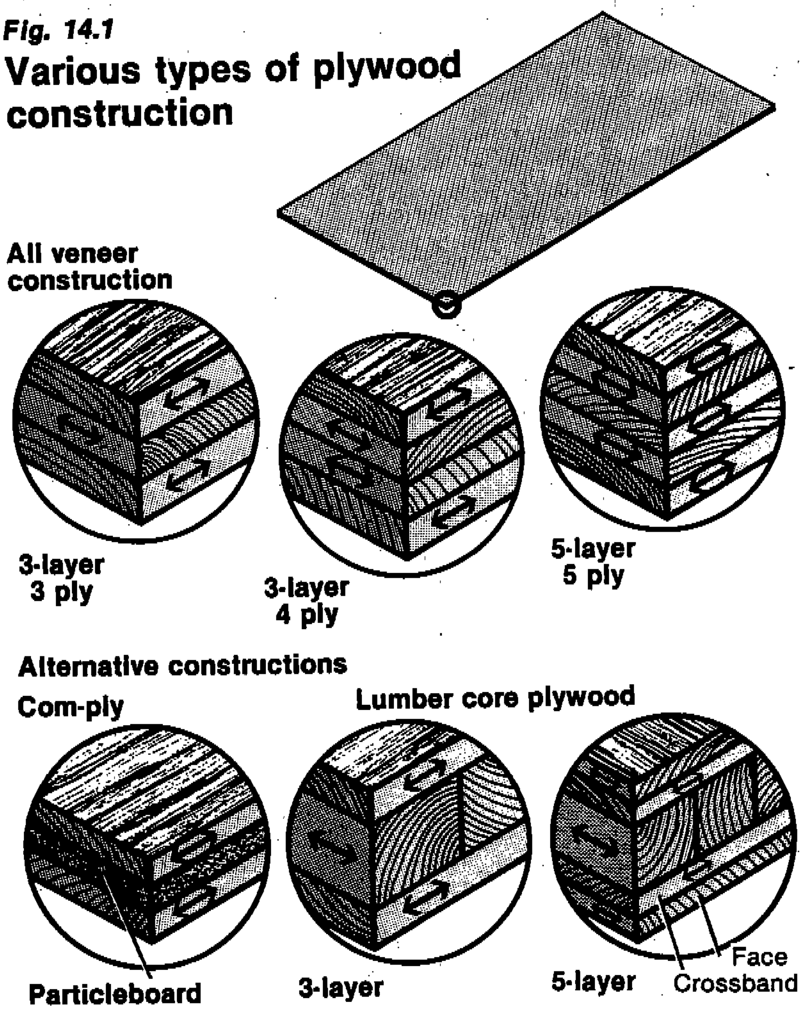
14 Plywood production and use

PLYWOOD is a panel product of wood veneers glued together so that the grain direction of some veneers runs at right angles and others run parallel to the long axis of the panel. In most types of plywood the grain of every other layer is laid parallel to the first. Therefore, to maintain a balance from one side of the panel to the other, an uneven number of veneers is used (3, 5, 7, etc.). Some plywood, however, is produced with an even number of veneers, the prime example being softwood plywood made up of four or six plies (veneers). In this case two veneers are laid parallel to form a thick center core. Such panels are illustrated in Figure 14.1.

Plywood is also produced with lumber or particleboard as the core. Nonveneer-core plywoods are commonly used in the furniture industry. Several plants have produced the three-ply composite panel shown in Figure 14.1. This type of wood panel, with a particleboard core, is used for the same purposes as construction grades of softwood plywood.

Although the plywood industry dates back only to about 1905, the product from which plywood is made, veneer, has an ancient history. The Egyptians around 1500 B.C. are credited with producing veneer to decorate furniture. The ancient Greeks and Romans also developed means of cutting veneer. Plywood did not become a major industry, however, until the 1930s. The adoption of the hot-press from Europe and the development of synthetic resin glues are credited as technical developments playing an important role in the early growth of the industry. Most of the technology for the softwood plywood industry developed in the United States. World War II greatly accelerated the technology for efficiently manufacturing exterior phenolic-resin bonded plywood, which was extensively used for small naval

Fig. 14.1
Various types of plywood construction



military craft. In the 1970s other areas of the world adopted the technology for producing softwood plywood from small logs.

There are about 560 plywood and veneer mills in the United States that produce 20–25 billion ft² of plywood each year, of which 90–95% is softwood plywood. The softwood plywood industry originally developed on the West Coast and was concentrated there because of the quantities of available high-quality timber. Developments in resin technology and manufacturing equipment in the early 1960s made possible the production of softwood plywood from relatively small southern pine logs. The softwood plywood industry has grown rapidly in the South, and production from that region has exceeded production from the West since 1980. About 15%

of the softwood timber volume consumed for industrial products goes into plywood production. The hardwood plywood industry, currently producing only about 1 billion ft^2, is concentrated in the South.

Plywood production technology differs considerably between softwood and hardwood mills. Grades and uses of the two kinds of plywood differ greatly as well. Softwood plywood is used principally as a construction material. Thick low-grade veneers are used extensively for construction plywood. Construction plywood is manufactured both in unsanded grades, which are applied mainly as sheathing and subflooring, and in sanded grades, which are suited for a wide variety of uses both decorative and structural.

Hardwood veneer is used to manufacture plywood for paneling, industrial parts, furniture, and as a construction material. Hardwood veneer is also used as a separate laminant in tables and case goods. The hardwood plywood industry is very diverse—from small firms that produce custom-ordered plywood for specific architectural applications to large, high-capacity plants producing thin panels in production lines similar to those in the softwood industry.

Most hardwood plywood in the United States is manufactured according to an American National Standard Institute (ANSI) and Hardwood Plywood Manufacturers Association (HPMA) standard HP-1983. The HPMA is the trade association involved in the development, quality control, and promotion of this product.

Most softwood plywood produced in the United States is manufactured to meet the requirements of U.S. Product Standard PS1-83 for Construction and Industrial Plywood. The grades and standards are also outlined in the Plywood Design Specifications of the American Plywood Association. This association develops marketing, engineering, and construction information for softwood plywood. The jurisdiction of PS1-83 includes plywood manufactured from hardwoods but intended for the same application as softwood plywood (general construction).

Wood panels, which are produced from flakes rather than veneers but are used much like softwood plywood, have become important since about 1980. These panels are of two general types: waferboard and oriented strandboard (OSB). Standards for these products have been promulgated by the American Plywood Association. These performance standards differ from product standards, such as PS1, in that they define the performance characteristics a product must possess to perform adequately in a designated application rather than how it must be made. A performance standard is oriented toward the end use of a panel, while a product standard prescribes minimum manufacturing requirements. Although waferboard and OSB standards and use are similar to those of plywood, the technology for manufacture is much like that of typical particleboards. For that reason these two products are discussed in the next chapter.

Plywood has become a valuable building material because it has unique properties ideally suited for construction. It is light in weight, yet strong. It is a sheet material; therefore large areas of a roof or floor can be covered by handling relatively few pieces. It can be nailed, glued, and sawed with about the same ease as lumber. The first major use of softwood plywood, around 1910, was for door construction. Since then, plywood has replaced lumber for many uses, the most important being sheathing. In recent decades softwood plywood has made possible the application of production-line techniques in the homebuilding industry.

Plywood has some advantages over lumber, but it is not stronger in all respects. A strip of plywood between two supports will not carry more load than a piece of lumber of the same width and thickness. In this situation the lumber will be somewhat stronger. Plywood, however, has strength in bending in either direction, so it will serve satisfactorily as flooring whether laid parallel or perpendicular to floor joists (beams) that support it. For the most efficient use of plywood in general construction, it should be laid perpendicular to the joists. In special uses such as stress-skin panels, it is often laid parallel. Another advantage of plywood is its rigid rectangular shape, which makes it almost impossible to deform by a force parallel to the plane of the panel. This is why, when plywood is used as sheathing for floors, roof, and exterior walls, the structure becomes extremely strong and resistant even to hurricanes or earthquakes. Figure 14.2 shows a lumber and plywood home hit heavily by an earthquake in Anchorage, Alaska, in 1966. The home remained whole because of the high racking strength provided by the plywood when nailed to the lumber framing.

(Courtesy U.S. Forest Products Laboratory)

Fig. 14.2
A plywood-sheathed home that remained structurally whole during the Alaskan earthquake of 1964.

Species used for manufacture

Douglas-fir and more recently southern yellow pine have been the two most important species used for the manufacture of softwood plywood in the United States. However, all major softwoods on the West Coast including the true firs, western hemlock, and western pines are also utilized. Softwood plywood is not usually sold by species name. Woods are grouped by stiffness and strength properties as shown in Table 14.1. The plywood is graded and classified for strength purposes as Group 1, Group 2, etc. The reason for the two classifications of Douglas-fir, as noted in the footnote to the table, is the lower strength found in the latter states. For most plywood grades the group is determined by the species of the face and back veneer. The inner veneers may be of a lower group.

A number of species from Southeast Asia and Latin America are listed in the groupings (Table 14.1). Cativo, Caribbean pine, and ocote pine are imported from Central and South America. Apitong and keruing are a group of species from the genus *Dipterocarpus* originating in the Philippines, Malaysia, and Indonesia. Lauan is the name of a group of species from the Philippines. In the past the lauan species were called Philippine mahogany, a misnomer since they are not true mahogany. Meranti refers to many of the same species as lauan, but this name is used if the wood originates from Malaysia or Indonesia. All these woods are brought into

Table 14.1. Grouping of species for softwood plywood

Group 1	Group 2	Group 3	Group 4	Group 5
Apitong	Cedar, Port	Alder, red	Aspen	Basswood
Beech, American	Orford	Birch, paper	Bigtooth	Poplar,
Birch	Douglas-fir No. 2*	Cedar, Alaska	Quaking	balsam
Sweet	Fir	Fir, subalpine	Cativo	
Yellow	Balsam	Hemlock, eastern	Cedar	
Douglas-fir No. 1*	California red	Maple, bigleaf	Incense	
Keruing	Grand	Pine	Western red	
Larch, western	Noble	Jack	Cottonwood	
Maple, sugar	Pacific silver	Lodgepole	Eastern	
Pine	White	Ponderosa	Black (western poplar)	
Caribbean	Hemlock, western	Spruce	Pine	
Ocote	Lauan	Redwood	Eastern white	
Pine, southern	Maple, black	Spruce	Sugar	
Loblolly	Meranti, red	Engelmann		
Longleaf	Pine	White		
Shortleaf	Pond			
Slash	Red			
Tanoak	Virginia			
	Western white			
	Spruce			
	Black			
	Red			
	Sitka			
	Sweetgum			
	Tamarack			
	Yellow poplar			

Source: APA (1985a).

*Douglas-fir from trees grown in the states of Washington, Oregon, California, Idaho, Montana, Wyoming, and the Canadian provinces of Alberta and British Columbia shall be classed as Douglas-fir No. 1. Douglas-fir from trees grown in the states of Nevada, Utah, Colorado, Arizona, and New Mexico shall be classed as Douglas-fir No. 2.

the United States in various forms—logs, veneer, and plywood. The logs and veneers may be used to produce all-hardwood plywood or in combination with U.S. softwoods. These woods are used in plywood produced under both the softwood and hardwood standards.

Almost all important hardwood species grown in the United States are used to some extent for plywood manufacture. The lower density species including the gums, poplar, cottonwood, and aspen are often used for the core and backs of plywood-faced with more expensive hardwoods. These low-density species also are suitable as base veneers for printed paper overlays or for direct printing to simulate fine veneer species.

Basic steps in manufacture

When logs are cut to the length required for rotary veneer cutting, they are called blocks. They are debarked for the same reasons that logs entering a sawmill are debarked. Similar equipment is used.

HEATING THE BLOCKS. Almost all hardwood and many softwood blocks are heated prior to cutting the veneer. Heating softens the wood and knots, making it easier to cut. It also improves surface quality, reducing roughness. Some of the dense hardwoods must be heated to produce satisfactory veneer. Softwood veneer from some species can be produced from cold logs because of their lower density and because the roughness limitations are less critical than for high-quality hardwoods. However, even in the softwood industry the advantages of heating the blocks generally outweigh the cost of the process. Baldwin (1975) lists four advantages of heating softwood logs:

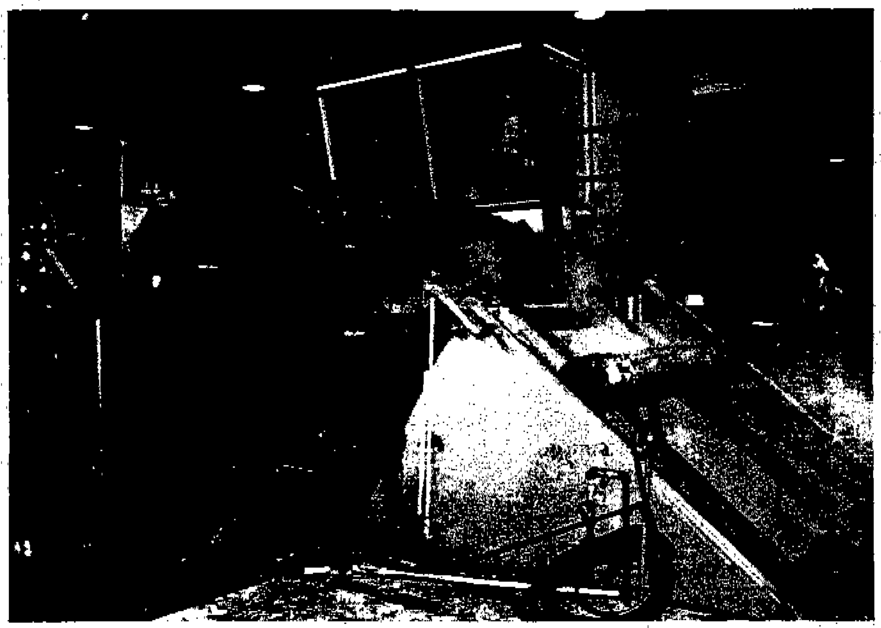
1. Higher yields of veneer can be obtained from the logs. The reduction of cutting imperfections increases the yield an average of 3–5%.
2. The grade of the veneer is improved. Studies by Lutz (1960), Grantham and Atherton (1959), and the American Plywood Association have found that grades of veneer are upgraded from 4 to 25%.
3. Labor costs are reduced. Veneer from heated peeler blocks tends to hang together in a more continuous ribbon as it comes from the lathe. This reduces handling.
4. The amount of adhesive used can be reduced. Glue spreads can be lighter because of the improved surface.

A variety of methods are used to heat the logs. Steaming, soaking in hot water, spraying with hot water, or combinations of these methods are all suitable to some situations. Dense hardwoods are usually heated by soaking at temperatures up to 200°F (93°C). Regardless of the heating medium, the objective is to heat the log to a suitable temperature as deeply into the log as veneer will be cut.

Mills develop their heating schedules based upon trial and error or by measuring the log temperature as the block is peeled (as veneer is cut). An optical pyrometer can measure the temperature during peeling to determine if the heating period has been adequate. The heating time required depends upon the diameter of the log, specific gravity, moisture content, and the temperature needed to properly peel the species. Fleischer (1965) showed that the higher the density, the higher the favorable temperature for cutting veneer. For example, basswood cuts well at 60°F (16°C), but white oak requires 200°F (93°C).

CUTTING VENEER. Two major methods for producing veneer are slicing and peeling. Most veneer is produced by peeling (rotary cutting), which is accomplished on a veneer lathe as shown in Figure 14.3. Slicing is used for producing decorative veneers from high-quality hardwood and is seldom used with softwoods. The cutting action on a lathe and on a slicer are very similar and are illustrated in Figure 14.4. In either case, the wood is forced under a pressure bar that slightly compresses the wood as it hits the cutting edge of the knife.

On the veneer slicer a cant of wood called the flitch is rigidly dogged, i.e., clamped, to a carriage that oscillates, cutting on the down stroke. Before each cutting stroke the knife and pressure bar move forward the thickness of the veneer to be cut. In a rotary lathe they move forward continuously as the block rotates. Careful adjustment of the knife angle and the horizontal and vertical gap between the pressure bar and the knife

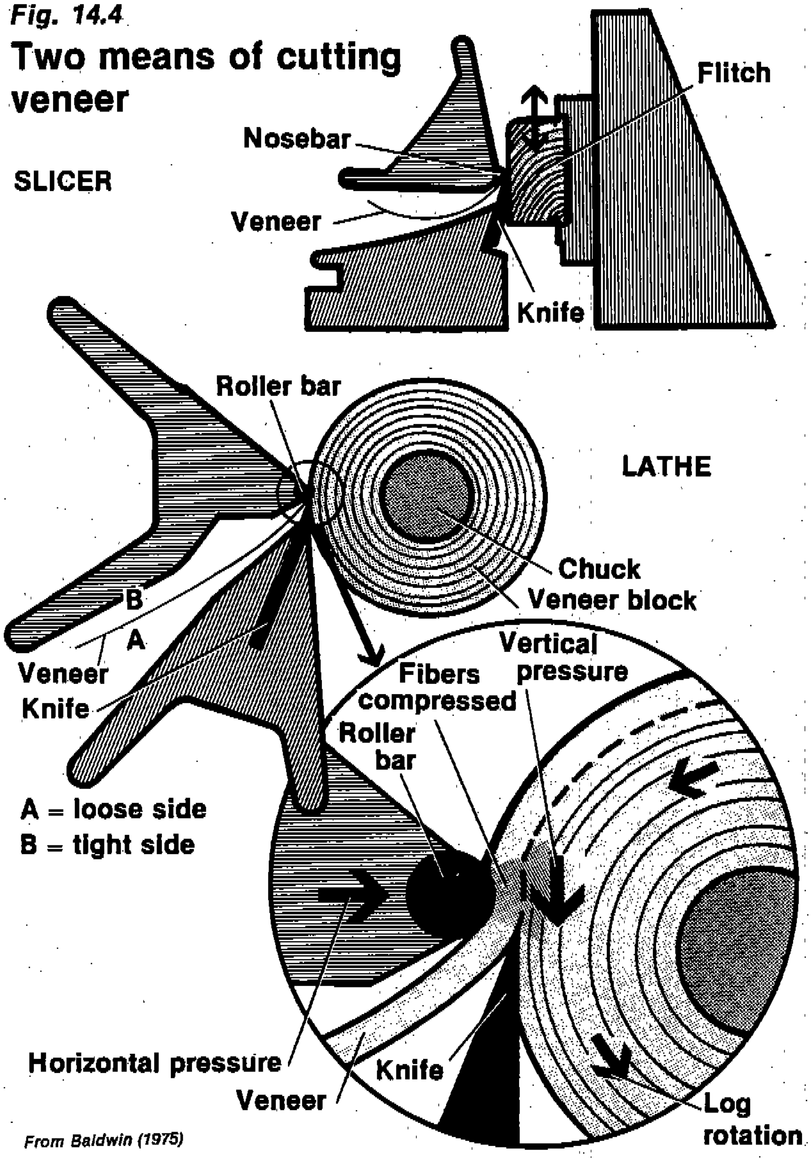


(Courtesy Coe Manufacturing Co.)

Fig. 14.3
A small-log veneer lathe and one of many types of lathe chargers.

Fig. 14.4

Two means of cutting veneer



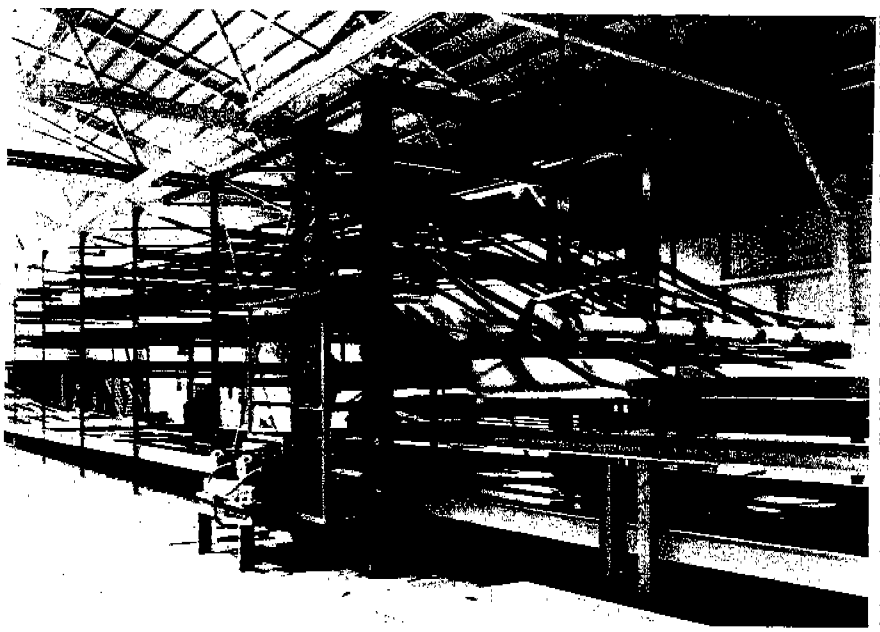
From Baldwin (1975)

edge is necessary to obtain the proper peel. The horizontal gap between the pressure bar and the knife is set slightly less than the thickness of the veneer to be cut to provide the necessary compression. Proper pressure must be developed at the pressure bar to reduce checking of the veneer as it is severed from the log. Proper setting of the pressure bar also minimizes surface roughness. After the cutting action has taken place and the veneer has moved past the pressure bar, the thickness of the veneer springs back as the compression is released.

The side of the veneer next to the knife edge is called the loose side. Close examination will show many hairline fractures called lathe checks running parallel to the grain. If plywood is subjected to exterior weathering, lathe checks may eventually show up as surface checks. On a smooth, painted surface these may prove to be objectionable, but on rough-textured exterior plywood they go unnoticed and add to the attractive character of the surface.

One of the keys to high-speed production in modern mills is an automated means to load (charge) the lathe. One type of lathe charger is shown in Figure 14.3. Equipment of this type can load the lathe with a small block, round up the bolt, peel the veneer down to a 4- to 5½-in. core, and discharge the core in about 10 seconds. As soon as the core is discharged, the charger has a bolt ready for the next cycle. Less highly automated means of charging the lathes are used in mills still cutting large logs and in many hardwood veneer plants.

VENEER STORAGE AND CLIPPING. In modern mills the green veneer must be handled gently and rapidly as it comes from the lathe. The veneer is peeled at from 300 to 800 lineal ft/min. A series of trays is used in many softwood plywood plants to handle these long ribbons of wood. Trays are often about 120 ft long, long enough to handle the veneer that comes from a typical 15-in. block. Figure 14.5 shows a typical tray storage system



(Courtesy Coe Manufacturing Co.)

Fig. 14.5
A typical veneer tray storage system as seen looking back toward the lathe. The veneer being discharged is moving to the clipper.

behind a lathe and ahead of the clipper. In hardwood mills the green veneer is often wound into a roll and then moved to the clippers. These are called reel storage systems. Other hardwood mills use directly coupled conveyors between the lathe and the clipper. This is possible when the clipper speed is as fast as the output from the lathe.

Clippers are high-speed knives that chop the veneer ribbons to usable widths. In hardwood veneer mills, clipping may be done manually to obtain the maximum amount of clear material from the flitch. In softwood mills and in some hardwood mills, clipping is often done automatically at speeds of up to 1500 lineal ft/min. The clipper will cut the veneer to about 54 in. (the panel width plus an allowance for shrinkage and panel trimming) if possible. However, if open defects are present, the veneer may be clipped to less than full panel width. Automatic clippers detect open defects with scanners that can be overridden by the operator when it is desirable to do so.

The type of log determines the grade of veneer expected and the best system for clipping. In sheathing mills, small logs with tight knots lend themselves to fixed-width clipping. Large logs with a variety of defect sizes, some exceeding the largest allowed in the veneer grades, require more careful clipping. In this case the clipper operator determines which oversize defects to cut out.

VENEER DRYING. The fundamentals of drying were outlined in Chapter 8. A number of innovations in veneer-drying technology have significantly reduced drying times and improved uniformity and flatness. Two types of dryers are in use in softwood veneer mills: roller-restraint dryers, heated by forced air, and platen dryers, heated by steam (Sellers 1985). The principle of operation of one type of dryer is illustrated in Figure 14.6. Hot air is forced at speeds of up to 4000 ft/min through small tubes, impinging on the veneer. This removes the boundary layer of moist air that acts as an insulator in dryers using low-velocity air circulation. Developments such as the use of microwave energy, use of high temperature preheaters, and increased drying temperatures (up to 800°F, or 427°C) may find use for some types of veneer drying. In most softwood veneers, however, temperatures over about 400°F (204°C) have adverse effects on glueability.

One technical problem encountered in the drying of veneers is the generation of emissions that contain hydrocarbons, some of which can produce a blue haze in the atmosphere. The opacity of these emissions is controlled by the Environmental Protection Agency and local authorities. Baldwin (1975) reported that Douglas-fir and ponderosa pine are the western species producing the greatest opacity under any given drying condition. Softwoods with a lower resin content provide less of a problem. Drying temperatures over 400°F (204°C) produce the greatest emission problems.

LAY-UP AND PRESSING. The process of applying adhesives to the veneers, assembling veneers into a panel, and moving the panels in and out of the press are often the most labor-intensive steps in manufacture. Veneer is

? Hardwood is not usually "peeled," "slice" when you slice how do you get large slices of veneer?

We have info on emissions

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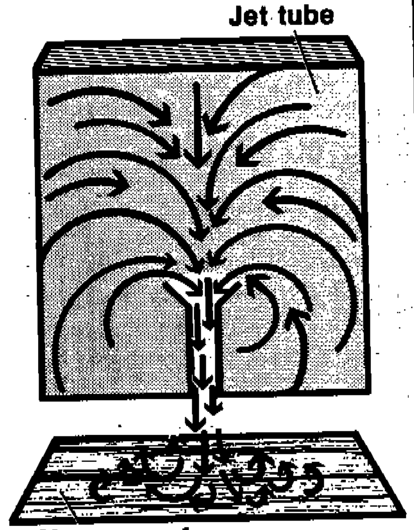
Fig. 14.6
Principle of the jet (impingement) drier



From McAllister (1967)

highly variable in width, length, and quality, which makes it a difficult material to handle with automated systems. Yet major advances have been made to increase automation in this stage of manufacture.

