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