One advancement has been in the application of adhesive to the veneer. The old method is to pass veneer through rubber-faced grooved rollers that apply glue by contact to the top and bottom surfaces. One person is required to feed the roller glue spreader while an offbearer places the veneer onto the panel being laid up. If veneer is extremely rough, the glue spread will not be uniform and skips may occur.

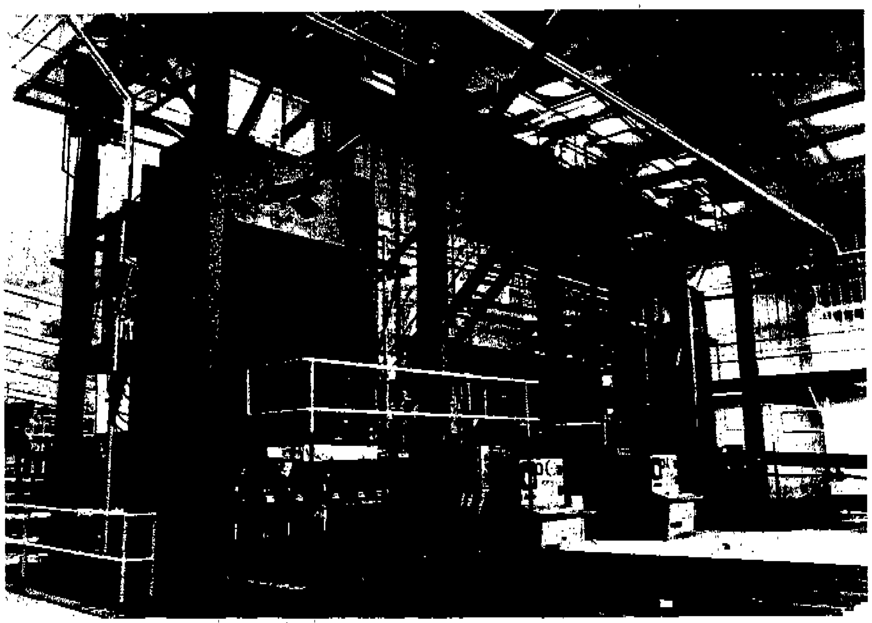
Newer means of glue application, spray and curtain-coaters, have distinct advantages in terms of uniformity of the glue spread and are suited to automated lay-up systems. These methods overcome the problem of poor glue spread on rough stock. In these systems the veneers travel on a belt conveyor under the spray or curtain. A curtain-coater consists essentially of a box with a slot in the bottom through which the adhesive flows in a continuous sheet or curtain. Glue not deposited on a piece of veneer passing through the curtain is pumped back up into the box. Although simple in principle, this method requires careful adhesive formulation and monitoring.

Recently, two new methods of adhesive application, liquid extrusion and foamed resin extrusion, have been used successfully. These systems lay down continuous beads of resin on the veneer. It is reported that with the foamed glue it is possible to cover more area with the same amount of glue. Also, the glue contains less moisture, so higher press temperatures are possible, which reduce press times.

The actual assembly of veneers into plywood panels can also be mechanized—at least in larger plants producing standard-size panels. Although equipment has been developed to do this almost automatically, most mills use systems that are partially manual and partially mechanized. For example, the full-size 4 × 8-ft veneers for the two faces may be handled by machine, but the narrower strips of veneer used in the core may be assembled manually. Means have also been developed to connect the veneer strips used for the core by pressing parallel strings of fiberglass coated with hotmelt adhesive at right angles to the veneer strips. This continuous core can then be handled by conveying systems rather than by hand. Many varieties of automated lay-up lines are used in the softwood plywood industry.

Most softwood plywood plants prepress the loads of laid-up panels prior to final pressing in the hot-press. This is done in a cold press at lower pressure. The purpose is to allow the wet adhesive to "tack" the veneer together. This permits easier loading of the hot-press and helps prevent shifting of the veneers during loading.

Pressing of the panels is usually done in multiopening presses of the type shown in Figure 14.7. Such presses can produce 20–40 4 × 8-ft panels



(Courtesy Superior Production Machines, Inc.)

Fig. 14.7

Two 24-opening 4 × 8 ft plywood hot-presses. The press openings are loaded by an elevator seen in front of one of the presses.

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at each pressing cycle, which may take 2–7 minutes. The purpose of the press is twofold: to bring the veneers into close contact so that the glue line is very thin and to heat the resin to the temperature required for the glue to polymerize. Adhesives made from phenol-formaldehyde resins are used for exterior and all southern pine plywood. These typically require temperatures of 240°F (115.5°C) in the innermost glue line for approximately 90 seconds to cure properly. Resin systems must be carefully tailored to the specific conditions in a plant. Press time and temperature can be modified; i.e., a shorter press time may be possible if press temperature is increased.

One of the goals in designing the pressing process is to use enough pressure to bring the veneer surfaces together without overcompressing the wood. The better job the lathe does in cutting the veneer (i.e., the smoother and more uniform the thickness), the less pressure is required. Some mills decrease the pressure during the press cycle to reduce unnecessary compression of the plywood. The finished plywood must meet industry thickness standards; therefore, if it is overcompressed during pressing, the thickness of the veneer must be increased to compensate. This reduces the yield from the blocks. Pressing pressures typically used in the industry vary from 110 psi for low-density woods to over 200 psi for dense species.

Adhesives

Almost all adhesives used in the plywood industry in the United States today are thermosetting (cured by heat) synthetic resins. These have almost completely replaced the blood and soybean flour protein glues that were used in the past for interior (nonwaterproof) grades of plywood. The two most important types of resins used are phenol-formaldehyde, which is used for interior and exterior grades of softwood plywood and for exterior grades of hardwood plywood, and urea-formaldehyde, which is used to manufacture interior grades of hardwood plywood. The basic components of these resins are formaldehyde, (which is derived from methanol,) urea, and phenol.

Research to develop satisfactory adhesives from a variety of natural organic materials has demonstrated the potential for replacing petrochemicals. However, in the immediate future, urea- and phenol-based resins will remain the two most important in the United States. Two possible sources of natural exterior-type resins are bark (actually tannin from bark) and lignin compounds obtained in the pulping of wood. In New Zealand, Scandinavia, India, and South Africa, some commercial use has been made of naturally derived resins.

Only rarely are pure or "neat" resins used as adhesives for plywood. In most cases they are mixed with fillers or extenders such as Furafil and fine flour produced from wood, bark, or nutshells. Furafil is a chemical lignocellulose by-product of furfuryl alcohol production that can be produced from corn cobs, rice hulls, and oat hulls. Starch and animal blood are also used as extenders to modify the viscosity, control the penetration into the wood, and control other characteristics of the adhesive mix such as the tack (stickiness).

A typical adhesive mix for southern pine plywood is given in Table 14.2. The purpose of caustic soda is to aid in the dispersion of the extender. The rate at which this adhesive is applied to the veneer is generally in the range of 35–45 lb of adhesive per thousand square feet of single glue line. Thus 1000 ft^2 of three-ply plywood (two glue lines) requires 70–90 lb of adhesive mix. This is referred to as a spread of 70–90 lb MDGL (thousand square feet of double glue line).

Table 14.2. An Adhesive mix for southern pine plywood

Component	Weight
	(*kg*)
Phenol-formaldehyde resin (42% solids)	2883
Water	726
Furafil	386
Wheat flour	204
Caustic soda	136
Total mix	4335
Total resin	2883

Source: Sellers (1985).

A new development in the late 1980s was the introduction of resins that could be applied to "wet" veneers with moisture contents of 15% or higher. Normal phenolic mixes generally are recommended for veneers at less than 10% moisture content. The major advantage of the wet-veneer adhesive is that it allows increased production through the veneer drier, which is often the process that limits the volume of production in a plant.

Types, grades, and uses

Adapting plywood to its proper use requires consideration of four main factors: (1) durability required of the glue line to avoid delamination; (2) strength, stiffness, and nailholding requirements; (3) visual quality or appearance of the faces; and (4) special requirements such as decay or fire resistance.

Softwood plywood is categorized by the durability of the glue line: Exterior, Interior, Exposure 1, Exposure 2. Interior is intended for use indoors or in applications protected from the weather. It has water resistance to withstand only occasional wetting. Exterior should provide satisfactory service under severe wetting and drying situations. The quality of veneers required in the core of Exterior plywood is higher than for Interior. Exposures 1 and 2 are durability categories for performance-rated panels. Exposure 2 and Interior panels are comparable.

In hardwood plywood, durability is indicated by the designation Type 1, 2, or 3. Type 1 is similar in durabilty to Exterior softwood plywood. Type 2 is moisture resistant and intended for general interior use. Type 3 is

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intended for noncritical uses. In the case of both hardwood and softwood plywood the quality of the glue lines is monitored by the trade association or an independent inspection bureau that supervises the grade stamping of the mill's production.

SOFTWOOD PLYWOOD. Plywood finds its way into many industrial, construction, and packaging uses. Its nature as a lightweight, workable, yet strong and rigid sheet material gives it unique properties not equaled by any other product, wood or nonwood. In 1984 about 70% of the softwood plywood produced in the United States was sheathing; 14% was represented by sanded grades for interior or exterior use; 10% was in the form of specialties, mainly siding; and the remainder was mill and shop grades.

In selecting the proper grade for any given application, the requirements of durability should first be considered. Next, unique strength or service requirements must be analyzed. If the application of the plywood primarily requires strength and rigidity, one of the unsanded or touch-sanded grades should be chosen.

Table 14.3 indicates some of the most important grades of softwood plywood intended for engineered or construction purposes. Table 14.4 lists the important sanded grades. Many of the grade names, such as C-D, A-B, and C-C, refer to the grades of veneer on the two faces. In Interior plywood the center layers (core) can be grade D veneers, but in Exterior grades no veneer below a C grade can be used. Table 14.5 lists the characteristics of the four major grades of softwood veneer. Veneer sheets can be upgraded considerably before assembly into panels by repair with circular plugs and patches. Once veneer is pressed into a panel, repair on the faces is often accomplished by use of synthetic patches or shims.

Table 14.3. Some commonly used grades of softwood plywood intended for construction applications

Grade	Description and common uses	Panel surface
C-D Int and Rated Sheathing	Wall and roof sheathing, subflooring, industrial uses such as pallets	Unsanded
CDX	Same as C-D but with exterior glue	Unsanded
Sturd-I-Floor	Combination subfloor underlayment, smooth surface for application of resilient floor coverings	Touch sanded
Underlayment	Application over structural subfloor, smooth surface for application of resilient floor coverings	Touch sanded
C-D Plugged	Built-ins, wall and ceiling tile backing, cable reels, walkways, separator boards	Touch sanded
C-C Ext and Structural 1 and II Rated Sheathing	Waterproof bond for subflooring and roof decking, siding on service and farm buildings, crating, pallets	Unsanded
Sturd-I-Floor	Combination subfloor underlayment under resilient floor coverings where severe moisture conditions may be present	Touch sanded
C-C Plugged	Tile backing where severe moisture conditions exist, refrigerated rooms, pallet fruit bins, tanks, boxcar and truck floors	Touch sanded

Roof sheathing and subflooring for residential light frame construction are two major uses of the construction grades of plywood. Generally, Rated Sheathing, C-D, or CDX is used for these applications. For floor construction Rated Sheating or C-D is applicable to two-layer floors where an underlayment panel is to be laid on top of the subfloor. If a single-layer floor system is used, a subfloor/underlayment grade, called Sturd-I-Floor by the American Plywood Association (APA), must be used. This provides a smooth and solid base for floor coverings. The APA (1983, 1985a,b) publishes a series of booklets for architects and builders describing the proper application of plywood for most construction situations. A list of all of their publications is available upon request.

Table 14.4. Some commonly used grades of softwood plywood intended for applications where appearance is important

Grade	Description and common uses	Panel surface
Interior type and Exposure I		
A-A	Interior applications where both sides on view, built-ins, cabinets, furniture, partitions	Sanded
A-B	Where appearance of one side is less important and two smooth solid surfaces are necessary	Sanded
A-D	Interior uses where the appearance of only one side is important	Sanded
B-B	Interior utility panel where two smooth sides are desired; permits circular plugs	Sanded
B-D	Interior utility panel where one smooth side is required	Sanded
Exterior type		
A-A	Where appearance of both sides is important; fences, built-ins, signs, boats, cabinets	Sanded
A-B	Similar to A-A Ext panels but where appearance of one side is less important	Sanded
A-C	Exterior use where appearance of only one side is important; soffits, fences, boxcar and truck lining, farm buildings	Sanded
B-B	Outdoor utility panel with solid faces	Sanded
B-C	Outdoor utility panel for farm service and work buildings	Sanded

Source: Modified from APA (1985a).

Table 14.5. Four main grades of softwood veneer

Grade	Description and characteristics
A	Smooth, paintable. Not more than 18 neatly made repairs permitted—synthetic, boat, sled, or router type and parallel to grain. May be used for natural finish in less demanding applications.
B	Solid surface. Shims, various synthetic or wood patches or plugs and tight knots to 1 in. across grain permitted. Some minor splits permitted.
C	Tight knots to 1½ in. Knotholes to 1 in. across grain and some to 1½ in. if total width of knots and knotholes is within specified limits. Synthetic or wood repairs. Discoloration and sanding defects that do not impair strength permitted. Limited splits allowed. Stitching permitted.
D	Knots and knotholes to 2½ in. width across grain and ½ in. larger within specified limits. Limited splits permitted. Stitching permitted. Limited to interior grades of plywood.

Source: APA (1985a).

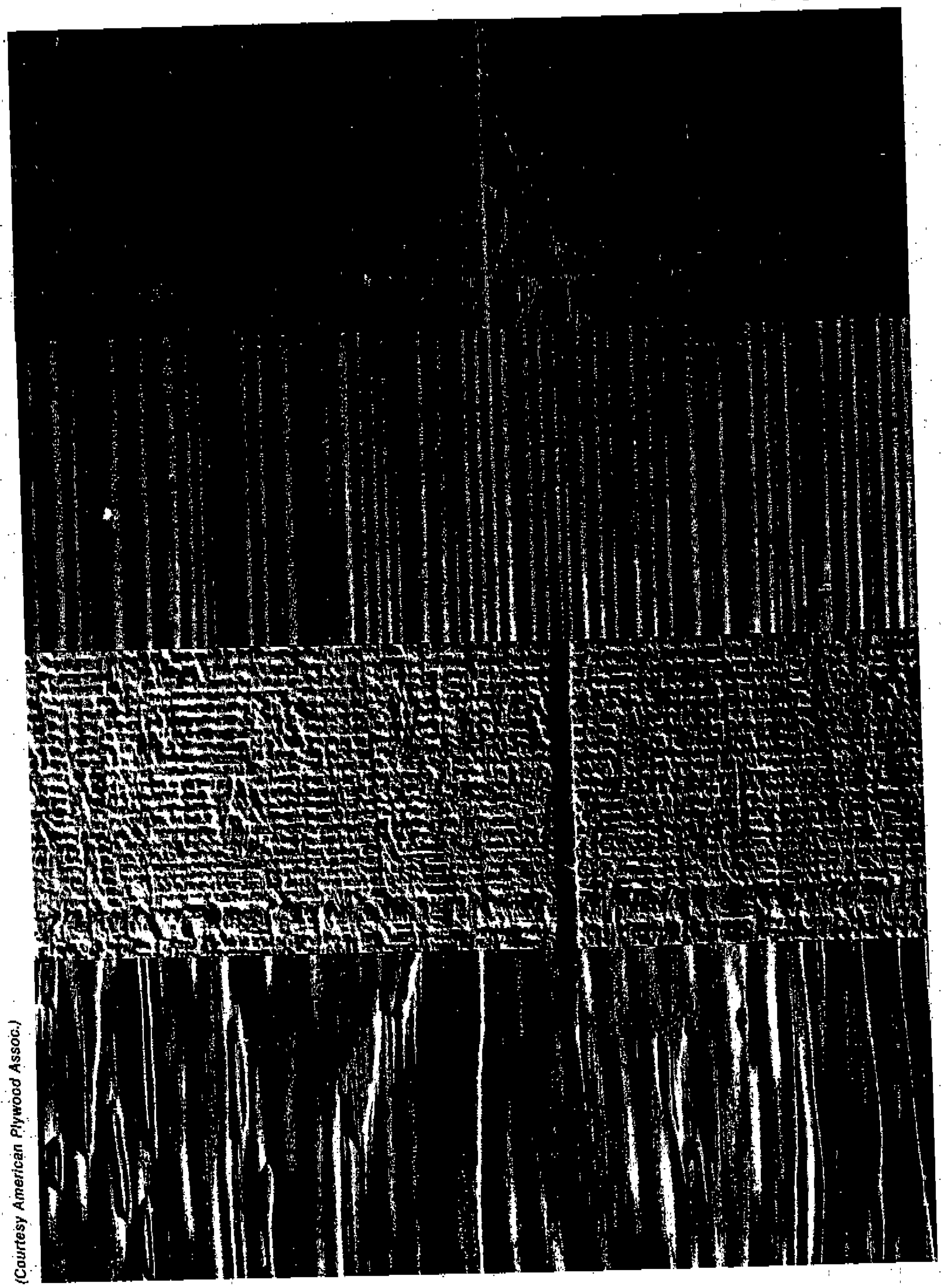
Many special types of plywood are manufactured to provide the surface properties needed for siding, highway signs, and painted industrial cabinets. Two approaches are used to overcome surface checking of plywood exposed to exterior conditions. One method is to overlay the plywood with a layer composed of medium- or high-density resin-impregnated wood fiber sheets. These wood fiber overlays hold paint well and provide a check-free base. The second approach is to provide a rough or textured surface that will not be downgraded by the presence of checks. These rough natural surfaces have become very popular. Figure 14.8 shows some of the types of softwood plywood surfaces that are manufactured.

Most plywood is grade stamped at the mills by graders supervised by grading associations or inspection agencies. The APA is the largest of these organizations. Typical grade stamps are shown in Figure 14.9. Note that these stamps include much more information than just the grade name. They may indicate the durability (Exterior, Exposure 1, or Exposure 2), thickness, species group, and the mill number or name. For grades to be used for roof sheathing or subflooring, two numbers, called the span rating, are given rather than the group number. The numbers in this rating refer to the maximum span allowed when the piece is used for normal residential construction. The first number refers to the maximum allowable spacing of rafters if the panel is used as roof sheathing. The second number is the maximum spacing of floor joists if the panel is used as subfloor. These are convenient guides to contractors and building inspectors alike.

HARDWOOD PLYWOOD. There are many more thicknesses, species, and finishes of hardwood plywood being produced than there are of softwood. The major domestic species used for plywood are birch, oak, gum, and walnut. Hardwood plywood is imported in large volumes from Korea, Japan, Indonesia, Taiwan, Malaysia, Finland, and the USSR. Figure 14.10 shows the proportion of domestic shipments of plywood by species. It is difficult to generalize about grades and uses since they vary so widely. Much hardwood plywood is not purchased with grade as the principal criterion; a combination of species, grade, and finish often determines the selection and use. Tables 14.6, 14.7, and 14.8 show the commonly used decorative species for hardwood veneer and the characteristics allowed in veneer grades A, B, Sound, Industrial, and Backing.

Hardwood plywood producers in the United States market their products for three major uses: prefinished plywood paneling, cut-to-size panels for furniture, and door skins. The biggest single market for hardwood plywood has been wall paneling. Fifty-seven percent of hardwood plywood consumed in the United States in 1978 was used for paneling. Many plants operate to produce this product only. The normal thickness for paneling has been ¼ in., although many less expensive panels are thinner.

In 1979 about 76% of the hardwood plywood consumed in the United States was imported. That proportion dropped to 64% by 1981. About three-fourths of this was used as paneling. Between 1950 and 1972 the amount of hardwood plywood that was imported increased each year. The peak year for consumption of hardwood plywood in the United States was



(Courtesy American Plywood Assoc.)

Fig. 14.8
Some of the wide variety of textures and patterns produced for decorative softwood plywood.

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assoc.

Fig. 14.9

Typical grade stamps for softwood plywood

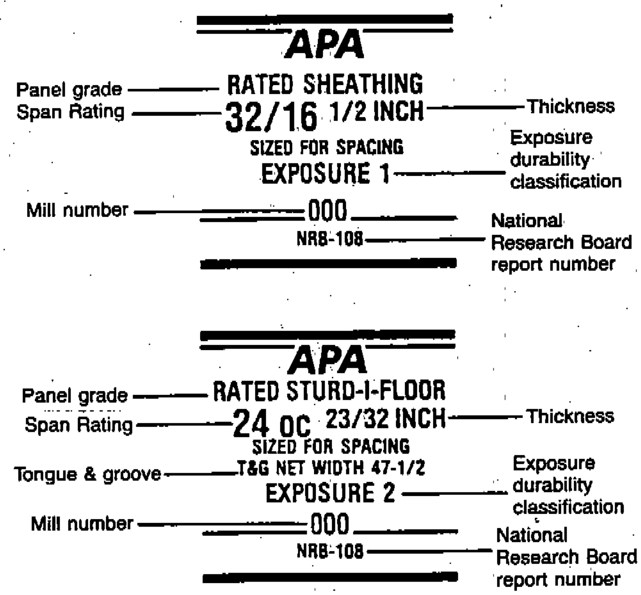
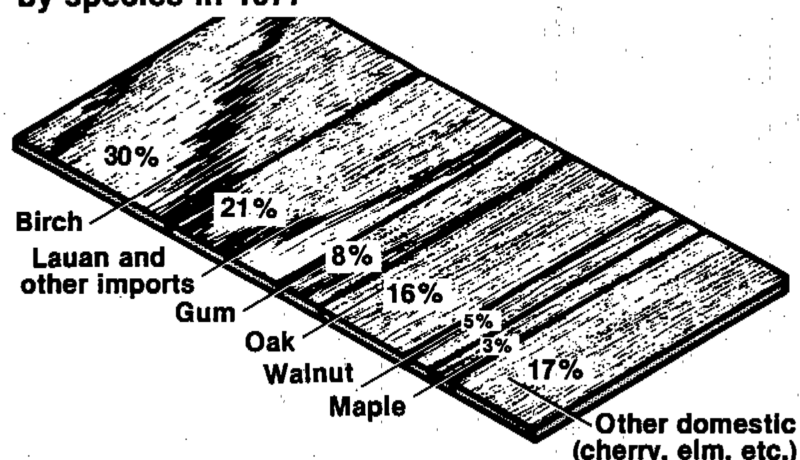


Fig. 14.10

Domestic shipments of hardwood plywood by species in 1977



From Bureau of Census (1977)

Table 14.6. Categories of commonly used decorative species

Category A	Category B	Category C	Category D
Ash, white	Ash, black	Alder, red	Aspen
Apitong	Avodire	Basswood, American	Cedar, Eastern red
Beech, American	Birch, paper	Butternut	Cedar, Western red
Birch, yellow, sweet	Cherry, black	Cativo	Fuma
Bubinga	Cypress	Chestnut, American	Willow, black
Hickory	Elm, rock	Cottonwood, black	
Kapur	Fir, Douglas	Cottonwood, Eastern	
Keruing	Fir, white	Elm, American (grey, red, or white)	
Oak (Oregon, red or white)	Gum, sweet	Gum, black	
Paldao	Hemlock, Western	Hackberry	
Pecan	Magnolia, Cucumber Sweetbay	Hemlock, Eastern	
Rosewood	Maple, sugar (hard)	Lauan	
Sapele	Mahogany, African	Maple, red (soft)	
	Mahogany, Honduras	Maple, silver (soft)	
	Maple, black (hard)	Meranti, red	
	Pine, Western white	Pine, ponderosa	
	Poplar, yellow	Pine, sugar	
	Spruce, red, Sitka	Pine, Eastern white	
	Sycamore	Prima-vera	
	Tanoak	Redwood	
	Teak	Sassafras	
	Walnut, American	Spruce, black, Engelmann, white	
		Tupelo, water	

Source: ANSI (1983).
Note: Based on an evaluation of published modulus of elasticity (MOE) and specific gravity values.

1972, when over 5 billion ft^2 (on a 3/8-in. basis) was consumed. Since 1972 the general trend in the consumption of hardwood plywood has been downward for both domestic and imported panels. Total consumption in 1981 was less than 2.5 billion ft^2 (3/8-in. basis). The shift by consumers toward simulated wood panel products such as printed or overlayed hardboard and particleboard is expected to level off, but production of hardwood plywood may never return to the mid-1970s levels. Hardwood use will increase, however, in nondecorative plywood panels.

Factors affecting the utilization of timber for plywood

In the early days of the plywood industry, production depended upon large, high-quality logs. Baldwin (1975) reported that some Douglas-fir mills in the 1920s did not accept logs less than 5½ ft in diameter or with any end defects. Those days are certainly gone in most areas of the world. Today, mills in the southern pine region often utilize material that averages 10–12 in. in diameter. It would take 44 such bolts to equal the volume of one 5½-ft block.

Fortunately, as the size of available timber decreased, the technology for producing veneer from small logs improved. Lathes were developed

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Table 14.7. Summary of hardwood veneer characteristics and allowable defects of Sound, Industrial, and Backing grades

Defects	Sound Grade (2)	Industrial Grade (3)	Backing Grade (4)
Sapwood	Yes	Yes	Yes
Discoloration and stain	Yes	Yes	Yes
Mineral streaks	Yes	Yes	Yes
Sound tight burls	Max. diam. 1″	Yes	Yes
Sound tight knots	Max. diam. ¾″	Yes	Yes
Knotholes	No	Max. diam. 1″	Max. diam. 3″
Wormholes	Filled or patched	Yes	Yes
Open splits or joints	No	Yes; 3/16″ for one-half length of panel	1″ for one-fourth length of panel; ½″ for one-half length of panel; ¼″ 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 plies and backs provided serviceability of panel is not impaired.	Areas of doze and decay provided serviceability of panel is not impaired.
Rought cut	Small area	Small area	Yes
Patches	Yes	Yes	Yes
Crossbreaks and shake	No	Max. 1″ in length	Yes
Bark pockets	No	Yes	Yes
Brashness	No	No	Yes
Gum spots	Yes	Yes	Yes
Laps	No	Yes	Yes

Source: ANSI (1983).

that could peel veneer down to a 3½-in. core. Means were developed to load blocks very rapidly into the lathes. These improvements have made possible the development of a large-scale plywood industry in northern Europe and the southern United States.

Mills in many tropical countries and the western United States are still able to obtain veneer blocks of relatively large sizes (16 in. or greater in diameter). One of the largest mills in the Philippines still operated in 1978 with the diameter of its lauan blocks averaging 24 in. (Fig. 14.11). Within 15 years, however, this mill expects to rely on plantation-grown eucalyptus and second-growth lauan. At that time only 8% of the log volume is expected to be as large as 24 in.

Mills still fortunate enough to be purchasing large logs, though not as large as in the past, are often using lower quality. In the western United States the best logs no longer go to the veneer mill. Because of the relatively high price for top grades of lumber and because sheathing grades of plywood can be produced from logs of intermediate quality, logs that have the fewest knots and other defects are directed to the sawmills. However, the softwood plywood plants producing the sanded grades still need to procure the best logs available. In the southern pine plywood region, by contrast,

.ble 14.8. *Summary of veneer characteristics and defects of A and B grade hardwood species*

	Rotary, half round, plain sliced birch						Plain sliced cherry		Rotary gum, tupelo, magnolia, poplar								Rotary, half round, plain sliced maple						Red and white oak		Hickory, pecan		Walnut	
	Natural		Select white	Select red	Uniform light	Uniform dark	6	7	Natural		Select for white		Select for red		Quarter sliced gum		Natural		Select white	Uniform light	Rotary		Half round, plain sliced		Rotary sliced		Half round, plain sliced	Rotary, half round, plain sliced
aracteristics	A	B	A	A	A	A	A	B	A	B	A	B	A	B	A	B	A	B	A	A	A	B	A	B	A	B	A	B
pwood	Yes	Yes	Yes	No	Yes	No	No, 8	No, 8	Yes	Yes	Yes	Yes	No, 8	No, 8	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes	Yes	No, 8	No, 8
artwood	Yes	Yes	No	Yes	No	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
lor streaks or spots	Yes	Yes	Slight	Slight	Slight	Yes	Yes	Yes	Yes	Yes	Slight	Slight	Yes	Yes	Yes	Yes	Yes	Yes	Slight	Slight	Slight	Yes	Slight	Yes	Yes	Yes	Slight	Slight
lor variation	Yes	Yes	Slight	Slight	Slight	Yes	Yes	Yes	Yes	Yes	Slight	Slight	Slight	Yes	Yes	Yes	Yes	Yes	Slight	Slight	Yes	Yes	Slight	Yes	Slight	Yes	Yes	Yes
ineral streaks	Slight	Slight	Slight	Slight	Slight	Slight	Slight	Slight	Yes	Yes	Slight	Yes	Slight	Yes	Slight	Slight	Small	Small	Slight	Slight	Slight	Yes	Slight	Slight	Slight	Yes	Slight	Yes
all burls and pin knots	Occ	Yes	Occ	Occ	Occ	Occ	Occ	Yes	Occ	Yes	Occ	Yes	Occ	Yes	Occ	Yes	Occ	Yes	Occ	Occ	Occ	Yes	Occ	Yes	Occ	Yes	Occ	Yes
ots (other than pin knots)	No	No	No	No	No	No	No	No	No	Sound	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	Sound	No	Sound
rm holes	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
ake or doze	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No	No
ugh cut	No	No	No	No	No	No	No	No	No	Small	No	Small	No	Small	No	No	No	No	No	No	No	Small	No	Small	No	No	No	No
onspicuous patches	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes

Source: ANSI (1983).

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Fig. 14.11

Contrast in the size of veneer logs. *(above)* Lauan blocks being floated to a veneer mill in the Philippines. *(below)* Southern pine logs to be sorted for use either in a chipper-canter headrig or a veneer lathe.

the best logs from the tree are used for plywood and the intermediate sizes and qualities are directed to the sawmill.

The quality of veneer logs is determined by the absence of knots or surface defects, by straightness and roundness, and by freedom from defects that are revealed on the ends. Heart rot is a serious problem in old-growth timber. Grades are usually established based upon straightness, freedom from heart rot or soft centers, and how many of the four sides of the log are free from knots or other defects. Large logs may be graded individually and sold on the basis of grade. Smaller logs are usually not sold by grade, although those containing serious defects may be culled.

The quality of logs entering the mill is important for two reasons: it controls the quality and yield of veneer that can be obtained and it affects the number of logs that prove to be defective once on the lathe, i.e., logs from which little or no veneer can be obtained. Most such logs are lost because the chucks on the lathe, which grip the end of the veneer blocks, spin out or split the log as pressure is applied. Logs with heart rot are unacceptable for this reason. Defective blocks can seriously reduce the production rate of a lathe.

The yield of veneer (volume of veneer per unit volume of the blocks) varies with log diameter, log quality including straightness of the block, the diameter to which the log is peeled (core diameter), and the efficiency with which the veneer is clipped and utilized. The source of losses during the manufacture of veneer from western hemlock blocks, according to a study by Woodfin (1973), is shown in Figure 14.12. Note that in this case less than one-half the original volume was converted to usable veneer. The greatest loss occurred at the clipper, the point where the defective portions of veneer are cut out. In this study the diameter of western hemlockblocks ranged from 12 to 45 in. and the core diameter averaged 11 in. As a result, the core made up 19% of the total volume.

Phillips et al. (1980) reported from a study of southern pine that as little as 1 in. of sweep or crook in an 8-in. diameter block reduced the veneer yield by as much as 44%. Although sweep is not as serious in larger blocks, 2 in. of sweep in an 18-in. block (a large diameter in most regions) would reduce the veneer volume produced by 23%.

The ratio of core volume to total block volume increases as the diameter of the block decreases. Table 14.9 shows how core diameter affects the amount of veneer produced from southern pine veneer blocks. Note that in an 18-in. block the increased veneer obtained by reducing the core diameter from 5 to 4 in. is insignificant (251–259 ft^2, or 3%). However, if 8-in. blocks were being peeled, the difference would be very important (33–40 ft^2, or 21%).

New technology continues to be developed, which improves the ability of plywood to remain a cost-competitive wood panel product. While in the early 1980s some industry leaders believed that the days of softwood plywood were nearing an end—to be replaced by waferboard and OSB—there is general belief today that new technology will allow plywood from logs as small as 5 in. in diameter to remain competitive. In 1980 it was stated that blocks less than 8 in. should not be peeled, but by 1985 a new spindleless lathe had been developed that made it possible to peel veneer down to a 2-

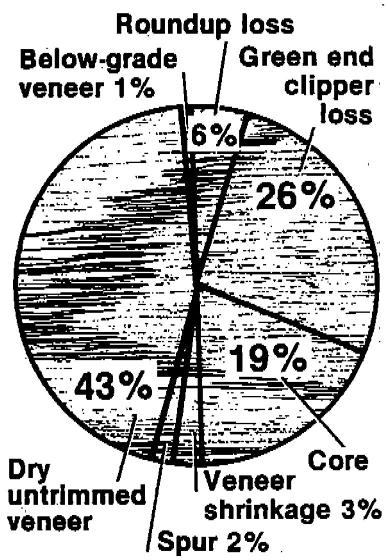
waferboard/OSB
(mention)

assoc.

Fig. 14.12

Losses during veneer production

Western hemlock veneer blocks



From Woodfin (1973)

Table 14.9. Relationship between block diameter, core diameter, and volume of veneer produced

Block diameter	Veneer yield* — Core diameter 3 in.	4 in.	5 in.
(*in.*)		(*ft²*)	
8	46	40	33
10	77	71	63
12	114	108	100
14	157	151	144
16	208	202	194
18	264	259	251

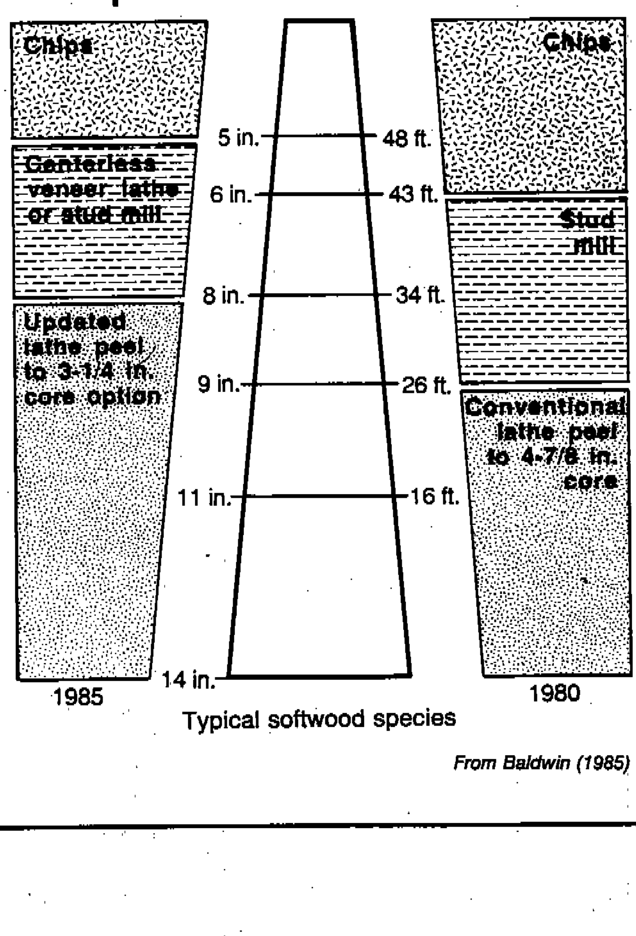
Source: Williams and Hopkins (1968).
* ⅜-in. basis, i.e., 3 ft² of ⅛-in. veneer equals 1 ft² ⅜-in. basis.

in. core (Baldwin 1985). The improvement in the utilization this development could make is illustrated in Figure 14.13. This figure contrasts 1980 technology, commonly used today, to state-of-the-art (1985) technology that is now available.

Most softwood plywood mills monitor yield on the basis of the log-measuring system they use. Thus they may express yield in terms of 1000 ft^2 of ⅜-in. plywood produced/1000 bd ft (MBF) of logs scaled by the Doyle or Scribner log rule or as determined from a weight scale. In some areas of the South a log weight unit of 5350 lb is referred to as a cord. The yield of a plant may be expressed in any of these units. For example, a plant may obtain an average yield of 2.4 thousand ft^2 of ⅜-in. plywood/MBF Scribner. Mills that measure small veneer logs on the basis of the Scribner log

Fig. 14.13

Impact of 1985 versus 1980 technology on the utilization of softwood logs for plywood production



From Baldwin (1985)

Waferboard/OSB
(mention)

2550C.

scale ordinarily consider yields of over 3000 ft^2/MBF to be good recovery. This is referred to as a recovery factor of 3.

Perhaps the next generation of forest products engineers and managers may help convert the industry to a uniform and consistent system of measuring log input to the mills. The present misunderstandings created through measuring by cords, Doyle, Scribner, hybrid log rules, weight, and very seldom by true cubic volume is confusing to many, and not just the new professional in the field. It would be beneficial to the industry if wood were measured by either true volume or weight. If measured by weight, the data can be converted to an estimated volume through appropriate checks on specific gravity and moisture content.

In the future a large proportion of plywood production will continue to be from small logs 8–15 in. in diameter. Much research and development remains to be done on how best to utilize plantation-grown genetically superior trees for plywood production. Are the wood properties important for pulpwood also the best for plywood? How can the effects of juvenile wood be minimized? What mechanisms can be developed to assure efficient allocation of raw material and to decide quickly and accurately which portion of the log should be used for veneer, lumber, fiber, or energy?

REVIEW

A. Terms to define or explain:

1. Blocks
2. Plies
3. Rotary cut
4. Lathe
5. Slicer
6. Flitch
7. Pressure bar
8. Charger
9. Lathe checks
10. Tray storage system
11. Curtain-coater
12. Extender
13. Jet dryer
14. Automatic clippers
15. Species groups (softwood plywood)
16. Exterior plywood
17. Type 1 plywood
18. Phenol-formaldehyde resins
19. Grade B veneer
20. Identification index
21. Lauan
22. Meranti
23. Overlayed plywood
24. Recovery factor

B. Questions or concepts to explain:

1. Two major methods used to cut veneer.
2. Differences in use of hardwood vs. softwood plywood.
3. Relative importance of plywood in the forest products industry.
4. Most important softwood species now used and trends in species use.
5. Basic steps in the manufacture of plywood.
6. Advantages of heating the block.
7. Importance of the pressure bar in veneer cutting.
8. Use of tray and reel storage systems behind the lathe.
9. Types of adhesives used for hardwood and softwood plywood.
10. Major veneer and plywood grades.
11. Speed at which veneer can be produced from small logs.
12. How veneer yield is expressed in terms of volume of timber input.
13. Classification of glue-line durability for hardwood and softwood plywood.
14. How core diameter affects the veneer yield of small logs.

15. Factors that determine the quality of veneer logs.
16. Factors that determine the yield of veneer from a block.

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Waferboard/OSB (mention)

Assoc.

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faces of framing lumber such as 2 × 4s, 2 × 6s, and 2 × 8s) where the bending stresses are the highest. Particleboard is used in the core where the bending stresses are lower but where maximum shear occurs. Recall the discussion of shear and flexural stresses in Chapter 10. The veneer on the surfaces of the panels or the lumber also acts to limit dimensional changes with fluctuations in moisture content. The restraint to dimensional change is only in the grain direction of the veneers.

COMPOSITE PANELS. Several panel plants producing a composite panel consisting of a particleboard core covered with softwood veneers were in production in the early 1980s. It is possible to combine a prepressed particleboard core with veneer in a process similar to plywood production, or the veneers and particle mat can be consolidated to the final thickness in a one-step pressing operation. This type of product is shown in Figure 14.1. The output of these plants was marketed for the same uses as softwood plywood, waferboard, and OSB.

Extensive tests carried out by the American Plywood Association indicate that in most characteristics, these veneer particleboard composite panels perform very much like plywood. One of the keys to the initially successful marketing of this product was that it looked like plywood. Due to poor market conditions, veneer-particleboard composite plants closed by the mid-1980s.

COMPOSITE LUMBER. Several composite wood products, intended as substitutes for lumber as well as other structural materials, are now on the market. Products available today include (1) parallel strand lumber, made from long strands of veneer, extruded along with resin into various cross sections and widths, (2) parallel laminated veneer, made from veneer similar to that used in making plywood but with the grain direction in all veneers oriented parallel to one another, (3) structural "I"-beams, most commonly made from parallel laminated veneer (for flanges—or for the top and bottom portions of the I) and plywood or OSB (for the web—or for the vertical portion of the member). [redacted] This product is produced by parallel-laminating veneer to the edges of strips of 1½-in.-thick particleboard. The product can be produced in any width desired and thus can be made to match common lumber sizes; a 3½-in. width would ordinarily be used for studs and wider material for floor joists. A Com-ply floor joist and an experimental home floor system constructed with this material are shown in Figure 15.19.

Most of the composite lumber products are used as substitutes for structural softwood lumber of large sizes and in applications where uniform strength is essential, such as for headers above double garage doors. I-beams, however, are finding wide application, with extensive use as floor joists and beams for various other structures.

There are several advantages of composite lumber as compared to sawn softwood dimension. First, these products allow production of large sizes of lumber (2 × 8 or 2 × 10) from small, low-grade logs. Normally, relatively large and high-grade sawlogs are needed for production of lumber of this size. Second, composite lumber compares favorably to solid sawn lumber in terms of both uniformity of quality and straightness. While the quality of lumber is determined to a great extent by the raw material, the quality of a reconstituted product is dependent upon the manufacturing process. Composite lumber products do have disadvantages, with higher costs relative to conventional lumber a significant factor today. It is likely, however, that use of composite lumber will increase in the future.

Haygreen/Bowyer (1989)

WOOD-CEMENT PRODUCTS. Mineral binders (mainly Portland cement) are used in several types of wood-based particle products. By far the most important of these is a porous low-density product produced from wood excelsior. In the United States this product is sold under several trade names and is used principally for acoustical ceiling panels in commercial and industrial buildings. In international trade this type of product is termed wood wool.

Wood wool board is about one-fourth to one-third wood by weight, the remainder being Portland cement or other mineral binder. The product is usually produced in densities from 20 to 25 lb/ft^3. It is well suited to developing countries of the world because it can be produced by very simple hand-forming methods, using the mineral binder that is locally available. Figure 15.20 shows a wood wool board and a prototype home with exterior walls of this product.

Species selection is extremely important in the production of wood wool. Many species contain wood sugars or other extractives that retard or inhibit the cure of the cement. This problem can be reduced by long-term storage of the wood bolts prior to shredding and by the addition of chemicals that accelerate the cure rate of the cement. However, it is necessary to carefully screen species being considered as raw materials to assess their curing problems. Seasonal variation in sugars should also be considered. The density of the wood is not critical except as it affects cutting on the excelsior machines.

Another type of cement-bonded product is manufactured in a manner more similar to conventional particleboard. It is produced in the density range of 60–75 lb/ft^3. Products of this type are being made in Europe and Asia, but none in North America. Wood makes up about 25% of these products by weight; thus the cost of the wood constitutes less than 10% of the cost of materials going into these boards.

Cement-bonded particleboard has excellent resistance to deterioration from decay, insects, and fire. Thus it is well suited for both interior and exterior wall surfaces and decking for public and commercial buildings. However, its high density and the difficulty of cutting and fastening it (compared to plywood) may be deterrents to its growth in North America.

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Fiber
395–419
HAYGREEN + BOWYER (1989)

Fiber products 16

WOOD FIBER PRODUCTS include paper, paperboard, hardboard, insulation board, and medium-density fiberboard. All these products are manufactured from wood that has been reduced to individual fibers, small fiber bundles, or fiber parts, which are subsequently formed into a mat.

Paper

In early times humans wrote messages on the walls of caves or clay tablets. The Egyptians, however, discovered that it was easier to write on the flattened stems of native papyrus plants (from which the word "paper" was derived). Other people developed writing parchment from split and dried animal skins. About 105 A.D. a Chinese scholar, T'sai Lun, became dissatisfied with the silk and bamboo writing materials then used in China. He experimented with bamboo and then the inner bark of mulberry trees. He pounded the material into pulp and added water. This was then formed into flat sheets and dried. It was the first real paper as we know it.

Although Lun's revolutionary new product was made from woody fiber, subsequent improvement in the manufacturing process involved replacement of wood raw material by linen rags. For almost a thousand years, rags were used as a source of papermaking fiber. Hundreds of substitute materials, the most notable of which was straw, were tried, but it was not until 1844 that wood gained importance as a fiber source. In that year a method of grinding wood to pulp was developed in Germany, and the process was soon adopted in the United States. Today, wood is clearly the dominant raw material for paper manufacture, with wood fiber providing 98+% of the fiber needs in the United States and 92+% of fiber used in paper worldwide (FAO 1982). Nonwood fibers in use include cereal and seed flax straws, bamboo, sugarcane bagasse, reeds, abaca, esparto and Sabai grasses, cotton linters, cuttings and rags, sisal, and kenaf.

Paper has assumed a position of almost incredible importance, especially in highly developed countries. It serves as a primary packaging product, communications medium, disposable products base, and industrial sheet material. In the United States the pulp and paper industry is the second largest consumer of wood, producing in 1983 a volume of paper and paperboard equivalent to 572 pounds for every man, woman, and child in the population.

THE MANUFACTURING PROCESS. In simple terms, the process of paper manufacture involves (1) reduction of wood to constituent fiber (pulp), (2) suspension of fibers in water, (3) beating or refining the pulp, (4) introduction of additives (fillers, sizing materials, wet-strength binders, etc.), (5) formation of a fiber mat, (6) drainage of water, and (7) drying of the sheet. For many types of paper, surface treatment may follow sheet preparation.

Pulp production. The primary difference among various paper manufacturing processes is the method used to accomplish the first step—pulping. Mechanical, chemical, or heat energy or combinations of these are employed in producing pulp. The forms of energy used determine to a large extent both yield and pulp properties.

Mechanical pulping. Two commonly used methods of producing mechanical pulp are the stone groundwood and the refiner groundwood processes. The grindstone is exactly that—a large abrasive stone that is rotated while the tangential surfaces of wood bolts are pressed against the surface (Fig. 16.1). As the abrasive surface travels rapidly across the wood, surface fibers are compressed, distorted, and loosened. At the same time, a high level of frictional heat serves to soften the lignin in the wood, helping to achieve separation of fibers from the wood mass. Groundwood pulp made from spruce is pictured in Figure 16.2; note the pieces of fiber and bundles of unseparated fiber in the mixture. A newer and more popular method of manufacturing mechanical pulp involves the use of a refining machine, called a double-disk refiner, composed of two fluted metal disks that can be closely spaced and rotated in opposite directions. A variation of this arrangement is to have one fixed disk and one that rotates; a machine configured in this way is called a single-disk refiner. In both types of refiners, wood chips are moved by a screw-feed mechanism into the center of the machine where they must pass between the two closely positioned disks; the resulting mechanical action reduces the chips to fiber (see Fig. 15.8). Pulp produced in this way is called refiner mechanical pulp, or RMP.

Because the separation of fiber is achieved by merely pulling apart or rending wood chips, little material is lost in the pulping process as long as the fibers are flexible enough to avoid shattering and production of fines. (Because of the fiber-shattering problem when pulping dense woods, species that are typically quite dense are not pulped by mechanical processes.) In mechanical separation, the proportion of wood raw material that becomes usable fiber is commonly on the order of 95–99%, a fact translating to relatively low-cost pulp. Unfortunately, high yield also results in low-

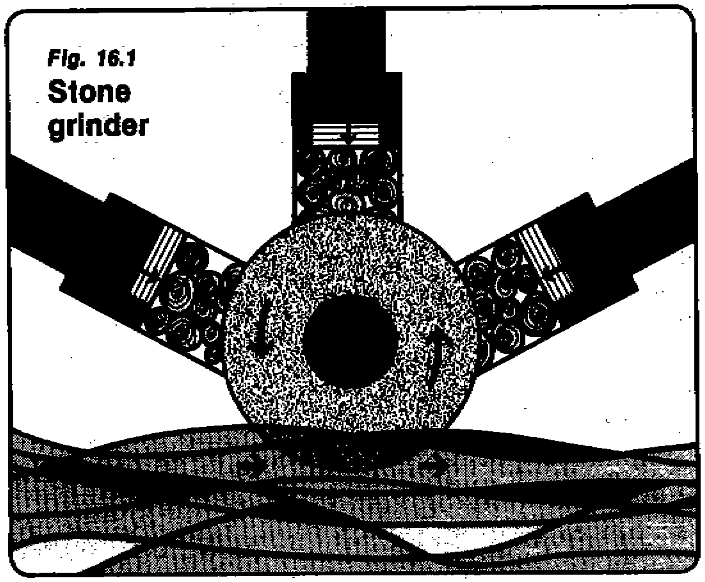
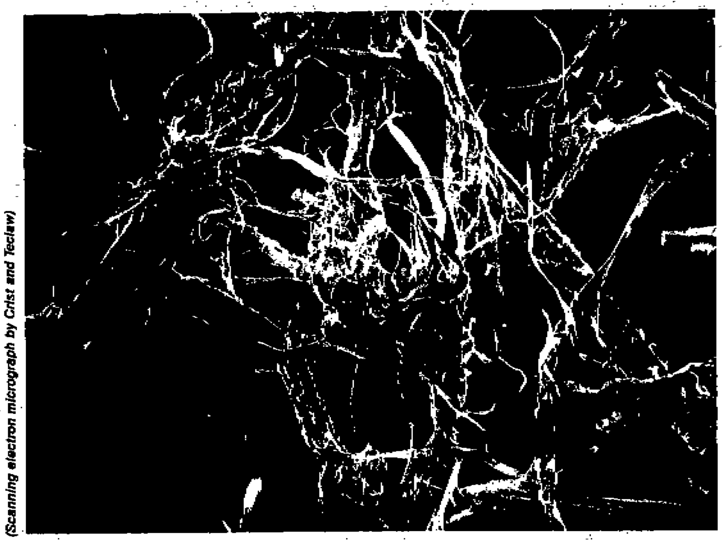


Fig. 16.1
Stone grinder



(Scanning electron micrograph by Crist and Teclaw)

Fig. 16.2
Unbeaten groundwood pulp
(Spruce) ×125

strength pulp unsuitable for many uses. As little is lost in separation, the cellulose, hemicellulose, and lignin that make up the wood are all part of the resulting pulp. The lignin, which serves to strengthen solid wood through stiffening of fibers, continues to give rigidity to the fibers of mechanical pulp. These rigid fibers have little fiber-to-fiber bond potential and form a coarse and bulky mat. The paper thus formed has low strength and relatively poor surface quality. The presence of lignin in mechanical pulp contributes to yet another problem, one related to long-term durability. Lignin and certain carbohydrates yellow with age, particularly when exposed to ultraviolet rays of sunlight; this is the reason for the yellowing commonly seen in old newspapers.

A variation of the mechanical pulping technique is the thermomechanical process. Here chips are subjected to steam as they pass through a refiner. Most commonly, thermomechanical pulping is done under pressure, with chips subjected to superheated steam at a temperature of 120–135°C as they move through the refiner. In some systems, however, steaming is done at atmospheric pressure. In both cases, the heat serves to soften lignin, allowing fiber separation with less fiber damage than that realized in manufacture of purely mechanical pulps. Both strength and absorbency are improved. Thermomechanical pulp is commonly referred to as TMP.

Chemical pulping. A technique used to achieve fiber separation, which at the same time removes troublesome lignin, involves the use of chemical and heat energy. Wood chips are placed in a chemical solution (called a cooking liquor) and heated in a pressurized vat (called a digester). Fiber separation occurs as cell-to-cell cementing lignin is dissolved.

Two different chemical pulping processes are used, and they differ in the types of chemical comprising the cooking liquor; these are the sulfite and sulfate processes. The sulfite process makes use of a mixture of sulfurous acid and ammonium, magnesium, calcium, or sodium bisulfites. The sulfurous acid (H_2SO_3) reacts with lignin to form lignosulfonic acid. This relatively insoluble compound is, in turn, reduced to soluble lignosulfonic salts in the presence of the basic bisulfites. Established in 1874–75, the sulfite process was found to yield high-quality pulp of the type desired for fine writing papers. The calcium-based bisulfite came to be the most commonly used companion to sulfurous acid. The calcium compound was cheap and worked quite well in pulping of long-fibered species such as spruce, hemlock, and true fir. There were, however, several problems associated with the use of the calcium bisulfite–based process. The most serious was that recovery of cooking chemicals and process heat was technically difficult and economically unfavorable. The result was that sulfite mills constantly had a used cooking liquor disposal problem (in a volume approximating 1500 gal/ton of pulp produced), which all too often was resolved by dumping the residue in a nearby waterway. Another problem was that the process did not work well in the pulping of highly resinous softwoods such as pine. Therefore, growth of the calcium bisulfite–sulfurous acid system ceased about 1940 and new sulfite installations were designed to use ammonium or magnesium bisulfites. Subsequent development of chemical recovery technology made it possible to achieve complete

chemical recovery of magnesium-based cooking liquors through a relatively simple process. Nonetheless, since the early 1960s there has been only limited expansion of all forms of sulfite pulp mill capacity, while use of the sulfate process has grown rapidly (Table 16.1).

Table 16.1. Estimated annual wood pulp production in the United States (thousands of short tons)

	Chemical pulping													
Year	Sulfite	% of total	Kraft	% of total	Soda	% of total	Semi-chemical pulping	% of total	Mechanical pulping	% of total	Total pulp from raw wood	Recycled paper	% of raw wood total
1983	2877	5.5	40,742	77.5	...	0.0	3851	7.3	5067	9.7	52,537	18,567	35.3
1977	3507	7.1	34,862	70.2	...	0.0	3876	7.8	7417	14.9	49,662	14,015	28.2
1970	4024	9.4	28,670	67.3	218	0.5	3297	7.7	6379	15.0	42,588	11,803	27.7
1960	3711	14.8	14,516	57.9	420	1.7	1970	7.9	4469	17.9	25,086	9,032	36.0
1950	2848	19.4	7,501	51.0	522	3.5	686	4.7	3151	21.4	14,708	7,956	54.1
1940	2608	29.3	3,748	42.1	532	6.0	165	1.9	1843	20.7	8,896	4,668	52.5
1930	2517	*	950	*	474	*	...	*	*	*	*	*	*

Source: Libby (1962), Evans (1978), Lowe (1978), Haas et al. (1979), American Paper Institute (1984).
*Figure not available.

The sulfate process is said to date back to 1884, a year in which a German patent was awarded for development of a new high pH (or alkaline) chemical pulping technique. The process is based upon use of a cooking liquor made primarily of sodium hydroxide and sodium sulfide. In the pulping process the sodium hydroxide attacks lignin, breaking it down to phenylpropane units that then go into solution. The sodium sulfide, when exposed to water, breaks down to sodium hydroxide (increasing the amount of that compound available for pulping) and sodium hydrosulfide (NaSH), which serves to increase the solubility of lignin.

An examination of reactive chemicals raises the question of why the sulfate process is so named. The answer is traceable to the discovery that when spent, black, lignin-rich cooking liquor is heated in a furnace in the presence of Na_2SO_4, the original pulping chemicals (sodium hydroxide and sodium sulfide) are almost completely recovered.

An interesting part of the history of the sulfate process is the explanation of how this technique was modified to become known as the kraft process. Historical records tell that in the course of operating a Swedish mill, a digester full of partially cooked pulp was accidentally blown (or dumped). The material was about to be thrown away when the mill manager decided to use it in making some low-quality paper; the surprising result was that the paper produced was far stronger than any previously made. The Swedish (and German) word kraft, meaning strong, soon became an alternate name for the technique.

The recoverability of cooking liquors (as well as process heat) means that the sulfate process is comparatively free of residue disposal problems. This process, furthermore, is effective in pulping any species, including those that are highly resinous. These factors, when added to the result that high-strength pulp is produced, explain the overwhelming popularity of the kraft or sulfate process. One negative aspect is a characteristic rotten cabbage smell caused by volatile reduced sulfur compounds. Costs of eliminating this smell are high. Because the human olfactory system can detect even minute concentrations, virtually 100% of the sulfur compounds must be removed from stack gases to completely solve the odor problem.

Because no mechanical action is needed to achieve cell separation, chemically produced pulp is composed of smooth and largely undamaged fibers (compare Figs. 16.2, 16.3A). Moreover, since a high proportion of the lignin is removed in the process, thus eliminating an important component of age-induced yellowing in bleached finished paper, pulp quality is high. The penalty paid for high quality is low yield (and therefore high pulp cost). The yield (expressed as the dry weight equivalent of usable fiber divided by the dry weight of chips placed in the digester) ranges from 44 to 55% for both sulfite and sulfate processes, which is lower than the lignin content might indicate. The reason for these very low yields is that the conditions that solubilize lignin also degrade both cellulose and the low-molecular weight hemicelluloses.

Semichemical pulping. Wood can also be pulped in a way that combines the high-yield advantages of mechanical processing and some of the high-quality features of chemical processing. Using techniques known as semichemical or chemimechanical pulping, wood chips are given short-term exposure to a chemical pulping liquor and then passed through a mechanical refiner to separate constituent fibers. The cooking liquor causes partial degradation of the ligneous bonds and serves basically the same function as heat in the thermomechanical process. Mechanical energy needed for fiber separation is greatly reduced and damage to fibers is decreased. The chemimechanical process permits pulping of hardwoods that are too dense to be suitably pulped by strictly mechanical means. The most widely used process in this category is the Neutral Sulfite Semi-Chemical Process (NSSC). In this case, sodium sulfite, buffered with sodium carbonate, is used in pretreating chips. Semichemical pulp yields of 65–75% are common and may occasionally be higher.

Biological pulping. A new method of pulping, which involves treatment of wood with lignin-degrading microorganisms, is currently in the early stages of investigation. Successful development of this concept would greatly reduce the energy required in pulping and decrease environmental impacts associated with pulping processes. Current efforts are focusing upon ways to accelerate the lignin-degrading process.

Fiber recycling. In North America, some 20–25% of all paper products are recovered for reuse. In Japan, by comparison, the paper reuse rate is about 45%; the highly concentrated Japanese population makes collection of paper for recycling more economical than in most other parts of the world.

The majority of recycled paper used in the United States goes into the manufacture of corrugating medium, the paper used in the inner plies of corrugated boxes. Other uses are in newsprint and other printing grades and in structural wood fiber products.

The recycling firm faces several significant problems in the production of secondary fiber, including removal of contaminants from recovered fiber (adhesives, plastics, waxes, latex, asphalt, etc.) and elimination of inks from fiber to be used in making printing papers. In addition, there is a limit to the number of times that material can be recycled. It is generally considered that 50% represents a practical maximum recycling rate. As explained by Smook (1982), "Significant losses of fiber substance occur during each recycling step . . . and at the 50 percent recycle level, it is apparent that half of the material being recycled has already been through at least one previous recycling process."

Washing and bleaching. It is necessary to clean pulp after it is formed to remove cooking liquor and/or impurities. After chemical pulping, the wood fiber–cooking liquor mixture is released from the digester into what is known as a blow pit. Here fiber is collected and initially separated from spent cooking liquor and the gases that may have been produced. Fiber is next cleaned in a multistage washing process to remove any residual liquor.

Untreated, wood pulp is brown to tan in color, due mainly to the presence of lignin or extractives from heartwood. Thus when manufacturing writing or book papers or other products where whiteness is important, fiber must be bleached. This is usually done by exposure to strong chlorine-based compounds. Oxygen-bleaching techniques have also been developed. Bleaching attacks residual lignin and can be carried to the point where lignin is either totally removed (as with the highest quality writing and printing papers) or simply lightened in color (as in the manufacture of newspaper or catalog quality stock). The latter degree of treatment is least expensive, having little effect upon yield, but it results in only temporary whiteness. Bleaching to achieve removal of essentially all lignin gives virtually permanent whiteness, but it is expensive. In this case, water use is high and pulp yield is significantly reduced.

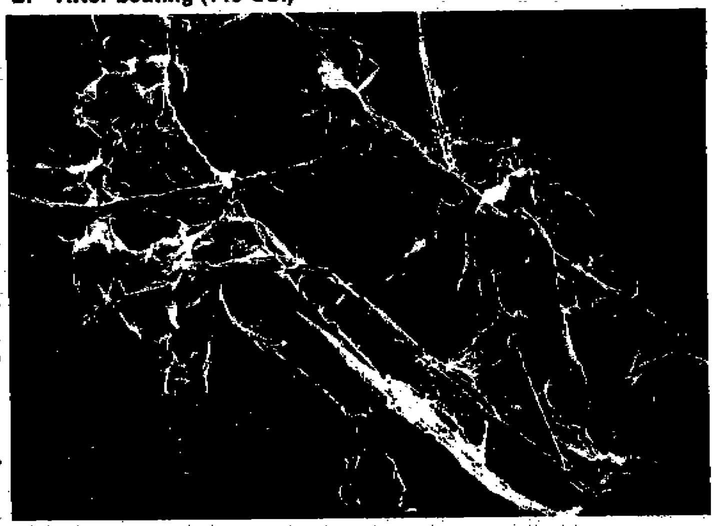
Beating and refining. Much of the strength of paper results from hydrogen bonding of cellulose molecules that make up adjacent fibers. To provide the maximum potential for bonding, fibers are pounded or ground to flatten them and to partially unravel microfibrils from the cell walls; the surface area of fibers (and thus the area available for bonding) is greatly increased by even a small degree of such flattening and unraveling (Fig. 16.3).

The mechanical flattening and unraveling of fibers is called beating and is accomplished in various types of refining machines. Disk refiners are commonly used for this purpose (see discussion under mechanical pulping). Another common type of machine is the conical refiner (known as a Jordan or Clafin refiner). In this type of machine (Fig. 16.4) a conically shaped, longitudinally fluted plug rotates inside a similarly shaped and ribbed housing. The location of the plug inside the housing controls the spacing between the flutes and ribs; when the space is small, fibers are subjected to a mechanical rubbing action as they pass through the conical refiner.

Because fiber-to-fiber bonding has a great deal to do with paper properties, it is desirable to have a quantitative measure of the bond potential of a pulp. In North America, bond potential is usually expressed in terms of Canadian Standard freeness (CSf). This is measured by suspending a given

A. Before beating (745 CSf)

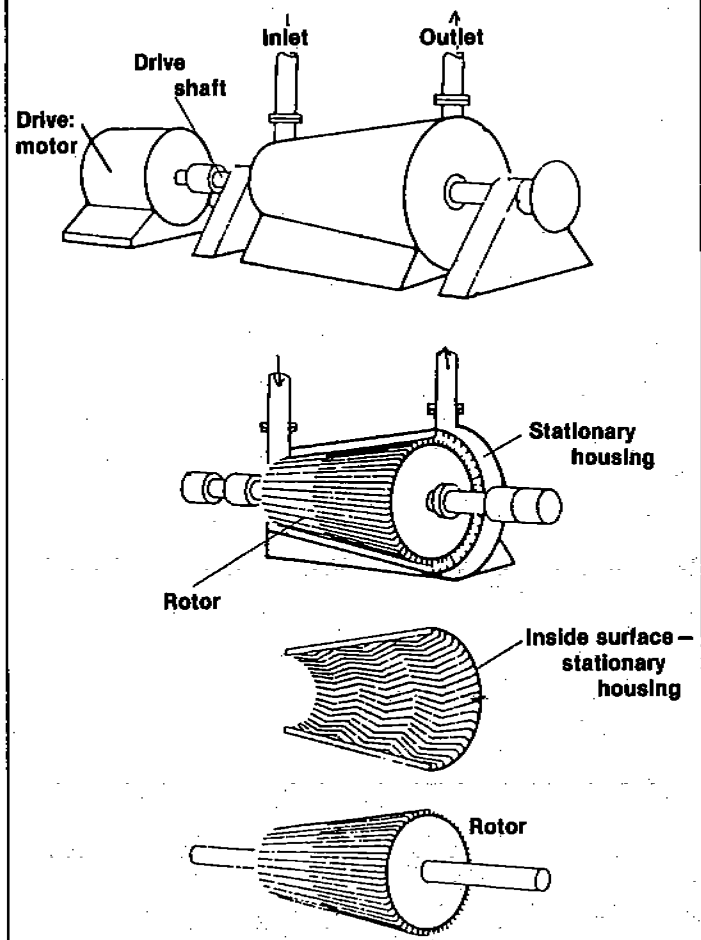
B. After beating (145 CSf)



(Scanning electron micrographs by Crist and Taclaw – x125)

Fig. 16.3
Beating flattens and partially unravels fiber walls (chemically pulped southern yellow pine).

Fig. 16.4
Jordan refiner



From Smook (1982)

amount of fiber in water and then determining the rate at which water drains through a wire onto which the fiber has been allowed to settle. Since the rate of drainage is inversely related to surface area of fiber and surface area is directly related to the amount of beating or refining, a mat of well-beaten fiber is quite resistant to drainage of water. The freeness of well-beaten fiber is thus low.

The relationship between beating time, freeness, and various strength properties is illustrated in Figure 16.5. Note that freeness is in all cases decreased by extended beating. Burst and tensile strengths tend to be higher the longer the beating time. As will be explained in more detail later, burst

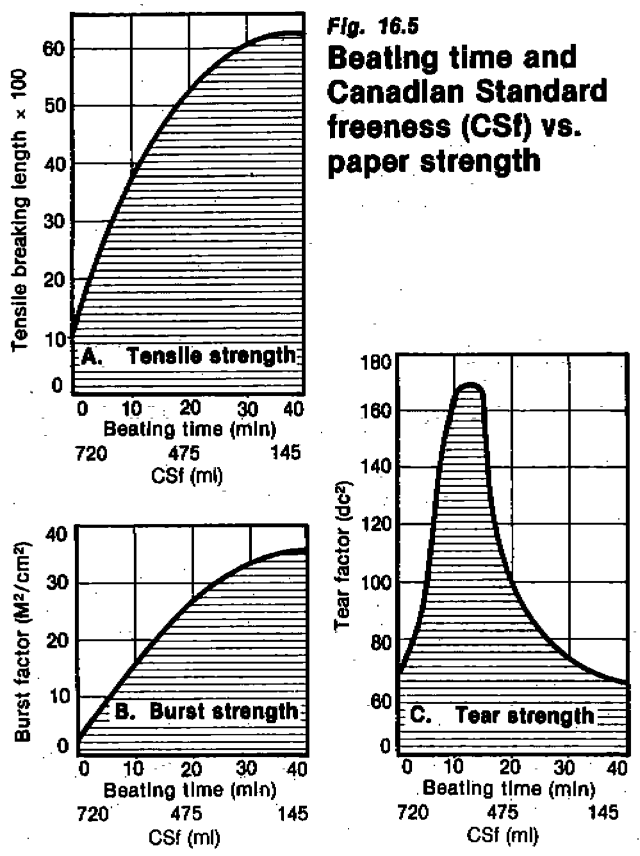


Fig. 16.5
Beating time and Canadian Standard freeness (CSf) vs. paper strength

and tensile properties are closely related to interfiber bonding and are thus directly affected by any treatment (such as beating) that increases bond potential (Fig. 16.5A,B). Figure 16.5C shows that tear strength is significantly increased as beating is begun but is reduced rapidly thereafter. The explanation for this is that tear is somewhat influenced by interfiber bonding but is much more influenced by integrity of individual fibers. With the first few minutes of beating, flattening of cells and some unraveling of microfibrils occur, which greatly increases surface area while causing little reduction in either length or strength of fibers; the increased surface area resulting from further beating is offset by the damaging effect upon individual fibers.

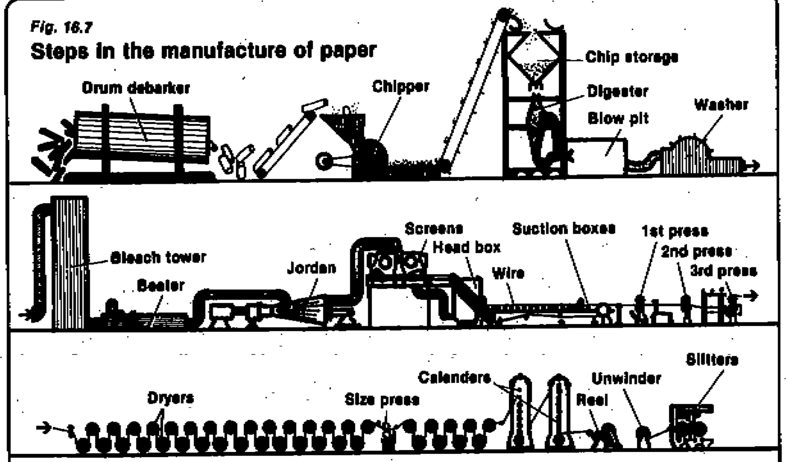
Sheet formation. Following beating, and in some cases secondary refining, fiber is mixed with water to a consistency of about 1% fiber by weight. It is quite common to mix different types of pulp (i.e., mechanical and chemical) at this stage, with the proportion of each dependent upon the kind of paper to be manufactured. Additives such as starch (for increased bond strength) or wet-strength resin are often added to the mixture at this point as well, as are clays (for brightness and opacity) and rosin size (for decreased liquid absorption). This mixture is then formed into a thin mat. The most commonly used machine to form the fiber mat is called a Fourdrinier (Fig. 16.6). It is basically a rapidly moving horizontal screen fitted with a device called a head box that accurately meters a pulp mixture onto the screen. Other types of paper machines form a paper mat on rotating wire cylinders. As pulp flows onto the screen, water drains away with the

Fig. 16.6
Fourdrinier paper machine

sy Blandin Paper Co.)

aid of suction boxes or other drainage-enhancing devices mounted under the wire, leaving a mat of fibers. The mat is then wet pressed, passed over a series of steam-heated drums, pressed again to desired thickness, and wound into large rolls. Application of coatings, sheet polishing operations (known as calendering), winding of the sheet onto a reel, and slitting of large rolls into smaller sheets are operations that might follow. The entire process is summarized in Figure 16.7.

Fig. 16.7
Steps in the manufacture of paper



PAPER COMPOSITION. Certain types of paper are almost invariably associated with specific types of pulps. Brown wrapping paper and grocery bags, for example, are almost always made from high-strength unbleached sulfate pulp, whereas gift wrap, including hard tissue paper, is typically produced from fine sulfite pulp. Though other examples of this kind can be given, most paper products are made from a blend of pulps. Wallpaper, for instance, is often made using a blend of sulfite, sulfate, and mechanical pulps in order to incorporate the advantages of tear strength (sulfate), printability (sulfite), and low cost (mechanical) into the product. Similarly, low-cost newsprint, which is made primarily from mechanical pulp, often contains a certain amount of sulfite pulp to improve sheet quality.

Blending of bleached hardwood sulfate pulp with that from softwoods is common when making most types of printable papers for periodicals, catalogs, and containers. The hardwood pulp provides a smooth, opaque paper, while the softwood fibers add strength. Mixtures of pulp containing from 50 to 80% hardwoods are commonly used for such products.

PAPER PROPERTIES

Common measures of quality. There are many ways to define paper quality. When making grocery bags, for instance, strength is quite important. As with solid wood, there are many measures of strength. A bag to be filled with heavy bottles or canned goods, which might be picked up by the sides, must have a high tensile strength. Similarly, a bag that may contain an exceptionally heavy item such as a large soft drink bottle should be able to resist this kind of concentrated load (measured by burst strength). High resistance to tear is another property obviously needed in an all-purpose bag. Moreover, the bag should retain its strength when wet.

If a book paper is being manufactured, tear strength is obviously critical. But other factors are quite significant as well. The sheet must accept ink but must have low absorbency to prevent ink diffusion and development of fuzziness around printed characters. High opacity is also necessary so that printing does not show through the other side. Other important properties might be brightness, permanent whiteness, and surface smoothness. If the paper is to be used in making a product like restaurant menus rather than books, all the properties outlined above would be needed as well as another property—folding endurance.

Paper used for toweling should have an entirely different set of properties. Strength, particularly wet strength, is important in a towel, and such paper should also be highly absorbent. And so it goes. For each of the thousands of paper products a similar list of properties might be enumerated. The point is that there are many kinds of paper, each with individual and often quite different requirements. Various measures of quality have been developed to permit evaluation of the suitability of different pulps for manufacture of these various kinds of paper.

Paper properties and fiber characteristics. Knowledge of only one characteristic of wood, i.e., density, allows prediction of the yield of pulp per unit volume of wood as well as a number of paper properties. Density is directly related to cell wall thickness. The general rule is that the lower the density and thus the lower the proportion of thick-walled latewood cells, the better the wood as a papermaking raw material. It should be noted that this rule does not hold if high tear strength is desired.

Thick-walled fibers result in paper with low burst and tensile strengths but a high degree of resistance to tear. Paper made primarily of thick-walled cells also tends to have very low folding endurance. The relationship of burst and tensile strengths to cell wall thickness is explained by the fact that these properties are very dependent upon a high degree of fiber-to-fiber bonding, which is affected by cell wall thickness. These facts might lead to the conclusion that thick-walled fibers are difficult to beat to a low freeness level as compared to thin-walled fibers. Actually the reverse has been found (Ellwood et al. 1965). The primary reason for low apparent bond potential of thick fibers is that paper is manufactured on a weight basis, meaning that the number of fibers in a sheet is inversely related to the density of fiber walls. Second, thick-walled fibers have less surface area per unit weight than thinner walled fibers. These two factors translate very simply to lessened opportunities for interfiber bonding. Tear strength, like burst and tensile strengths, is influenced by the extent of interfiber bonding. More important, however, is the effect that individual fiber strength has upon tear resistance. Thick-walled fibers are obviously stronger than those having thin walls.

A second characteristic of wood that has an effect upon paper properties is fiber length. Tear strength is the property most affected and the relationship is direct (i.e., the greater the fiber length the higher the tear resistance) up to a length of 4–5 mm. Some reference can be found in the literature to direct relationships between fiber length and other important strength factors such as burst and tensile. Other investigators, however, discount fiber length as a significant influence on these properties.

In a study of the effect of chemical constituents on papermaking potential, Ellwood et al. (1965) found cell wall thickness to be closely correlated with chemical composition of the wall, making it difficult to separate chemical and other structural effects. It was nonetheless found that thick-walled cells that provided high tear strength were composed of a high proportion of cellulose and were correspondingly low in hemicellulose and lignin. Burst and tear strengths were thus highly correlated to a high proportion of hemicellulose. High levels of hemicellulose are evidently related to rapid hydration of pulp, formation of more and better interfiber bonds, and development of dense mats.

The proportion of various cell types making up a wood can affect the quality and quantity of pulp. This is particularly true of hardwoods and the portion of their volume accounted for by vessels. Because of their shape, vessels do not bond readily to fibers, thereby contributing little to strength (Dadswell and Watson 1962). Vessels may separate from the surface of the finished sheet in subsequent printing (Allchin 1960). Vessels are also more likely to break up during processing, and therefore woods containing a high proportion of these cells are likely to give lower pulp yields than those with a higher fiber content.

IMPORTANT TYPES OF PAPER

Linerboard. This is a relatively lightweight board typically produced from unbleached kraft fiber to be used as the outer surface on corrugated containers. The production of linerboard in the Unites States is very large, exceeding even newsprint in tonnage. Linerboard generally is made from softwood fiber and is produced on a Fourdrinier machine. Its most important properties are stiffness and burst resistance, although some degree of printability is also desired on the outer surface. This latter property may be enhanced by forming a small amount of highly refined fiber on top of the base of coarser high-yield fiber.

Corrugating medium. This lightweight paperboard is used for the fluted inner plies of corrugated boxes. Linerboard is glued to both sides of corrugating medium to produce what the public calls "cardboard." Since corrugating medium provides much of the rigidity to corrugated containers, it must have both good stiffness properties and good resistance to crushing. Some is produced from 100% recycled fiber, but most is produced from a mixture of semichemical and recycled pulp. Since this paper does not require high tensile and tear strength the use of long-fibered softwood pulp is not necessary.

Newsprint. The primary requirement of newsprint is that it can be run through modern high-speed printing presses and provide a reasonably good printing surface. It must also be low in cost. Newsprint is generally produced from a mixture of mechanical and chemical pulp. Few additives of the type added to enhance the printing properties of fine or magazine papers are added to newsprint. In order to develop adequate strength for printing at high speeds, some unbleached sulfite or bleached kraft is usually added to the groundwood pulp. Since mechanical pulp is cheaper to produce than chemical pulp, only enough chemical pulp to meet the print speed requirements is used.

Publication grades. Papers for high-quality printing purposes must be coated in the papermaking process to improve the gloss, slickness, detail, and brilliance that can be obtained in printing. The addition of fillers and coatings at various stages in the process can greatly alter the properties of the paper. Coatings can make up over 30% of total sheet weight in some lightweight grades. There is a trend to lighter weight printing papers because of increasing postage rates. A higher proportion of chemical pulp is usually required as paper weight is reduced. TMP pulp and groundwood pulp are used in these papers, as are bleached kraft pulp from both hardwoods and softwoods.

Fine paper. This classification is for white, uncoated printing and writing paper containing only a small amount of mechanical pulp. Sulphite and highly refined bleached kraft pulp may be used in those cases where wood furnish is incorporated. Nonwood fibers are also used.

Tissue. This category of paper covers a wide variety of facial and bathroom tissues, paper napkins, and toweling. Because these are lightweight papers that must have a loose structure, they cannot be produced on conventional paper machines. One of the keys to success in this business is to have an effective proprietary system of producing a low-density sheet. These products generally require a high-quality furnish with long, lightly refined fiber, since softness is a function of fiber properties and bulk.

Paperboard. This category of thick paper includes linerboard, described above. However, there are a number of other important types of paperboard that usually have a multi-ply construction. Folding boxboard is made from virgin pulp in the outer ply and from secondary fiber for the inner plies. Foodboard, utilizing 100% bleached virgin pulp, is used for food packaging. The paper for the outer layer of gypsum board, i.e., sheetrock, is a paperboard usually made from 100% secondary fiber.

Kraft sack paper. This paper is produced from unbleached softwood kraft pulp. Tear strength and tensile energy absorption are two of the most important properties. Sizing is often added to the well-refined fibers in the papermaking process to provide additional internal and wet strength.

MEASUREMENT AND SOURCES OF RAW MATERIAL. In the United States, about half the wood used for the manufacture of paper is in the form of small-diameter bolts (Fig. 16.8). Because of the large volume of pulpwood handled at a mill and irregular shapes of individual pieces, pulpwood is measured by calculating the volume of large stacks of roundwood or by determining weight.

(Courtesy S. Sinclair)

Fig. 16.8
A load of pulpwood begins the trip to the paper mill.

A standard unit of measure for pulpwood in the United States is the cord, which is defined in Chapter 13. It is important to remember that a cord does not contain 128 ft³ of wood but 128 ft³ of space. A cord of 7- to 10-in. (18–25 cm) diameter, 4-ft (1.2 m) length, and undebarked bolts contains, for example, only about 80 ft³ (2.3 m³) of wood and another 10 ft³ (0.3 m³) or so of bark. A greater amount of wood is contained in cords composed of larger diameter and—or shorter bolts.

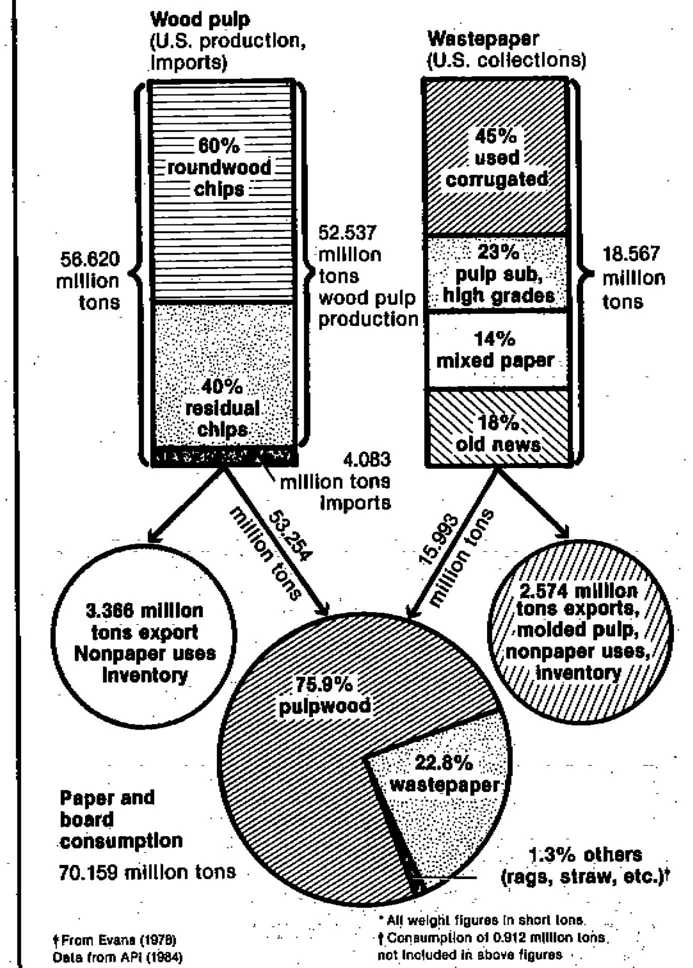
In addition to being bought and sold by the cord, pulpwood is also purchased by weight. Payment for this wood is made either directly by weight ($/ton), or weight is converted to cords, with payment then made on a cord basis. Elsewhere in the world, pulpwood volume is commonly expressed in cubic meters.

Almost one-third of the raw material used annually for pulp manufacture in the United States is in the form of wood chips produced as byproducts in sawmills, plywood mills, and other wood products operations. Pulp chips are often purchased on a weight basis (by the green or dry ton), volume basis (by the 200 ft³ unit), or combination weight/volume basis (by converting weight measurement to cords).

In 1983 the equivalent of some 71 million short tons of wood pulp were produced in the United States for use in making a variety of paper and

paperboard products. About 31.5 million tons were obtained from roundwood, while some 20 million tons were produced from wood in chip form. The remaining 18.6 million tons, or over 26% of production, were obtained from wastepaper (Fig. 16.9).

Fig. 16.9
Sources and uses of fiber for pulp, paper, and paperboard, 1983*



Approximately two-thirds of the nonrecycled pulpwood produced annually in the United States comes from the Southeast. The rest comes from the West (about one-fifth) and the North and Northeast (approximately one-sixth).

Though the fiber used in making paper is overwhelmingly wood fiber, it is important to realize that a considerable quantity of nonwood resources are used in the manufacturing process. Both the quantity of sheet additives (such as clay and rosin) and process ingredients (such as sulfur and salt cake) can be substantial. Saltman (1978) cites a list from Nekoosa Papers, Inc., of ingredients needed in making 1 ton of a particular grade of their paper:

Water	55,000 gal	Salt cake	80 lb	Coal	1.2 ton
Sulfur	102 lb	Caustic	66 lb	Alum	61 lb
Magnesium hydroxide	94 lb	Starch	108 lb	Clay	289 lb
Lime	350 lb	Wood	2 cords	Rosin	16 lb
		Power	112 kWh	Dye and pigment	20 lb

Hardboard

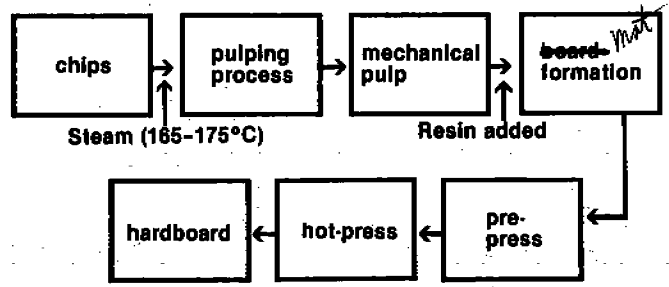
Hardboard is a medium- to high-density wood fiber product that is most commonly manufactured to a specific gravity near 1.0. The product is made in the form of flat sheets ranging from 1/16 to 1/2 in. (0.16–1.27 cm) in thickness and can also be molded to a variety of shapes. It is reported that hardboard was developed accidentally in 1924 by a William H. Mason, who had developed a quick explosion process for transforming chips to pulp and was attempting to make a low-density insulation-type product from it. Having placed a wet fiber mat in a steam-heated press for the purpose of drying the fiber, Mason left his laboratory to eat lunch. When he returned, he found that a small steam valve had failed, causing high and prolonged pressure on the fiber mat, resulting in a hard, dense panel. The product, dubbed pressed wood by its discoverer, soon came to be known as hardboard. The invention led to immediate formation of the Mason Fiber Company, a name later changed to Masonite Corporation. The name Masonite is still sometimes used interchangeably with the term hardboard. Today, the hardboard industry is sizable, with approximately 2 billion ft² of hardboard produced annually in the United States.

MANUFACTURING. An important distinction between hardboard and other fiber products is that in hardboard, lignin plays a role in fiber-to-fiber bonding. Ligneous bonding is the primary force holding the finished product together. Because of this, the only kind of pulp suitable for making hardboard is the mechanically produced variety (made by the thermomechanical process or a variation involving presteaming of chips) in which the lignin of wood is retained.

The basic procedure employed in commercial hardboard manufacture

is shown in Figure 16.10. Note that resin and wax are added during drying or just after the pulping process. Water-compatible resins such as phenol formaldehyde are normally used, with the concentration generally on the order of 1–2% of dry board weight. These small amounts improve board strength, and the resin as well as the wax increases water resistance.

Fig. 16.10
Basic steps in hardboard manufacturing



HAYGREEN + BOWYER (1989)

Following production of pulp, fibers are formed into a mat and prepressed. This step can be accomplished using either water or air as a forming medium. The difference in these techniques, known as the wet and the dry processes, is explained below. The manufacturing sequence is concluded with a hot-press operation in which high temperature (190–235°C) and pressure (500–1500 psi) are employed to bring the lignin to a thermoplastic condition and densify the fiber mat.

Wet process. As the name suggests, the wet process of mat formation makes use of water. In this technique, pulp is mixed with water much as when making paper and this water-fiber mixture is then metered onto a wire screen. Water is drained away with the aid of suction applied to the underside of the wire, and the fiber mat along with the supporting wire is moved to a prepress where excess water is squeezed out. The prepress operation is an important part of the wet process, since the subsequent step involves pressing at high temperatures; unnecessary vaporization of water and resulting waste of heat would result from omission of this step. Following prepressing, the compressed mat is moved into the hot-press along with the wire screen on which it was formed. High levels of pressure and heat serve to re-form ligneous bonds, squeeze out additional water, and dry the mat. The screen is retained in the hot-pressing operation to allow escape of water vapor.

Wet-process hardboard is typified by evenly distributed density (because water is an efficient forming medium) and one rough side (caused by the screen used in the hot-press).

Dry process. Dry-process hardboard is made using air rather than water as a forming medium. Following production of pulp, the fiber is dried and introduced into a forming device in which is created a "snowstorm" of the dry fluffy fiber. The fiber blanket formed in this way is quite thick (perhaps 4–5 in. for what will eventually be a ¼-in. panel), so a press roll is placed downstream of the former to compress the loosely piled fibers. Hot-pressing completes the sequence. Since fiber is dry when it enters the hot-press, no screen is needed beneath the mat; thus the panels are smooth on both sides (S-2-S).

Dry-process hardboard tends to have less evenly distributed density than the wet-process variety, and strength is often slightly lower if similar amounts of resin are used; therefore more resin (about 2% resin solids based on dry weight) is normally used in making dry-process panels.

Tempering. Hardboard is sensitive to moisture, particularly liquid moisture; therefore, unless specially treated, it is intended as an interior product. Moisture can cause linear expansion of panels, thickness swelling, and formation of surface blisters. Hardboard intended for exterior use is thus treated by one of several processes to meet commercial standards for reduced sensitivity to moisture. The resulting product is known as tempered hardboard.

Traditionally, tempering was achieved by soaking finished panels in various oils, followed by baking at high temperature to flash off the volatile fractions. The result was greatly improved water resistance, increased abrasion resistance, improved hardness, and better overall strength. Another process for tempering involves high-temperature treatment without a preliminary oil soak; the purpose of exposure to heat, which may be as great as 200°C, is to increase cross-linking between cellulose and other polymers. Performance under wet conditions can also be improved by simply using more resin in board manufacture. The latter mentioned methods for tempering have become more popular in recent years because air pollution problems associated with baking of oil-soaked panels are avoided.

APPLICATIONS. Hardboard is used in furniture in the form of flat panels for television and radio cabinet backing, drawer bottoms, dust stops, sliding doors, general purpose backing, and table tops (Fig. 16.11). It is also commonly used for wall paneling, cabinet doors and tops, interior door faces, garage door panels, and store fixture components. Unfinished panels are perforated with holes and used as pegboard for decoration of workshop, laundry room, and garage walls. Smooth-faced hardboard sheets are also often painted or covered with vinyl or other material for use as exterior siding or as decorative paneling for interior use. Appearance grade panels can be made with contoured or sculptured surfaces by using sculptured platens (or dies) in the hot-press. This technique allows lifelike reproduction of rough-sawn surfaces, simulated brick, or other textures. Another family of hardboard products is based upon the fact that finished panels can be steamed and molded to various shapes (Fig. 16.12). Molded hardboard products are particularly evident in the auto industry, where they are

Fig. 16.11
Hardboard panels have a variety of uses.

Fig. 16.12
Hardboard can be molded to different shapes.

used as door and roof panels, back window decks, dashboards, and occasionally even heating system ductwork.

Insulation board

A group of fiber panel products is manufactured to specific gravities ranging from about 0.25 to 0.45. These range from low-density acoustical ceiling tile (Fig. 16.13) to relatively high-density structural insulation board that is used under siding in frame construction (Fig. 16.14). The structural insulation product provides added insulation to a wall construction, eliminates the need for corner bracing in the frame wall, and serves to reduce noise transmission through exterior walls.

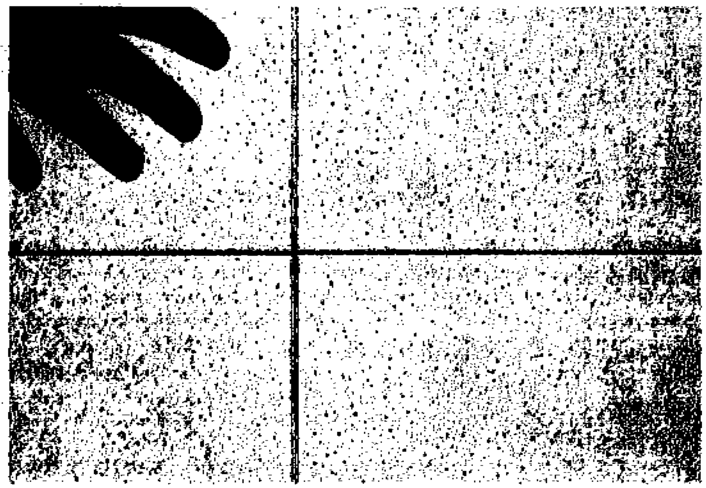


Fig. 16.13
Acoustical ceiling tile is commonly made of wood fiber.

MANUFACTURING PROCESS. The process used to produce insulation board is quite similar to that employed in making hardboard but with one important difference. As with hardboard, the insulation board sequence involves thermomechanical pulping of chips, subsequent refining of fiber, and board formation (normally using water as a forming medium). The difference is in the pressing and drying of the mat. A hot-press is not used in making insulation board. Instead, the mat is simply brought to desired thickness using a press roll and then dried. The omission of hot-pressing

Fig. 16.14
Structural insulation board is applied prior to siding.

means that ligneous bonding is not achieved in insulation board. Fiber-to-fiber linkages are provided primarily by hydrogen bonding, although additives such as starch or asphalt are often used for bond enhancement.

Medium-density fiberboard

A new type of wood panel developed in the 1960s is similar to both hardboard and particleboard yet distinctly different from either. The new product, which is manufactured to a density of 31–50 lb/ft^3 (500–800 kg/m^3), is known as medium-density fiberboard (MDF). Like hardboard, MDF is made from wood that has been reduced to individual fibers and fiber bundles. Bonding of fiber in the finished product is, however, achieved through the use of synthetic resin or other synthetic binder rather than through redevelopment of ligneous bonds; in this respect MDF resembles particleboard.

The most significant use of MDF is in furniture manufacture, where it is used in much the same way as particleboard is. Particleboard is generally preferred where square-edged panels are needed because it is less expensive. However, use of particleboard where edge-profiling of panels is required, such as in table tops, requires special and expensive treatment. The edges are too porous to be shaped and finished directly and are thus commonly edge-banded with solid wood (Fig. 16.15). MDF, on the other hand, has a more uniform density and smooth, tight edges that can be machined almost like solid wood, eliminating the need for edge-banding. MDF can also be

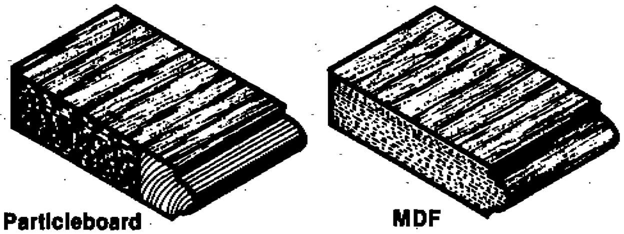


Fig. 16.15
In contrast to particleboard, MDF requires no edge-banding prior to shaping

finished to a smooth surface and grain-printed, thus eliminating the need for surface veneers or laminates. For these reasons there is a well-defined market for MDF furniture panels.

MANUFACTURING PROCESS. The first steps in making MDF are very similar to those employed in manufacturing hardboard. Logs are reduced to chips, with these then subjected to a thermomechanical pulping. The process thereafter closely resembles that used in making particleboard (see Chapter 15). Fiber is dried, blended with resin and occasionally wax, and formed into a mat that is subsequently pressed to desired thickness and density. Like particleboard, resin solids compose 6–7 of the dry weight of the product.

REVIEW

A. Terms to define or explain:

1. RMP	9. Jordan refiner
2. TMP	10. Fourdrinier
3. NSSC process	11. Opacity
4. Cooking liquor	12. Tempering
5. Digester	13. Insulation board
6. Pulp	14. MDF
7. Blow pit	15. Linerboard
8. Beating	

B. Questions or concepts to explain:
1. What are the primary processes used to produce pulp? What kinds of pulp yields are realized when these various processes are employed?
2. Mechanical pulp is used in making certain kinds of paper and paperboard. Why is it a favored material for production of newsprint? Why is mechanical pulp avoided when making high-quality papers?
3. What are the two chemical pulping processes most commonly used? What are the advantages and disadvantages of each? Which process is also known as the kraft process?
4. What is the meaning of the term "freeness"? How is freeness related to properties of paper?
5. How is hardboard made? What is the difference between wet and dry process hardboard and what are the advantages of each?

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grade timber on its lands to heat and power.

Wood for energy is also interesting to nonforest industries and to those who generate commercial power, although the extent to which wood will be used for these purposes in the next decade will probably not be large. In looking further to the future, wood has potential as the raw material for production of many industrial chemicals. Here again, the rate of development will be affected by availability of alternate raw materials and by economic factors.

The value of wood as a fuel has made complete utilization of the harvested forest biomass not only possible but economically attractive. Continuing economic and technological developments will determine how various components of the tree are to be used—whether for solid wood, particles, fiber, or fuel. Certainly on a worldwide basis, and even a national basis, there is still a long way to go before the goal of complete utilization is reached. It is reasonable to expect, however, that this goal will be approached in the United States in the next decade. Doing so will contribute significantly toward assuring that the supply of timber will meet the increasing demand for products and that forest products will remain cost competitive with alternative materials.

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17 Wood for energy and feedstocks

PRIOR to the energy crisis of the 1970s, lumber, panel products, and paper were considered the major products from wood. Since then, energy production increasingly has become a significant use of forest biomass. It appears that the use of wood to provide home heating, industrial processing heat, and electricity will continue to grow. Today, energy must be considered as one of the major products from the forest.

The emergence of wood as a significant source of energy came about because of the rapidly escalating cost of petroleum and natural gas during the 1970s. The cost of imported oil in the United States increased from $3 to $30/barrel. Prior to 1973 the design of industrial equipment and processes was based on the fact that energy was cheap. Therefore, the capital cost of equipment for manufacturing processes was more important than its energy efficiency. It made economic sense, in those days of cheap energy, to install an inexpensive natural gas-fired boiler to heat a dry kiln rather than to spend several times as much money for a combustion system to use the bark and wood residue that were available. Even though this residue was available at little or no cost, the high cost of wood-burning equipment made its use uneconomical. Although the cost of liquid and gas fuels declined sharply in 1987, wood is still an economically attractive source of energy for the forest products industry.

An illustration of the value of wood fuel when compared to alternative fuels is shown in Table 17.1. Note that the amount of heat obtained from wood depends upon the moisture content. Thus dry wood fuels are more valuable than wetter material. The value of wood fuel shown in the table does not take into account the additional cost of the equipment to store, handle, and burn wood as compared to the fossil fuels. Nevertheless, the equivalent value of wood fuel is high.

High values for fuel can result in serious wood procurement problems

Table 17.1. Equivalent value of wood fuel at alternative fossil fuel prices

Type of wood fuel	Cost of fossil fuel required to produce the same amount of heat as 1 ton wood fuel* — Natural gas (per 1000 ft³) $2	$4	$6	#2 Fuel oil (per gal.) $1	$1.50	$2	Bituminous coal (per ton) $50	$75	$100
					($)				
Ovendry wood	36	70	106	120	181	240	30	45	60
Dry planer shavings 15% MC	30	60	90	102	153	204	26	38	51
Sawdust and bark									
30% MC	26	52	78	88	132	176	22	33	44
60% MC	20	40	60	68	102	136	17	25	34
90% MC	16	32	48	54	81	108	13	20	27

* These values assume normal combustion efficiencies for each fuel type. They do not include the additional costs for wood fuel resulting from handling, storage, maintenance, and capital costs. Value of wood fuel is thus considered to be the cost of the fossil fuel required to produce the same amount of heat as 1 ton of wood.

for a firm dependent on low-cost wood residue for raw material. As an example, consider a particleboard plant that is purchasing planer shavings for $30/ton. Suppose it is using oil for energy and the price increases to $1.50/gal. In this situation the equivalent value of the shavings for energy would be approximately $153 (this is the cost of oil to produce the same number of Btus as burning a ton of the shavings). The precise equivalent value will depend upon the efficiency of the oil and wood combustion systems. In such a situation there is obviously a strong economic incentive to use wood as the source of energy. The decision to convert to wood for energy will be influenced by the cost of the new combustion and fuel-handling system. However, the major factor in a decision to convert to wood energy is likely to be the adequacy of the supply of wood fuel.

The importance of wood (or forest biomass) as a source of energy will continue until economical alternatives to petroleum and natural gas are developed. These may take the form of nuclear fission or fusion, solar energy, or thermochemical hydrogen. Despite the decline in world oil prices in the mid-1980s, the use of wood energy by the forest products industry is not likely to decrease. In 1980 the 14 largest forest products companies in the United States produced 70% of their energy from wood waste. Those companies produced one-fourth of the lumber and one-half of the plywood and particleboard in the United States. From 1980 to 1986 most new forest products–manufacturing plants were designed to obtain almost all their process and space heat from combustion of their mill residues.

It has been traditional to refer to the portion of the forest biomass not used for primary forest products as residues. Mill residues consist of planer shavings, bark, slabs, plywood trim, and sawdust. Woods or logging residues include tops, limbs, and cull trees. This terminology should be changed, since the term residue usually implies nonuse or low value. It would be more appropriate to refer to these materials as potential fuels or feedstocks.

The international importance of wood as a home heating and cooking fuel should be recognized. On a worldwide basis, the use of wood for fuel

has always been the single largest use of wood and remains so today. It is estimated that about 45% of the wood consumed in the world is used for home heating and cooking. Shortage of wood in many developing countries has very serious implications to the maintenance of the remaining forests. Forests are disappearing in many countries where the growing population needs both fuel and agricultural land for survival. Some projections have suggested that 24 million ha of forests in the world are being lost each year. Other analysts place the loss at only about one-third that amount, but still a serious concern. Clearly, the implications of the use of wood for fuel are quite different in the United States, where much woody material suitable for fuel is available.

Figure I.2 in the introductory chapter shows the decline in the use of roundwood as a fuel in the United States until about 1975. Since 1978, dramatic increases have taken place in the use of roundwood for home fuel. The fact that over 3 million wood-burning stoves were sold in the United States between 1972 and 1979 and that sales are now estimated at 1 million units annually certainly indicates such a trend. The U.S. Department of Energy (1982) estimated that in 1981 about 48 million tons on an oven-dry basis were used as residential fuel. This was about 60% as much wood fuel as used by industry at that time.

Materials available for energy

Four sources of potential wood material for generating energy are roundwood from growing stock, mill residues, logging or woods residues, and plantations. Roundwood and mill residues are also in demand to produce fiber and particle products. Logging residues could technically be used for particle and fiber products also, but because of the higher bark content and because it often contains grit and other contaminants, this material may be better suited to the production of energy.

The use of short-rotation intensive forest management to produce biomass in so-called energy plantations caught public attention in the 1970s and generated considerable study and controversy. Such plantations have existed in developing countries for some years. In the United States there has been no commercial development of energy plantations to date and none seems likely, although plantations devoted to producing a variety of products, including energy, are nothing new.

It appears that the cost of short-rotation plantation-grown wood for energy purposes will not be competitive with that from the natural stands of low-grade hardwoods abundant in much of eastern North America today.

Mill residues are a highly desirable fuel because they are available at the mills (no transportation cost) and they are often partially dried. Estimates of the volume of mill residues in the United States in 1976 (Table 17.2) indicated that at that time only one-third of the mill residues were available for use (unused). The mill residue utilization picture has changed dramatically since then. In some areas of the United States today, mill

Table 17.2. Estimated volumes of mill residues in the forest products industries (excluding pulp and paper)

Mill residue	Lumber industry	Plywood industry	Other wood products industries	Total
		(mil. dry tons)		
Wood chips				
Used	32	9	3	44
Unused	6	1	0.3	7
Sawdust				
Used	5	0.4	0.6	6
Unused	9	0.1	0.5	10
Bark				
Used	9	2	1	12
Unused	6	1	0.6	8
Total used				62
Total unused				25

Source: Pingrey (1976).

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residues are still not completely utilized, although in other regions bark and sawdust have a ready market as fuel.

The material left in the woods after logging represents a huge store of potential fuel. Because of its small stem size, however, this material is expensive to collect. Its utilization will depend upon the development of cost-effective harvesting systems. Wahlgren and Ellis (1978) estimated that about 105 million tons (on a dry basis) of logging residue could be available annually for use. At present little logging residue is being utilized for energy.

It is very difficult to estimate the total annual growth of forest biomass in the United States. Forest inventories have traditionally been concerned with estimating the volume of stems of merchantable size rather than the total biomass. Only limited data are available regarding total tree biomass, although this situation is improving rapidly. Projecting how much biomass might be available in the future for energy production is an even more difficult problem. Much biomass can never be used for energy because of its location, ownership, or environmental concerns. Nevertheless, the data available indicate that biomass could contribute in a significant way to U.S. energy needs.

The information in Table 17.3 suggests that the amount of unused above ground biomass produced annually in the United States is more than twice as great as that being consumed for forest products. This situation is not expected to change significantly despite the increased volumes that will be used for forest products. If all of this potential biomass were converted to energy, it could produce about 9.5 quads (10^{15} Btus). This is about 13% of the total energy used in the United States in 1976 (over 75 quads). As of 1984 the amount of energy obtained from wood in the United States was estimated at about 2.5 quads, 3% of total U.S. energy production.

A major deterrent to the use of the total forest biomass for fuel has been the cost of harvesting. Specialized equipment to harvest small-diameter stems and collect and transport the material has been needed. Several

Table 17.3. Estimates of U.S. aboveground forest biomass potential

Source	1970	1976*	2000*
		(mil. dry tons)	
Net growth from commercial forests	450	530	600
Mortality†	120	120	120
Other sources‡	110	110	110
Harvest for conventional products uses	−195	−200	−260
Total	485	560	570
Energy equivalent in quads	8.2	9.5	9.7

Note: Estimates derived from Zerbe (1978) and U.S. Forest Service. Moderate industrial demand is projected (SAF 1979).
* Net growth estimates from Ellis (1975).
† Assumes the mortality is recoverable for fuel.
‡ From land clearing, noncommercial forests, urban removals, and urban waste.

specialized machines to do this job are being developed and improved by equipment manufacturers and forest products firms. Such a machine is shown in Figure 17.1.

Whole-tree chippers (see Fig. 18.7) of the type used to harvest stands for pulp chips can also be used to produce chips for energy. A number of firms are using whole-tree chippers for this purpose. However, these machines are not well suited for harvesting the small-diameter stems in a stand or for handling tops and limbs.

In many parts of the United States, mill residues are presently available

(Courtesy, P. Koch)

Fig. 17.1
An experimental machine designed to harvest total forest biomass.

at costs far below the equivalent value of the heat shown in Table 17.1. Active distribution systems and markets have not generally been developed for wood fuels. However, as more firms convert to wood-fired systems, the value of mill and forest residues should increase.

Nature of wood as fuel

The most common method of converting wood into energy is by burning, i.e., combustion. The first step in combustion is the evaporation of the water that is present. Then the volatile components of wood, both combustible and noncombustible, are driven off at temperatures from 100 to 600°C. From 75 to 85% of the wood can be volatilized. In the last stage of combustion the carbon is oxidized. A standard test method to evaluate solid fuels is termed proximate analysis. The proximate analysis of several fuels is shown in Table 17.4.

Table 17.4. Proximate analysis of several fuels

Fuel	Volatile matter	Fixed carbon	Ash
		(%)	
Douglas-fir			
Wood	86.2	13.7	0.1
Bark	70.6	27.2	2.2
Western hemlock			
Wood	84.8	15.0	0.2
Bark	74.3	24.0	1.7
Hardwoods (avg.)			
Wood	77.3	19.4	3.4
Bark	76.7	18.6	4.6
Western coal	43.4	51.7	4.9

Source: Corder (1975), Arola (1976), Pingrey (1976).

The combustion reaction involves the combining of carbon from the wood with oxygen to form carbon dioxide and the combining of hydrogen from the wood with oxygen to form water. The oxygen in the reactions comes partly from the wood but mostly from the air. Wood contains approximately 6% hydrogen, 49% carbon, and 44% oxygen. The amount of oxygen (and thus air) required for the burning process can be theoretically calculated based upon the chemical analysis (termed ultimate analysis) of the species involved. However, in practice, more air than this theoretical amount is required to assure complete combustion. This is termed excess air. In modern wood furnaces, excess air is carefully controlled to assure efficient burning.

Table 17.5 gives average heating values for wood and bark. Resin has a heating value almost twice as high as wood; therefore resinous woods have a somewhat higher value than those with no resin. Bark and wood from softwoods generally tend to be somewhat higher in heat value than from hardwoods. Heating values also vary by species because of the varying

Table 17.5. Average heating values for wood and bark

Type of wood	Ovendry heating values (higher heating values) Wood	Bark
	(*Btu/dry lb*)	
Nonresinous	8000–8500	7400–9800
Resinous	8600–9700	8800–10,800

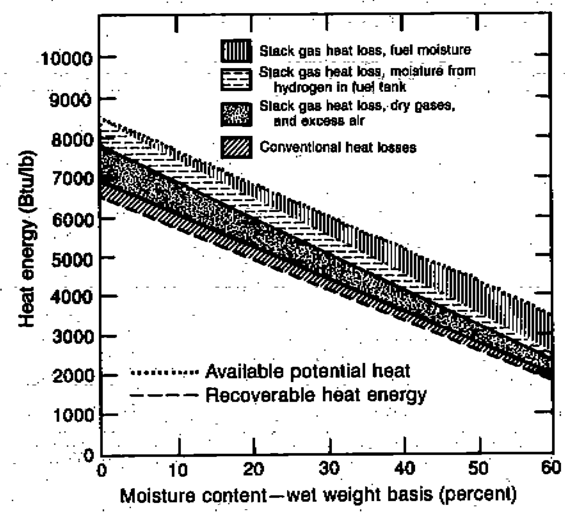
Source: Corder (1975).

proportion of carbon, oxygen, and hydrogen present. However, in engineering practice an average heat value of 9000 Btu/dry lb for resinous woods and 8300 Btu for other woods is sometimes used.

The total heat generated by complete combustion under controlled conditions is termed the higher heating value (HHV). The actual heat that can be recovered in conventional burners is considerably less than the HHV, due to the loss in vaporizing the water in the fuel and from other losses occurring in the process. These other losses include energy to heat the excess air and to heat water formed during combustion. Figure 17.2 (Ince

Fig. 17.2

Recoverable heat, available potential heat, and heat losses for a pound of typical wood fuel burned in a boiler



1979) illustrates the relationship between the potential and recoverable heat energy per pound of wet wood and the moisture content.

The available potential heat at any moisture content, as illustrated in Figure 17.2, is sometimes called the gross heating value (GHV). The example shown in the figure is for a fuel with a HHV of 8500 Btu/lb in a combustion system with a 500°F stack gas temperature. Note that the GHV represents the HHV in the portion of fuel composed of dry wood. The GHV of wood can be calculated from the HHV as follows:

$$\text{GHV} = \text{HHV} \times [1 - \text{\% MC (wet basis/100]}$$

The ratio of the recoverable heat to the available potential heat (see Fig. 17.2) is called the combustion efficiency. With wood fuels and current combustion equipment, combustion efficiencies range from about 80% for dry fuels to 60% for wet fuels. Unfortunately, green rather than dry fuels are most available. When comparing the cost of alternative fuels, it is the recoverable heat value that is of most importance. It is this heat energy that produces the steam for industrial processes or to drive a turbine or that can be used for space heating.

The terms net heating value (NHV) and lower heating value (LHV) are sometimes encountered in combustion engineering. NHV and LHV are the net heat released by a fuel after reducing the HHV by the heat of vaporization of the water generated by combustion of the hydrogen in the fuel. LHVs are customarily used in Europe, while in America HHV is used as the basis on which fuel is bought and sold (Georgia Institute of Technology 1984).

As discussed in Chapter 8, the moisture content of forest products is normally calculated on a dry-weight basis; if the moisture content is based upon the wet weight it should be so indicated. However, the wet basis is commonly used in wood fuel literature without reference to the basis of calculation. Moisture content on dry weight basis can be converted to moisture content on wet weight by the relationship

$$\text{\% MC (wet basis)} = \frac{\text{\% MC (dry basis)}}{100 + \text{\% MC (dry basis)}} \times 100$$

An example may aid in understanding the relationship between the moisture content and the recoverable heat. Assume it is known that a species of wood is at 75% MC and has a HHV of 8800 Btu/lb.

1. What will be the gross heating value?

75% MC is equal to 75/(100 + 75) = 43% MC (wet basis)

So the gross heating value is

8800 Btu (1 − 0.43) = 8800 × 0.57 = 5016 Btu/wet lb

2. If the combustion efficiency of the boiler is 70%, how much recoverable heat will be obtained per pound of wood fuel at 75% MC?

5016 Btu/lb × 0.70 = 3511 Btu/lb

3. If recoverable heat is valued at $4/mil Btu, how much more could be paid for this fuel without increasing the cost of energy if it were purchased at 15% MC rather than at 75% MC? (At 15% MC the combustion efficiency of the boiler is 78%.)

15% MC = 15/(100 + 15) = 13% MC (wet basis)
8800(1 − 0.13) = 7656 Btu/lb (gross heat)
7656 Btu/lb × 0.78 = 5972 Btu/lb (recoverable heat)

Therefore, the usable heat is increased by 5972 − 3511 = 2461 Btu/wet lb when using wood at 15% MC rather than 75%. The difference in value would be

(2461 × 4)/1,000,000 = $0.01/lb or $19.69/ton

The forest products engineer should know how to estimate the amount of wood fuel required to supply an industrial boiler or an electrical generation plant. Such an estimate requires consideration of the operating characteristics of the boiler system as well as the nature of the fuel to be used.

The energy output of a boiler is commonly expressed in pounds of steam per hour (pounds of water evaporated per hour). The heat required to produce a pound of steam varies depending upon the pressure and temperature, but it is generally in the range of 1100–1300 Btu/lb. Typically boiler sizes in the forest products industry run from 20,000 to 400,000 lb/hr.

The following example will explain the general approach to estimating fuel requirements. Assume a 50,000 lb/hr boiler requires 1250 Btu/lb steam to heat the feed water and generate the steam. This boiler is to be fired with fuel at 75% MC having a gross heat value of 5016 Btu/wet lb (see 1 in example above). The efficiency of the boiler is 67%. Weight of fuel required per hour equals

$$\frac{\text{50,000 lb steam/hr} \times \text{1250 Btu/lb steam}}{\text{0.67 (boiler efficiency)} \times \text{5016 Btu/lb fuel}} = 18{,}600\ \frac{\text{lb fuel}}{\text{hr}}$$

Calculations for estimating the wood requirements of a wood-fired electric generating plant are discussed by Garrett (1981). The process can be outlined by the following example: 1 kWh is the equivalent of 3412 Btu/hr. Thus if an electric generating plant operates with a typical overall efficiency of 25%, it requires 13,648 Btu input (3412/0.25) to produce 1 kWh. The daily energy requirement for a 20-megawatt (MW) plant would be

13,648 Btu/kWh × 20,000 kWh × 24 hr = 6.55 × 10^9 Btu/day

If the wood fuel going into the plant has a higher heating value of 8300 Btu/lb and 45% MC (wet basis), then the gross heating value is 8300 (1 − 0.45) = 4565 Btu/wet lb. Thus the daily wood fuel requirement for the plant is

$$\frac{6.55 \times 10^9 \text{ Btu/day}}{\text{4565 Btu/wet lb}} = 1.44 \times 10^6 \text{ lb fuel/day}$$

Therefore, even this rather small power plant requires about 720 tons green chips/day for fuel. This is as much wood as required to supply a 200 ton/day pulp mill with fiber.

The gross heat of a hardwood at different moisture contents and the usable heat, assuming typical combustion efficiencies, are shown in Table 17.6. Note that the usable heat per wet pound at 100% MC is less than half that at 15% MC.

Table 17.6. The gross and usable heat of hardwood at different moisture contents and assumed combustion efficiencies

Moisture content, ovendry basis	Gross heat value	Assumed combustion efficiency	Usable or recoverable heat
(%)	*(Btu/net lb)*	(%)	*(Btu/net lb)*
0	8300	80	6640
15	7218	78	5630
30	6385	76	4853
60	5188	72	3735
100	4150	67	2780

There are two approaches to reducing the moisture levels in such cases. The most common means of drying is by supplying heat energy to vaporize the moisture, i.e., by thermal means. The second is by applying mechanical energy to squeeze the free water from the wood or bark. This is referred to as dewatering or compression drying.

Thermal drying is the most common approach to wood fuel drying. It has been demonstrated that the installation of thermal fuel–drying equipment can sometimes be well justified, particularly if increased boiler capacity is needed. The heat for these dryers is typically supplied by burning dried fines separated from the fuel being processed. Cascade dryers, which utilize waste heat from stack gases, are also available. This equipment is widely used in Scandinavia, and there are several installations in the United States.

The drying of wood chips or particles by evaporation of moisture in a tube, drum, or cascade dryer makes it possible to dry particles to any moisture content desired but has the disadvantage that it requires high energy input, generally greater than 1800 Btu for each pound of water removed. Thermal drying thus requires an energy input that is greater than the increase in heating value resulting from the drying. Nonetheless, drying wood fuels by evaporative means may prove advantageous in those cases where the input energy is from flue gas or another low-cost source.

The other approach to the drying of wood-chip fuels now being used commercially is by compression (mechanical means). Although equipment for mechanically dewatering bark and very wet residue has been available to the forest products industry for many years, these existing processes are limited in application because they can reduce the moisture content to only about 50% (wet basis). These mechanical dewatering systems are thus best

suited for removing water added in processing, not the water naturally occurring in green biomass. Process water is typically added in log storage, saw cooling, debarking, and fiber processing.

Research is being conducted to develop other less costly means of reducing the moisture in wood-chip fuels. These methods include drying after felling but prior to chipping, air drying bins of forest residue, and high-pressure compression drying of wood chips. The latter method can reduce the moisture content to about 40%, lower than presently available commercial equipment can accomplish (Haygreen 1981, 1982).

The use of dry rather than wet wood fuel has advantages in addition to the increased heat value described above. The capacity of a boiler is increased if dry fuel is used rather than green. The greater efficiency of the furnace when burning dry wood and the smaller amount of steam generated from moisture in the wood result in less flue gas volume. This permits an increase in the amount of wood that can be fired, thus increasing total heat production. If fuel at 40% (wet basis) MC is burned rather than fuel at 50%, the steam output of the boiler will typically increase by about 10%. Thus greater steam production can be obtained from an existing installation if fuels are dried rather than burned green. Likewise, in a new installation designed to meet specific steam requirements, a smaller boiler can be installed if drier fuels are to be burned. Newby (1980) cites a 7% increase in the rate of steam generation in a boiler as a result of reducing the fuel moisture from 60 to 55%.

When drier fuel is burned, the volume of stack gases generated per pound of steam produced is decreased. Thus a boiler designed for a specific steam capacity using dry fuel will have lower capital and operating costs for stack gas emission control equipment than a boiler designed for wet fuel. In a test to evaluate the effects of fuel moisture on particulate emissions, Johnson (1975) shows that the increase of fuel moisture from 52 to 63% caused a doubling of the rate of particulate emissions. Thus drier fuels yield significant savings because of reductions in both the stack gas volume, which must be handled by the environmental control equipment, and the quantity of particulate emissions that must be collected.

A further advantage of drier fuels is discussed by Vanelli and Archibald (1976). A conventional hog fuel boiler requires constant adjustment of controls, with fluctuation in fuel moisture content. Thus the maximum efficiency for the boiler may not be obtained. A fuel drying system that can provide fuel at a relatively uniform moisture content would reduce or eliminate this problem.

Gasification and pyrolysis processes also realize benefits from using dried wood fuels that are similar to those for combustion systems. The use of fuel at high moisture levels reduces the temperature of combustion products and generally the efficiency of the system. In low-Btu gasifiers, efficiency may be lowered about 15% when burning green wood. In some gasification systems, only dry wood can be used.

Despite the advantages of burning drier fuels, most wood residue fuels are combusted as received, without the benefit of drying. This is because of the costs associated with drying. With wet fuels the drying is accomplished in the boiler during the first step in combustion. With very wet fuels and with some burning systems, it may be necessary to dry the fuel in a separate step prior to burning in the boiler or reactor.

A desirable characteristic of wood for industrial fuel is the fact that it is low in sulfur and nitrogen. This reduces the cost of air-cleansing equipment as compared to fossil fuels that produce significant amounts of sulfur dioxide and nitrous oxide emissions. The major air pollution problem with industrial wood fuels is one of particulate emissions, largely unburned carbon particles. Particulate emissons can be controlled by mechanical collectors and scrubbers. With large boilers, electrostatic precipitators are suitable for reducing particulate emissions to acceptable levels.

There is a popular belief that dense species such as oak are far better than others for fuel. This is true in the sense of the volume of wood to be handled to obtain a given amount of heat or in terms of the rate at which the wood burns in a stove or fireplace. However, in terms of industrial applications, species is relatively unimportant. Remember that the amount of heat per ovendry pound varies little among species; the moisture content of the wood is much more important. Difficulties do exist, however, in handling and grinding the bark of some species because of their fibrous or stringy nature. Also, if extremely low-density woods are burned, the mass of wood in the furnace at any time, and thus heat output, may be reduced.

Chemical Wood Products

Chemical wood products in use today are made from wood or bark that has been reduced to basic chemical components such as cellulose, hemicellulose, or lignin. The raw material for many of these products is waste liquor, which results from the chemical pulping of wood. Also included in the chemical wood products category are products made from the resins of pines and other softwood species. Chemical products are seldom recognizable as wood based.

Wood is used today in making a wide range of chemical products, from animal feeds, adhesives, and lacquers to photographic film, plastics, and rayon. These can be categorized as cellulose ethers, lignosulfonates and lignin-based chemicals, modified cellulose, regenerated cellulose, or naval stores.

CELLULOSE ETHERS are made by treating alkali cellulose with various reagents. The cellulose ethers include carboxymethyl cellulose, which is used in making products as diverse as laundry detergent additives, adhesives, and strengtheners in unfired ceramics. Other cellulose ethers are used as sizing in papers and textiles and as emulsifying agents in paints and foods.

LIGNOSULFONATES originate from used cooking liquors that are employed in the chemical pulping of wood. These versatile compounds are

used as dispersing and stabilizing agents in oil well drilling muds, printing inks, dyes, and concrete and as binders in such thing as gravel roads, animal food pellets, and textiles. Artificial vanilla, used widely in products such as ice cream, cookies, and cakes, is also made from lignosulfonates.

MODIFIED CELLULOSE includes the cellulose acetates and cellulose nitrates. Both of these are important ingredients in adhesives and lacquers. Acetylated cellulose is used in the making of rayon acetate, a material from which women's dresses, scarves, and the like are made. In addition, photographic film is made frm cellulose acetate, as are a number of extruded and injected moulded plastics. Cellulose nitrate is itself an important source of plastics and was, in fact, the primary ingredient in celluloid, the first synthetic plastic made commercially. Moulded plastic articles such as table tennis balls and piano keys are made from this material. Cellulose that is highly nitrated is used in making guncotton and cordite, both common ingredients in explosives.

REGENERATED CELLULOSE products are produced by partially breaking down cellulose through chemical treatment and then recombining components to form a synthesized fiber. Products in this category include cellophane and viscose rayon, a colorfast material used extensively for curtains and drapes, clothing, and bedspreads. Rayon fiber is also commonly used in the inner plies of radial tires and in conveyor belts.

NAVAL STORES include turpentine and rosin. Both of these materials, along with pine pitch and tar, were once essential to the operation of wooden sailing ships, explaining the term "naval stores." Almost all naval store products are obtained today from tall oil and from volatile fractions recovered after the chemical pulping of pine wood. Tall oil itself is an ingredient of some lubricants. Turpentine and its derivatives are used in the manufacture of paints and lacquers and various chemicals including insecticides, perfumes, and artificial flavors. One derivative, pine oil, is used in making cleaners and disinfectants. Rosin, produced when turpentine is distilled from pine gum, is a very important industrial chemical. Used principally in sizing of paper to reduce penetration of liquids, rosin also is employed in making paints, lacquers, varnishes, hot melt adhesives, printing inks, plastics, and linoleum floor coverings; it is used as well as a plasticizing agent in synthetic rubber.

Wood for energy in the forest products industries

Wood-based materials range from products of low energy intensity (lumber) to high energy intensity (pulp and paper). The lumber manufacturing process has the characteristic of generating many more residues than do pulp and paper. The plywood and particleboard industries fall some-where between these two extremes in terms of energy requirements and in residues generated.

If a typical sawmill were to burn all the sawdust, bark, and other residues generated, it would produce more energy than consumed in the manufacturing process. Therefore, it is potentially energy self-sufficient. Pulp and paper mills by contrast can only be about 45–50% energy self-sufficient when using all their residues.

The potential use of internal mill residues to supply energy to manufacture a variety of forest products is shown in Table 17.7. These data show that there is potentially an excess of residues in some industries but a deficit in most. The data do not include the use of residues from logging. If fiber products and particleboard plants were to generate all their energy from wood, it would require in most instances that more biomass be brought from the woods. A report (NGM systems 1981) on the waferboard industry suggests that these plants could have total energy self-sufficiency through the use of new gasifier-gas turbine systems.

Arola (1976) estimated that to satisfy the energy needs of a kraft paper mill producing 1000 tons paper/day, about 4000 tons of green wood would be needed. This is in addition to the 4000 tons/day for the paper itself. Supplying such a quantity of wood would not be a reasonable possibility in

Table 17.7. Energy required to produce selected wood-based and non-wood materials

Commodity	Energy				
	Harvesting	Manufacture	Total	Available from processing residual fuel	Supplementary requirements for manufacture
	(mil Btu/ovendry ton)				
Wood-based					
Softwood lumber	0.9	4.8	5.7	8.3	0 (3.5)
Oak flooring	1.1	5.7	6.8	11.4	0 (5.7)
Lumber laminated from veneer	0.7	6.6	7.3	3.5	3.0
Softwood sheathing plywood	0.7	6.9	7.6	3.7	3.2
Structural flakeboard	1.0	7.5	8.5	8.6	0 (1.1)
Medium-density fiberboard	0.8	9.3	10.1	2.7	6.6
Insulation board	0.6	10.5	11.1	0.7	9.9
Hardwood plywood	1.0	10.2	11.2	10.6	0 (0.4)
Underlayment particleboard	4.6	8.1	12.7	1.5	6.6
Wet-formed hardboard	0.7	19.7	20.4	0.8	18.9
Not wood-based					
Gypsum board	0.1	2.7	2.8		
Asphalt shingles	0.0	5.7	5.7		
Concrete	0.5	7.6	8.1		
Concrete block	0.5	7.6	8.1		
Clay brick	0.6	7.7	8.3		
Carpet and pad	6.6	28.7	35.3		
Steel wall studs	2.5	46.2	48.7		
Steel floor joists	2.5	46.2	48.7		
Aluminum siding	26.8	172.0	198.8		

Source: Jahn and Preston (1976).

Note: In calculations of supplementary requirements it is assumed that energy from processing residual fuel can be used in the manufacturing process but not in harvesting. Values in parentheses are for excess energy from processing residual fuel that would be available for other uses.

many mills. Nonetheless, although complete energy self-sufficiency may not be realized, it appears that the harvesting of biomass for energy will be more widely used by the forest products industries in the future.

Most forest products industries generate energy from wood combustion in the form of heat. Their single largest use of heat is for drying; about 70% of the energy used in lumber manufacture and 40% in papermaking is for this purpose.

In relatively large plants that operate continuously, it is economically feasible to also use wood to generate electricity. In small plants, generating electricity from residues has not been practical in recent years because of the high cost of the high-pressure steam boilers, turbines, and generators that are required. However, pulp and paper mills have large energy needs and continuous operations, which make such installations cost effective. Individual plywood plants or sawmills generally rely upon purchased electricity.

Since the major energy requirements of the forest products industries are in the form of heat and electricity, they are well sited to the simultaneous generation of electricity and low-pressure steam, a process called cogeneration. It can be accomplished by special equipment consisting of a high-temperature, high-pressure boiler and a special turbine that generates electricity from the high-pressure steam and exhausts low-pressure steam to use for process heat. Figure 17.3 illustrates a cogeneration system for a plant requiring only one pressure of process steam.

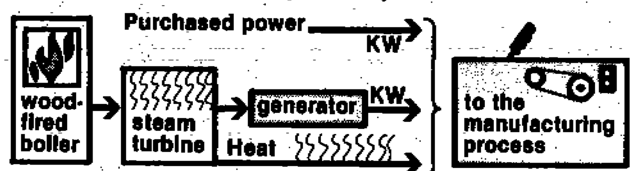
Cogeneration is more economical than the generation of electricity by itself because the heat from the exhausted steam is utilized. According to Engelken and Farrell (1979), an efficient steam turbine power plant requires about 9500 Btu to produce 1kWh of electrical power. The heat equivalent of 1 kWh is about 3400 Btu. For each KWh, generated, about 5000 Btu can be used for heat in the plant. A typical utility company producing only electricity from wood may be only 25% efficient in its energy conversion, but cogeneration could increase that to about 75%.

Large forest products complexes can utilize wood-fired cogeneration

Fig. 17.3

Typical cogeneration system

for a mill requiring one pressure of process steam and where additional electricity can be purchased if needed



Modified from Engelken and Farrell (1979) plants to provide their own heat and electrical needs and may in addition sell their excess electrical capacity to public utilities. Tillman (1979) discussed the economic considerations involved in cogeneration. The attitude of the public utilities is important. The National Energy Act of 1978 provides incentives for cogeneration and the use of fuels other than oil and gas. While cogeneration units once had to be at least 25 MW in size to be economical, today 5-MW units or smaller may be feasible.

Energy use of wood by other industries

It is reasonable to expect that the forest products industry will remain as the major industrial consumer of wood for energy. Although other industries will purchase wood fuels where the local situation makes this feasible, they will generally be at a disadvantage compared to forest products industries because of the additional transportation and handling costs involved and the uncertainty of a continuing supply. Nonforest-based industries consumed only 3% of the wood energy used in the industrial sector in the United States in 1984 according to estimates by the U.S. Department of Energy.

About a dozen commercial electric companies in the United States were using wood as the major fuel in 1986. The Burlington Electric Department in Burlington, Vt., converted two 10-MW boilers to wood in 1978 and in 1984 opened its 50-MW plant, powered by wood (Dennis and Dresser 1985). About 500,000 tons green biomass/yr are required to run one 50-MW plant. One of the major deterrents to public utilities investing their capital in wood-fired power plants has been the uncertainty as to the long-term cost and availability of wood. Controversy as to the environmental impact of large-scale wood harvesting has also created delays and public opposition (Robbins 1985). It seems likely that these questions will continue to plague such projects.

The use of wood for industrial energy is more attractive in other countries where fossil fuels are scarce or nonexistent. In Brazil, iron blast furnaces are fueled with wood charcoal, much of which comes from eucalyptus plantations. This process requires three times as much wood per year as do all of Brazil's paper mills.

One of the disadvantages of wood as a fuel for small commercial firms and public buildings is that it is bulky and difficult to handle and store. Also, the heating value varies over time as the moisture content changes. One way to reduce these problems is to pelletize the wood residue. Some advantages of wood pellets as fuel are that pellets are dry and therefore of a uniform and high heating value; they have a high bulk density, so storage space is minimized; and they can be burned in many systems designed for coal. The major disadvantage is the added cost of pelletizing. Because of this cost, there probably will be little use of pelletized fuel within the forest products industry. However, it may be an attractive fuel for others where convenience is important. Several types of wood pellets are shown in Figure 17.4.

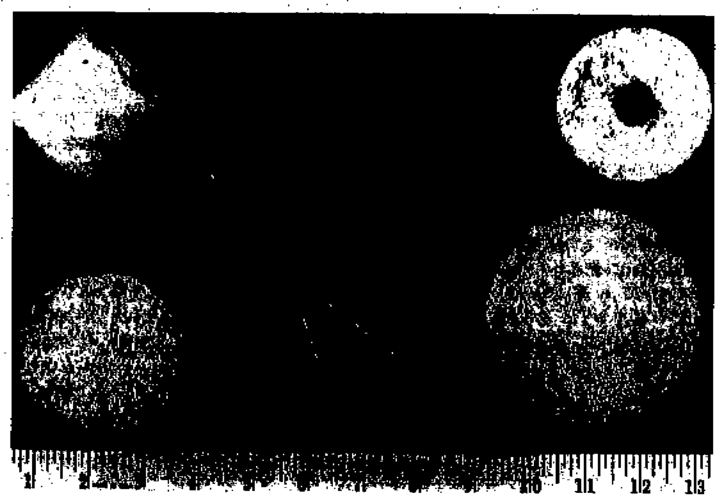


Fig. 17.4
Several types and sizes of wood fuel pellets and briquettes.

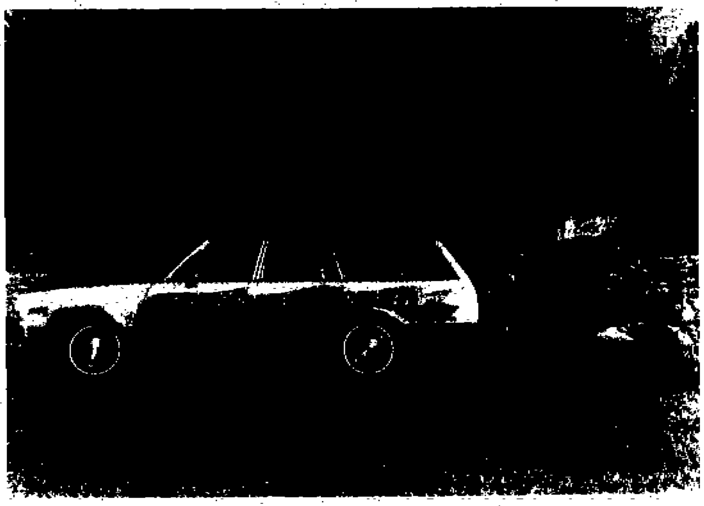
Chemical conversion of wood to energy and feedstocks

Combustion is the major method of converting wood to energy at the present time. Wood, however, can provide the organic chemicals for a number of other processes or products that provide alternatives to the use of fossil fuels. Gasification and pyrolysis are two processes that provide combustible products from wood. Also, wood can serve as a chemical feed stock providing the cellulose, hemicellulose, and lignin that can be used to produce other chemicals ordinarily derived from fossil fuels. To date only limited commercial application of these processes has been made in the United States, but this situation is changing. During the early 1980s a number of wood gasification units were installed in commercial and industrial plants, primarily for heat and process steam.

Gasification is the thermal decomposition of wood with limited amounts of air or oxygen, which produces a combustible mixture of gases called producer gas. Once the operating temperature of a gasifier is reached, gases (primarily carbon monoxide, nitrogen, and hydrogen) containing 10–35% the Btu content of natural gas (methane) are generated. If oxygen rather than air is used for gasification, the heat value of the gas produced is at the higher end of this range.

Gasification is an old process and was used to produce gaseous fuel from coal before the days of electrification. Gasification can utilize coal, wood, or agricultural biomass. Several types of wood gasifiers have now been developed that are generally suitable for smaller industrial or institutional applications.

Gasification of wood has been used in the past as a direct source of heat for industrial plants by combustion of producer gas and even as fuel for motor vehicles. During World War II many trucks and buses in Europe were powered by small wood gasification units. A demonstration vehicle powered with a wood gasification unit is shown in Figure 17.5. Producer gas can be fed to internal combustion engines much like the normal gasoline and air mixtures.



(Courtesy Econ Inc. Alexander City, Ala.)

Fig. 17.5
A demonstration car powered by a wood gasification unit.

Producer gas can be cleansed of nitrogen and carbon dioxide and converted to synthesis gas (syngas). Synthesis gas can be used as the raw material to produce ammonia, methane, and methanol.

Pyrolysis is a process of thermal decomposition of wood (or other organic material) in the absence of oxygen. It was formerly referred to as destructive distillation and has been used in the past to produce charcoal, acetic acid, and methanol. In contrast to gasification, which produces only gas, the products of pyrolysis are gas, liquid, and solid fuels. The pyrolysis gas is often burned on site to produce heat for the process. The solid

product produced is charcoal, the liquid a heavy complex oil somewhat similar to heavy fuel oil.

In many pyrolysis systems a part of the wood is burned to generate the heat needed to start the decomposition process. Once adequate temperatures are reached, the oxygen supply is restricted and finally cut off entirely. In charcoal operations only the solid fuel may be recovered, but in more sophisticated pyrolysis systems all three products are recovered and must be utilized to make the systems economically viable. The pyrolytic oil could be burned for heat, since it contains from 10,000 to 13,000 Btu/lb. It is being studied as a source of organic chemicals. The primary use of pyrolysis today is for charcoal production.

Anaerobic fermentation can be used to produce methane from wood wastes. Methods to refine this process are under way. Since this is a biological reaction resulting from the activity of bacteria, it is critical to use the right type of wood and maintain the material under proper conditions to maximize methane formation. Fermentation can be slow, and large containers are needed; thus costs may be high. Some agricultural and municipal wastes appear better suited to methane production than wood.

Wood can be converted to ethanol, which can be used for gasohol or for other energy purposes. In Brazil and some other tropical countries, much ethanol is produced from sugarcane. Conversion of wood to ethanol is a two-step process. The wood is first hydrolyzed to glucose and then the glucose is fermented to produce the alcohol. In the United States today there is much more interest in the use of agricultural crops for the production of alcohol than in the use of wood.

Fossil fuels provide most of the raw materials (feedstocks) for the synthetic fiber, adhesives, and plastics industry. Goldstein (1978) has described the factors under which wood could become a major chemical feedstock. He points out that just as there was an earlier change (in the chemical industry) from a coal-tar base to a petroleum base, coal and cellulose could become the chemical feedstocks of the future. Nonetheless, in regions of the world where coal is available, it is likely to be used before wood as an organic chemical source.

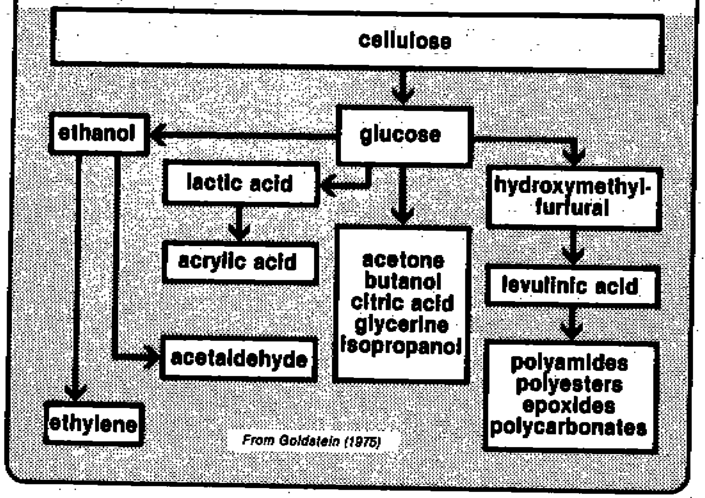
All the chemical components of wood have potential for providing organic chemicals. However, cellulose has perhaps the widest possibilities. The first step in the process of converting cellulose to other chemicals is to hydrolyze it into glucose. From that point a variety of chemicals can be produced, as indicated in Figure 17.6.

Energy from wood in the form of chemicals may not become important in the 1980s, but it is a technically feasible possibility that will be available.

Fig. 17.6

Use of cellulose for chemicals

Hydrolysis of cellulose to glucose and further conversion of glucose to chemicals



REVIEW

A. Terms to define or explain:

1. Mill residues
2. Logging residues
3. Energy plantations
4. Proximate analysis
5. Excess air
6. Higher heating value
7. Gross heating value
8. Usable or recoverable heat value
9. Combustion efficiency
10. Synthesis gas
11. Gasification
12. Cogeneration
13. Pelletizing
14. Lignosulfonates
15. Regenerated cellulose

B. Questions or concepts to explain:

1. Reasons why the forest products industry relied upon fossil fuels for energy in the past.
2. How the value of wood fuels is related to the cost of oil and natural gas.
3. How the moisture content of wood fuel affects the heating value.
4. Importance internationally of wood for home heating and cooking.
5. Advantages of wood fuel with respect to air pollution problems.
6. Factors affecting the amount of usable heat obtained from burning wood.
7. The degree of energy self-sufficiency possible in the forest products industries.

8. Advantages of cogeneration for the forest products industries as compared to generating electrical energy alone.
9. Disadvantages of wood fuel for industrial or commercial heating.
10. Availability of mill and woods residues for fuel.
11. How to estimate the fuel requirements for a wood-fired steam boiler or an electric generation plant.

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18

Complete utilization of wood and biomass

Haygreen/Bowyer (1982)

THE PAST FOUR decades have brought dramatic technological change to the utilization of timber in the United States. Bingham (1975) provided an example of what was accomplished in utilizing old-growth Douglas-fir timber in western Oregon between 1948 and 1973. The logs harvested on an acre of this timberland typically contained about 17,900 ft^3 of wood. He reported that the [redacted] was as follows:

In 1948, [redacted]

TOTAL = 3600 ft^3 for products

14,300 ft^3 of residue (fuel and waste)

In 1963, [redacted]

3800 ft^3 for paper
800 ft^3 for plywood

TOTAL = 9200 ft^3 for products

8700 ft^3 of residue (fuel and waste)

In 1973 [redacted]

1700 ft^3 for plywood
5900 ft^3 for paper
1500 ft^3 for particleboard

TOTAL = 14,100 ft^3 for products

3800 ft^3 of residue (fuel and waste)

In that 25-year period the usable products obtained from similar acres of Douglas-fir increased nearly four times. In 1973 there was still considerable room for further improvement, however. In addition to the 3800 ft^3 of residues harvested per acre there were 8100 ft³ of wood left in the portions of the tree not harvested. These logging residues represent a potential source of fiber, particles, or energy. This example from the West is indicative of what was accomplished in other regions during that period.

A more general look at the improvement in utilization in the U.S. forest products industry is shown in Figure 18.1 (USDA Forest Service 1982). During the 30-year period shown, the tonnage of products produced per unit of roundwood input rose at an average rate of about 1% per year.

The total U.S. input of wood and output of products from primary wood processing is estimated in Figure 18.2. This diagram shows the direct flow of logs and pulpwood into the mills as well as the flow of by-products and residue between the major products. Note that in the pulpmills only 63% of the input is directly from the forest, and in particleboard mills only 8% of their raw material is roundwood. [redacted]

[redacted]

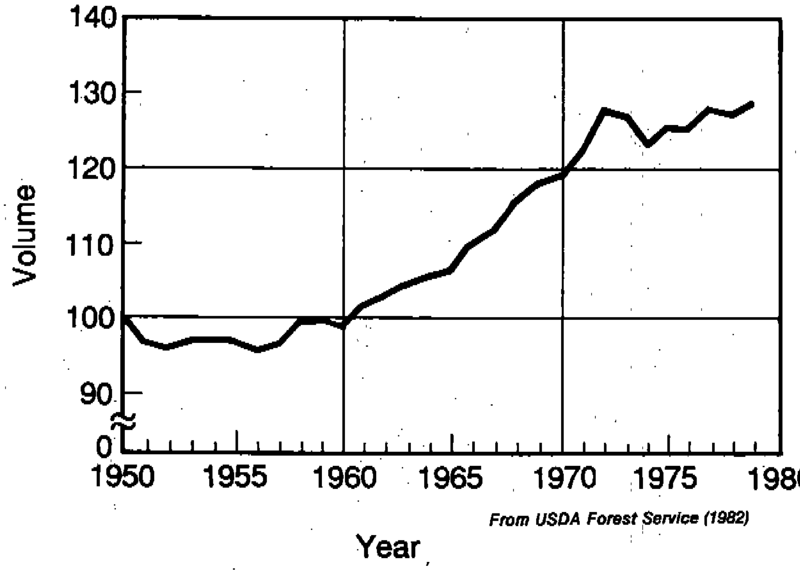
Haygreen/Bowyer (1989)

integration (uses)

Fig. 18.1

Output of timber products per unit of roundwood input, 1950–1979

Index (1950 = 100)

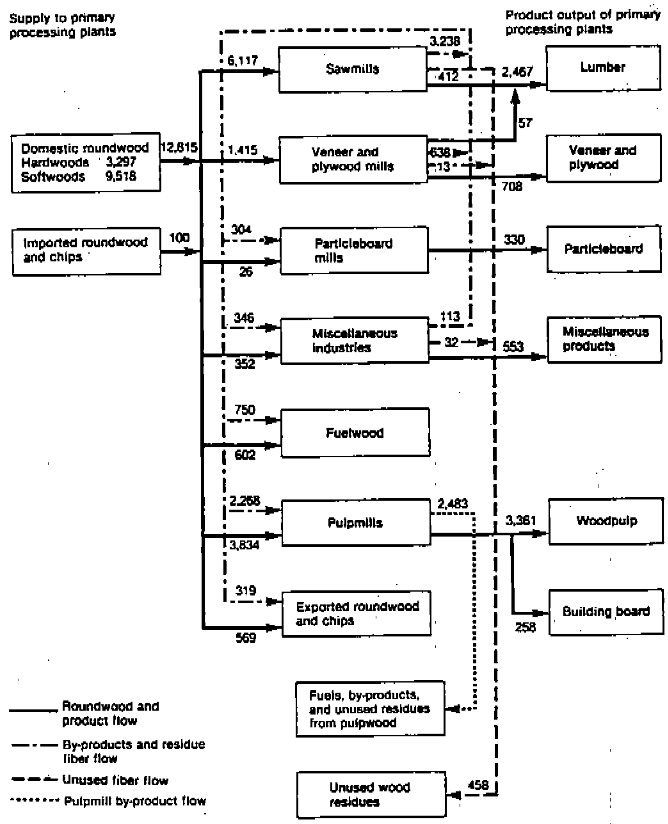


From USDA Forest Service (1982)

Fig. 18.2

Timber supply to and product output from primary processing plants

(million cubic feet)



From USDA Forest Service (1982)

[redacted] Even under such an ideal situation, however, considerable biomass is left unutilized in the woods.

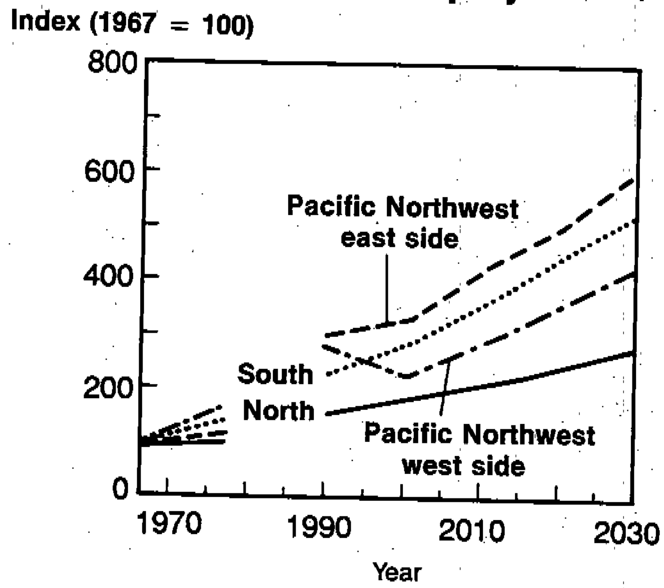
[redacted] (2) development of veneer lathes capable of peeling small logs, (3) development of the particleboard industry and more recently the structural composite panel industry, [redacted] (6) improved logging systems for full-tree harvesting and development of equipment for whole-tree chipping, and (7) development of burners and energy conversion systems that can use all types of bark and wood residues.

Most of these developments are still being modified and improved. The driving force behind many of these advances has been the cost of stumpage (standing timber), which rose dramatically during the late 1970s. Although log prices slumped in the mid-1980s, some expect that prices will increase in the future as projected in Figure 18.3. The higher expected price escalation in the Pacific Northwest and the South reflects competition and industry structure.

Despite the advances in technology there is still much to be done to bring the goal of complete utilization of each harvested tree to reality. As shown in Figure 18.2, large volumes of mill residues generated in the manufacturing process are not used for products or energy. Although residue utilization has improved greatly, there are still regions of the United States where bark, sawdust, and solid wood scrap are not being used. This is

Fig. 18.3

Softwood stumpage price* indexes by region, 1967-1976, with projections to 2030



*Per thousand board feet, International 1/4-in. log rule

From USDA Forest Service (1982)

particularly true where the wood-based industries are small and widely scattered. In this situation there often is not enough residue produced in one locality to make the cost of collection and transport economically feasible. Generation of energy at the mills themselves may be the only use of residue in these situations.

The appropriate level of utilization is not necessarily the same as total biomass utilization. When the complete biomass of an area is repeatedly harvested, there is the possibility that the productivity of the land will be reduced as a result of the loss of necessary plant nutrients. This is analogous to intensive agriculture that requires the use of fertilizers in the production of annual crops such as cotton or corn. The situations in which the loss of plant nutrients may be a real problem depend upon soil and site factors, the portion of biomass left in the woods, and the length of time between harvests. Research is under way to establish the methods and conditions by which complete forest biomass harvesting can be accomplished without damage to future productivity of the land.

Improvements in the degree of utilization of the harvested stem and of the total biomass can make a significant contribution to the balance between the demand for wood products and the supply of timber. [redacted] For timberland this includes all trees, not just those suitable for manufacture into given products. Therefore, improvements in use of currently harvestable stems and advances in the use of currently unmerchantable trees can add to the resource base and enhance utilization of the total biomass. Under present systems, less than half the total biomass produced in many forests is being utilized. Therefore, if means were developed to make possible the use of all the woody material produced, only half as much land would have to be harvested per year to supply the same needs. Or perhaps more realistically, it would be possible to supply the increasing demand for wood without increasing the area harvested.

Forests and forest industry operations in tropical countries are very different from those in North America and Europe. Tropical forests contain many, often hundreds, of species on each hectare. Hardwoods predominate, and often no softwoods are present. Only a few of the many species in these forests currently have value for lumber, plywood, or other solid wood products. In many developing countries the ideal of total utilization of the forest biomass is so far from reality that it is not a reasonable goal at this time.

Attempts have been made by many countries and firms to increase the domestic use and export of many of the lesser-known tropical species (Yeom 1984). However, to date this problem has remained intractable. The factors contributing to the problem include (1) difficulty in the identification of timber species, (2) inadequate data on physical and mechanical properties, (3) marketing stressing incorrect end uses, (4) poor grading and manufacturing standards, and (5) interrupted or unreliable supplies. Bethel (1984) pointed out that this problem relates directly to the fact that most tropical forests are in the exploitation stage and have not progressed to the point of being managed forests. When timber is harvested from such forests the yield of products from a tree typically averages no more than 30%.

Natural forests in Southeast Asia are more homogeneous than those in Africa and Latin America, though still very diverse. In parts of the Philippines, Indonesia, and Malaysia there may be 30–50 species on any hectare, but many are similar and can be utilized and marketed together. One firm in the Philippines (Haygreen and Gregersen 1979) converts almost all the timber harvested into lumber, plywood, paper, or energy. This is an example of horizontal integration, i.e., combining a variety of related manufacturing processes; vertical integration, by contrast, is the combination of different functions such as harvesting, manufacturing, distribution, and sales. Unfortunately, integrated operations of this type are rare in tropical countries. In the past, much of the timber harvesting in these countries has involved extraction of only the best logs for export or for local conversion to lumber or plywood. This situation is changing slowly. Improved utilization is becoming important to the economic health of the forest products industry in tropical countries, as it is in North America and Europe.

The development of plantations (called man-made forests in some parts of the world) may contribute to improving forest utilization in tropical regions. Projects such as a the Jari paper mill complex in the Amazon region (Kalish 1979; McIntyre 1980; Hornick et al. 1984) are relying entirely on plantation-grown wood. There is controversy over the desirability, from an ecological and social viewpoint, of replacing natural forests with plantations. However, in terms of assuring industry a uniform source of fiber at a predictable cost, this appears to be a rational approach.

[redacted]

The constraints to complete utilization of a stand of timber vary considerably with the type of forest. The size and quality of trees, extent of stocking, distance to the market, ownership patterns, public and political attitudes, and the general state of the economy may all be constraints in certain areas and at certain times. However, average diameter and species are the two single most important factors that determine the type of utilization best suited to an area.

The definition of sawtimber in U.S. Forest Service surveys is a tree at least 11 in. in diameter at breast height for hardwoods and western softwoods and a minimum of 9 in. for eastern softwoods. Much of the wood available for fiber, particle, and energy use is currently below sawtimber size. The Forest Service category of growing stock, which is material 5 in. in diameter and larger, is a better indication of material available for all types of forest products, from fiber to solid wood. The growing stock category does not include trees less than 5 in. in diameter that may be suitable for some product uses.

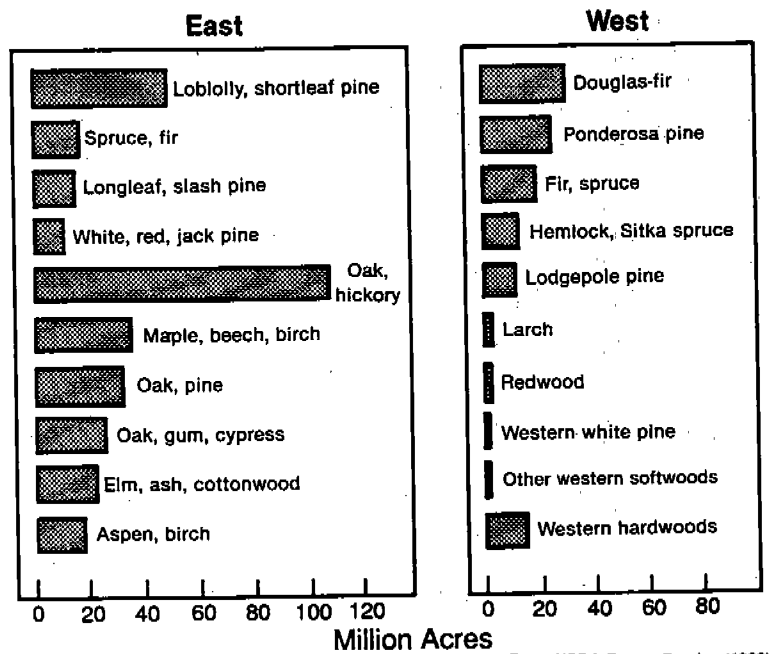
The area of commercial timberland in the East and West, by general timber species type, is shown in Figure 18.4. The major western species, Douglas-fir, distributed from the Rocky Mountain region to the Pacific Northwest, was the mainstay of the plywood industry for decades and still provides an important amount of softwood lumber and plywood. However, in the past decade hemlock, spruces, the firs, and lodgepole pine have become increasingly important in the West.

The product standards for plywood accept the product manufactured from any of the western species, although panels from Douglas-fir and western larch carry higher strength values. While lumber standards still classify western lumber by species or small species groups, for example, hem-fir, in the marketplace there is a gradual tendency away from using species as an important lumber characteristic.

In the South the major softwood species group for plywood, lumber, and pulp is southern pine. This group includes the loblolly, shortleaf, slash, and longleaf pine species. Southern pine is the most important wood in the United States for both panel products and pulp. The other softwoods of the eastern United States play only a minor role in the forest products industry when viewed from a national perspective. Locally, however, these species may be critical to the economic health of a region.

Fig. 18.4

Commercial timberland area by type



From USDA Forest Service (1982)

The annual growth of southern pine increased over 50% during the 20 years prior to 1977 to over 3 billion ft^3 of growth per year. However, since about 1977, total annual growth of pine in the region is believed to have flattened out, or perhaps begun to decline. During the period from the early 1960s until today there has been a steady increase in removals of southern pine, mostly for industrial wood. As a result of these trends there is concern that removals of southern pine are beginning to exceed the net annual growth. If these trends continue, the result will be that inventory of southern pine, upon which much industrial expansion has been based for the past 20 years, will decline (Peterson 1986).

Zobel (1980) discussed the problem in the South and elsewhere in the world from the standpoint of an imbalance in the age and size of the timber supply. There are extensive young stands but inadequate forests of an intermediate size. It is evident that future softwood products in the South and many other areas of the world will be manufactured primarily from small logs.

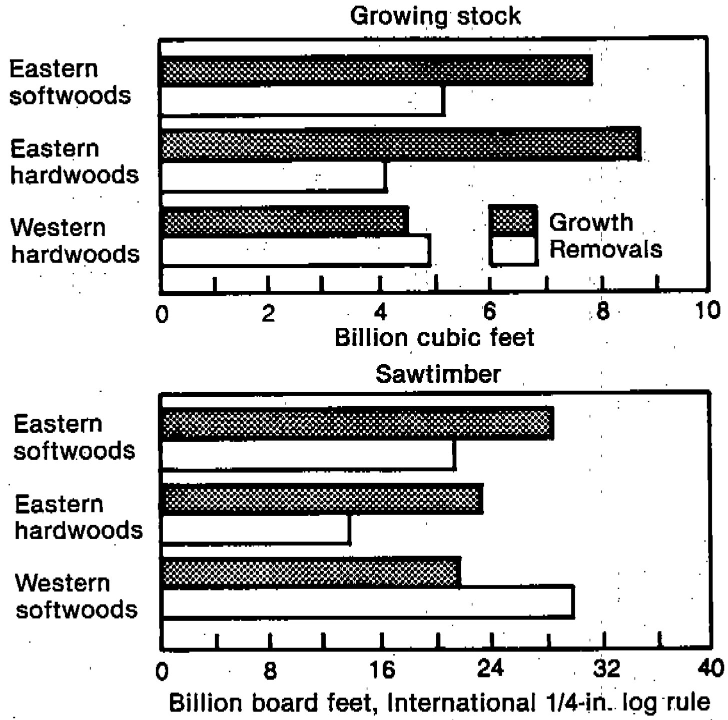
Popovich (1979) provided an interesting discussion of the timber supply situation in the South:

> According to the *Outlook* (USDA Forest Service 1980), the South is where it's at. In fact, by 2030, the South will have exchanged places with the Northwest, supplying over half the nation's roundwood and sawtimber. In 2030, as sawtimber output drops sharply in the Northwest, it increases by 75% in the South, to 31.4 billion board feet. . . . But the South is not all sunshine either. The Northwest may have longer rotations, higher transportation costs, militant environmentalists, and federal restrictions, but the South has hardwoods, lots of them, and in many places you can't give them away. In fact, seen through the *Outlook* study, the South's Third Forest is a mixed hardwood forest thanks to poor rate of pine regeneration on small woodlots.

Eighty-nine percent of the hardwood sawtimber in the United States is located in the South, the East, and the Lake States. Figure 18.5 shows the annual growth and removals for both growing stock and sawtimber of these eastern hardwoods as well as for eastern and western softwoods. Note that the growth of hardwoods exceeds removals by a large margin in both of these diameter classifications. The largest increase in timber volume is in the lower-density hardwoods, i.e., yellow poplar, gum, cottonwood, and aspen. These woods are suited to the manufacture of plywood and solid products that can serve as alternates to softwood construction material. In addition, these woods are well suited to fiber and particle products. The high-density hardwoods present the greatest technical limitations. Developing new means of utilizing these dense species is a very challenging opportunity.

The West is not a large producer of hardwoods; only 11% of all sawlog-size hardwood timber is located there. However, the volume of cottonwood and aspen in the West increased 87% from 1952 to 1977. There may be more emphasis on hardwood utilization in the West if softwood resources decline further.

Fig. 18.5
Timber growth and removals



From USDA Forest Service (1982)

The change in wood volume on timberlands during the quarter century from 1952 to 1977 is tabulated in Table 18.1. The proportion of softwood timber over 15 in. in diameter increased slightly in the South but decreased in all other regions. The decrease was dramatic in the North. In the case of hardwoods, there was a small decline in most regions in the proportion of growing stock over 15 in. in diameter.

Table 18.2 shows the net annual growth and removals of growing stock by regions from 1952 to 1976. In 1976 the volume of hardwood growth was more than double that removed for wood products or other purposes. In the case of softwoods, growth exceeded removals by only 20% on a national basis, but removals exceeded growth on the Pacific Coast.

Potentially, the commercial forestland base can produce several times as much wood as at present. Dramatic increases could result if all commercial forestland were fully stocked with trees and if these forests were fully

Table 18.1. Percent of hardwood and softwood growing stock (timber 5 in. and larger) by diameter class and region of the United States in 1952 and 1977

Region and diameter class	Percent by size category of growing stock volume: Hardwoods 1952	Hardwoods 1977	Softwoods 1952	Softwoods 1977
North				
5–15 in.	74	78	69	87
15 in. and larger	26	22	31	13
South				
5–15 in.	67	70	80	77
15 in. and larger	33	30	20	23
Pacific Coast				
5–15 in.	61	63	18	25
15 in. and larger	39	37	82	75
Rocky Mountains				
5–15 in.	80	86	50	58
15 in. and larger	20	14	50	42
Total United States				
5–15 in.	70	74	38	49
15 in. and larger	30	26	62	51

Source: Erickson (1978).

Table 18.2. Net annual growth and removals of growing stock in the United States by species group and section, 1952, 1962, and 1976

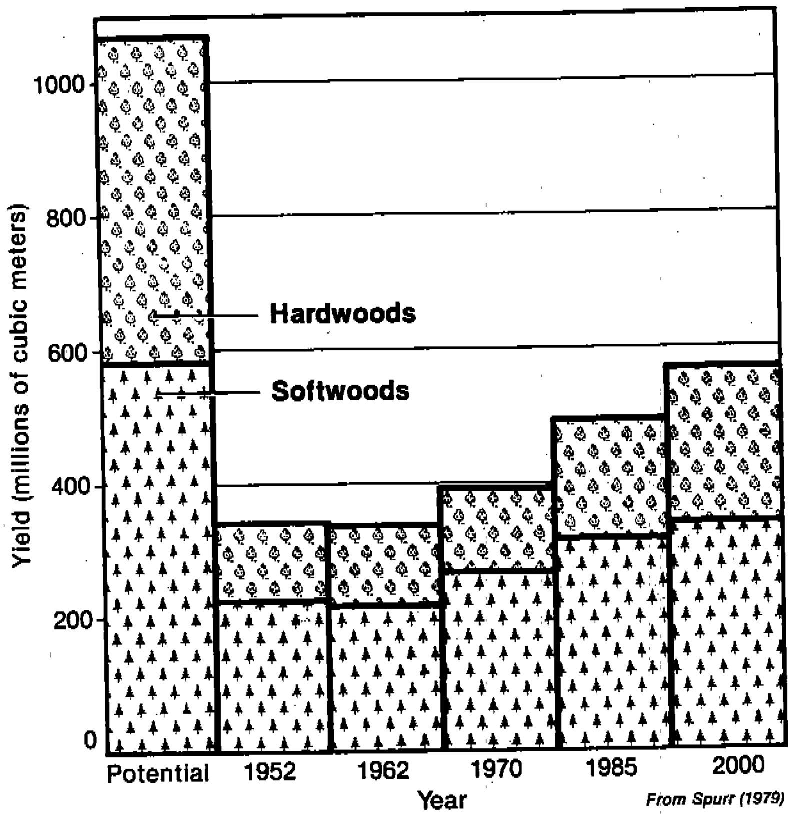
Section	All species 1952	All species 1962	All species 1976	Softwoods 1952	Softwoods 1962	Softwoods 1976	Hardwoods 1952	Hardwoods 1962	Hardwoods 1976
	(bil. ft³)								
North									
Net growth	3.8	4.4	5.5	1.0	1.2	1.6	2.8	3.2	3.9
Removals	1.9	1.9	2.5	0.6	0.5	0.7	1.3	1.4	1.9
South									
Net growth	6.7	8.1	11.2	3.6	4.7	6.3	3.0	3.4	4.9
Removals	5.8	5.6	6.7	3.1	2.8	4.5	2.7	2.8	2.2
Rocky Mountains and Great Plains									
Net growth	1.2	1.4	1.7	1.1	1.3	1.6	0.1	0.1	0.1
Removals	0.6	0.8	0.9	0.5	0.7	0.8	*	*	*
Pacific Coast									
Net growth	2.3	2.7	3.4	2.0	2.3	2.9	0.3	0.4	0.5
Removals	3.5	3.6	4.3	3.5	3.6	4.2	*	0.1	0.1
Total United States									
Net growth	14.0	16.6	21.8	7.7	9.5	12.4	6.2	7.1	9.5
Removals	11.8	11.9	14.4	7.7	7.6	10.2	4.1	4.3	4.3
Ratio of growth to removals	1.2	1.4	1.5	1.0	1.2	1.2	1.5	1.6	2.2

Source: USDA For. Serv. (1977).
* Less than 0.1 billion

managed using conventional silvicultural practices. Figure 18.6 compares this potential with actual production of wood volume since 1952. The potential as illustrated here does not include what could be done under more intensive management (irrigation, fertilization, genetically superior stock, cultivation for weed control). Thus the maximum potential for timber production is at a level much higher than suggested in Figure 18.6.

Fig. 18.6

Harvest of wood in the United States
in 1952, 1962, and 1970; projected by U.S. Forest Service for 1985 and 2000; and compared with potential growth if conventional forest management used



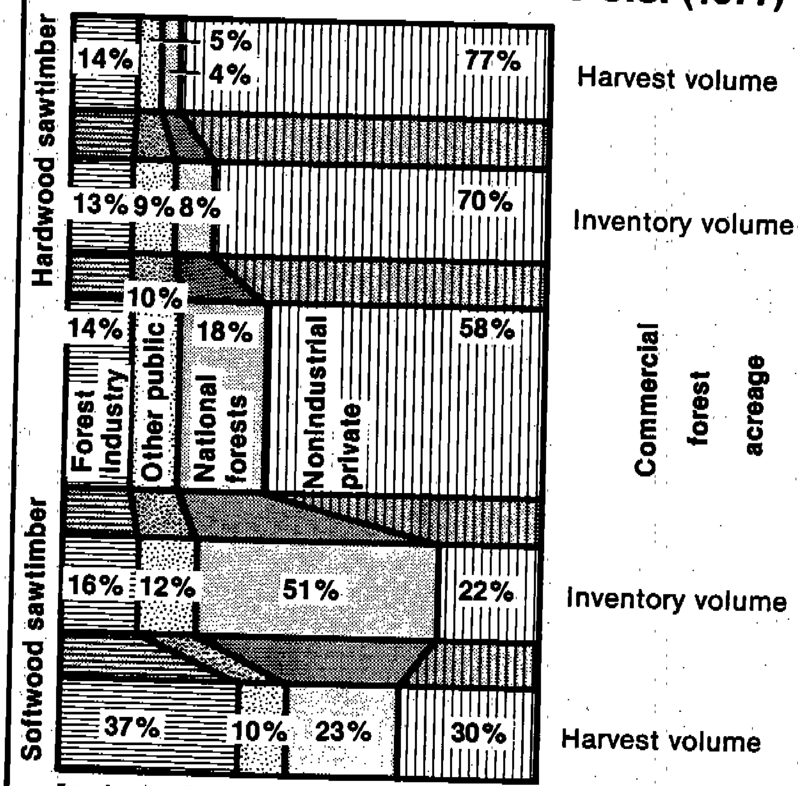
The degree to which the growth potential of forestlands will be realized depends to a large extent on the economic incentives for full production and the goals and desires of those who own the forests. Forests in public ownership (principally national forests) are under heavy public pressure for recreation and aesthetic purposes. Wood production is obviously not the primary objective on all publicly owned commercial forestlands. Likewise, small private owners may be more interested in their lands for hunting, for leisure time use, or as an investment than for income from timber growing. Since 50% of the commercial forestland is held by the private nonindustrial owner, management of these holdings is very important to the nation's future supply of timber.

Figure 18.7 shows the ownership pattern in commercial forests and the volume of sawtimber harvested from the different ownerships. Most of the hardwood timber (inventory) is on private, nonindustrial lands. In contrast, almost two-thirds of the softwood timber inventory is on public lands. Despite this fact, only one-third of the softwood sawtimber is cut from public lands. Also note in Figure 18.7 that industry-owned forests produce a very significant portion of the softwood harvest but only a small amount of the hardwoods.

The large public ownership of the softwood timber resource is likely to result in continuation of the tight softwood sawlog supply situation during the late 1980s and the 1990s. Industry will thus have an increasing incentive to improve production of softwoods on industry lands as well as to use

Fig. 18.7

Ownership, inventory, and harvest on commercial forestland in the U.S. (1977)

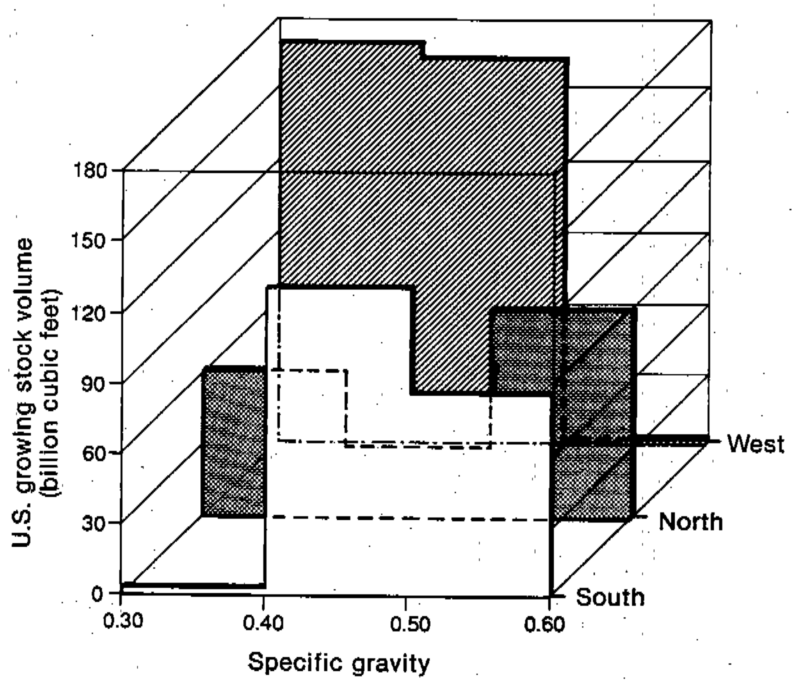


From American Forestry Institute (1979) hardwoods and small-diameter softwoods.

[redacted] The reasons for this have been discussed at various points in the text. The range of wood density encountered in different regions of the United States varies a great deal. These differences will affect technologies adapted in these regions. Figure 18.8 was prepared to illustrate how the density of timber growing stock varies between the West, the South, and the North (Lake States and Northeast). To obtain this graph the growing stock inventory in each region was classified by the wood density of the species into three density categories. Note that in the West almost all wood has a specific gravity of 0.50 or less. The South has very little wood below a specific gravity of 0.40. Both the South and the North have a significant amount of "dense" wood with a specific gravity over 0.50. This figure combines hardwood and softwood volumes.

Fig. 18.8

Growing stock of high-, medium-, and low-specific gravity species



[redacted]

intro?

Hawgreaves/Bolyar (1989)

A variety of terms is used to describe complete utilization of the material from the forest. Young (1964) described the complete tree concept as the entire tree from roots to leaves. The wood and bark above the ground has been referred to as the full tree or the whole tree. The term forest biomass refers to all woody materials in a stand, regardless of size or species.

By whatever terminology, the goal for any utilization system should be to use all the harvested stem in the way that provides the greatest net benefits for the producer and consumer. Any impact on the soil nutrient balance needs to be considered. In many cases, systems that include harvesting roots, branches, saplings, and brush may lack economic justification and thus will not be implemented. However, in special situations, use of all tree components can prove economically feasible. As mentioned in Chapter 6, roots have been harvested commercially in northern Europe and the United States. Equipment for pulling and processing roots (Koch and Coughran 1975) has been developed for use with southern pines. Stumps harvested in the United States are used principally to extract resin for chemicals.

As presently practiced, whole-tree utilization generally involves the entire stem to a small top diameter of 2–4 in. [redacted] to the lengths and log qualities suitable for sawlogs, veneer blocks, and pulpwood. Or [redacted] A third possibility is to [redacted] Some branches not broken off during felling, bunching, and hauling are also utilized when stems are chipped in the woods. Figure 18.10 illustrates a whole-tree chipper in operation. The three types of harvesting mentioned above utilize only stems of merchantable size (generally over 4 in.). Equipment of the type shown in Figure 17.1 offers the possibility of using even smaller material in a forest.

1
2
3

[redacted] the timber owner but presents problems to those utilizing the material. Bark content is high, often 10–20% by weight. Grit or dirt in the bark can cause excessive equipment wear in the mill and dulling of saws and knives when using the final product. There is a tendency to chip all trees on a tract rather than separating out the higher value logs for lumber or veneer production. This lowers the economic benefits derived from the resource. These problems can be overcome, however, with proper application of technology and management skill. Whole-tree chipping does make it possible to harvest and utilize (for particles, fiber, or energy) some stands of timber that have such low merchantable volumes per acre or low quality that they would not be economically operable under other harvesting systems.

In situations where [redacted] Facilities designed for processing tree-length logs are costly

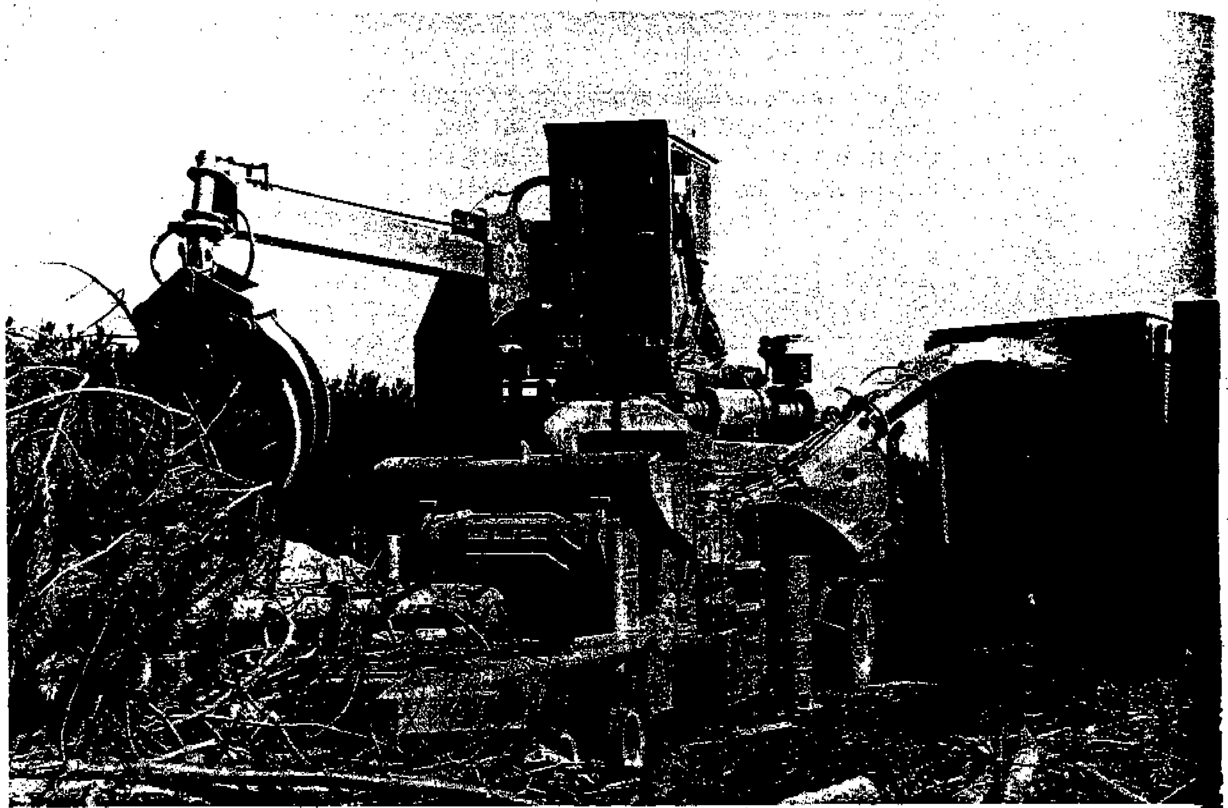


Fig. 18.10
Whole-tree chipper
operating in a pine plantation.

because of the size of logs handled and the large number of segregations that may be required for the different species, sizes, and qualities. Such installations are called log-processing centers or merchandisers. A log-processing center is shown in Figure 18.11.

Most decisions made in log-processing centers regarding allocation of the various parts of the stem are based largely upon the diameter and straightness. As electronic scanning and control systems are improved, more importance will be paid to additional factors of log quality such as size and location of knots and other defects. Improvements will be made by combining electronics, computers, and appropriate software. Breakdown and allocation of tree stems to the highest use is an area where major advancements will be made in the next few years.

Once logs are allocated to a specific manufacturing process, the elements of technology discussed in Chapters 13–16 control the effectiveness of utilization. A good way to visualize what happens to the raw material through a process is to prepare a materials balance, which shows the input of raw materials and output in terms of products and residues. Outputs must balance inputs. Figure 18.12 shows typical material balances for three manufacturing processes—softwood lumber, softwood sheathing plywood, and hardwood plywood. Note that no portion of the logs should be unaccounted for. In these examples, the proportion of the wood input used as fuel ranges from 12% in the softwood sheathing plant to 23% in the hardwood plywood plant.

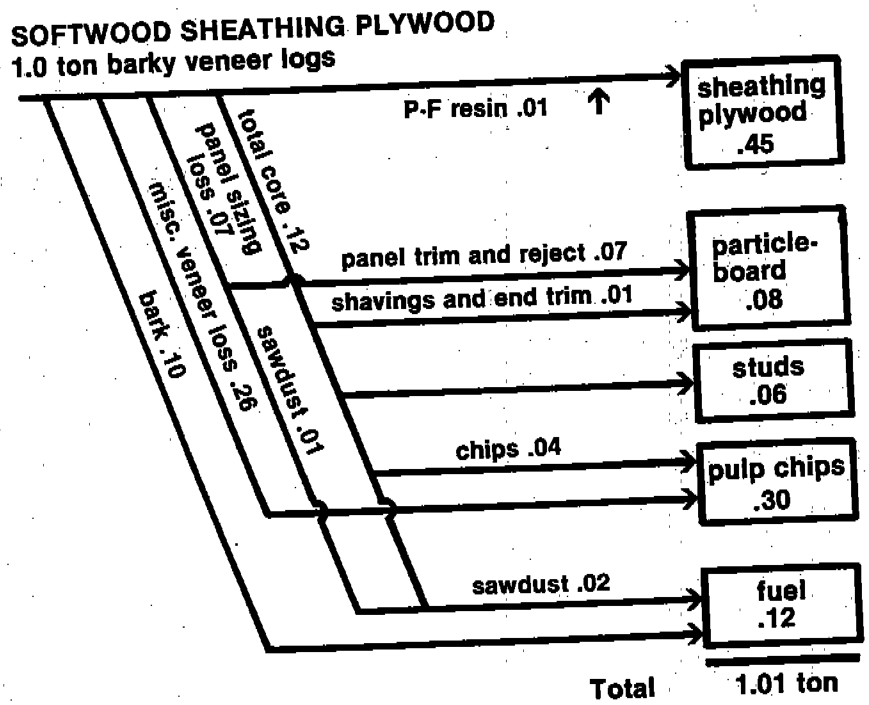
There undoubtedly are improvements possible in the processing of lumber, veneer, and particle and fiber products that have not yet been conceived. Shifts in the relative value of different forest products can greatly alter the balance of materials that should be produced. New types of wood-based materials and ways of combining different products will be developed in the next generation. These are exciting challenges for those with a strong academic background in the science and technology of wood as an industrial raw material.

Fig. 18.11
Log-processing center
Cutting logs to length for a variety of products.

Fig. 18.12

Material balances for lumber and plywood

Tons of various products produced per ton of log input (all units in ovendry weight)



p 465 with Koch (1976)

HAYGREEN & BOWYER (1989)

Table A.10. Nomenclature of commercial softwood lumber

Standard lumber name under American Softwood Lumber Standards	Official Forest Service tree name used in this handbook	Botanical name
Cedar		
Alaska	Alaska-cedar	*Chamaecyparis nootkatensis*
Eastern red	Eastern redcedar	*Juniperus virginiana*
Incense	Incense-cedar	*Libocedrus decurrens*
Northern white	Northern white-cedar	*Thuja occidentalis*
Port Orford	Port-Orford-cedar	*Chamaecyparis lawsoniana*
Southern white	Atlantic white-cedar	*C. thyoides*
Western red	Western redcedar	*Thuja plicata*
Cypress, red (coast type), yellow (inland type), white (inland type)	Baldcypress	*Taxodium distichum*
Douglas-fir	Douglas-fir	*Pseudotsuga menziesii*
Fir		
Balsam	Balsam fir	*Abies balsamea*
	Fraser fir	*A. fraseri*
Noble	Noble fir	*A. procera*
White	California red fir	*A. magnifica*
	Grand fir	*A. gandis*
	Pacific silver fir	*A. amabilis*
	Subalpine fir	*A. lasiocarpa*
	White fir	*A. concolor*
Hemlock		
Eastern	Eastern hemlock	*Tsuga canadensis*
Mountain	Mountain hemlock	*T. mertensiana*
West Coast	Western hemlock	*T. heterophylla*
Juniper, western	Alligator juniper	*Juniperus deppeana*
	Rocky Mountain juniper	*J. scopulorum*
	Utah juniper	*J. osteosperma*
	Western juniper	*J. occidentalis*
Larch, western	Western larch	*Larix occidentalis*
Pine		
Idaho white	Western white pine	*Pinus monticola*
Jack	Jack pine	*P. banksiana*
Lodgepole	Lodgepole pine	*P. contorta*
Longleaf yellow*	Longleaf pine	*P. palustris*
	Slash pine	*P. elliottii*
Northern white	Eastern white pine	*P. strobus*
Norway	Red pine	*P. resinosa*
Southern yellow	Longleaf pine	*P. palustris*
	Shortleaf pine	*P. echinata*
	Loblolly pine	*P. taeda*
	Slash pine	*P. elliottii*
	Pitch pine	*P. rigida*
	Virginia pine	*P. virginiana*
Sugar	Sugar pine	*P. lambertiana*
Redwood	Redwood	*Sequoia sempervirens*
Spruce		
Eastern	Black spruce	*Picea mariana*
	Red spruce	*P. rubens*
	White spruce	*P. glauca*
Englemann	Blue spruce	*P. pungens*
	Engelmann spruce	*P. engelmannii*
Sitka	Sitka spruce	*P. sitchensis*
Tamarack	Tamarack	*Larix laricina*
Yew, Pacific	Pacific yew	*Taxus brevifolia*

*The commercial requirements for longleaf yellow pine lumber are that not only must it be produced from the species *Pinus elliottii* and *P. palustris* but each piece must average either on one end or the other not less than 6 annual rings per inch and not less than ⅓ summerwood. Longleaf yellow pine lumber is sometimes designated as pitch pine in the export trade.

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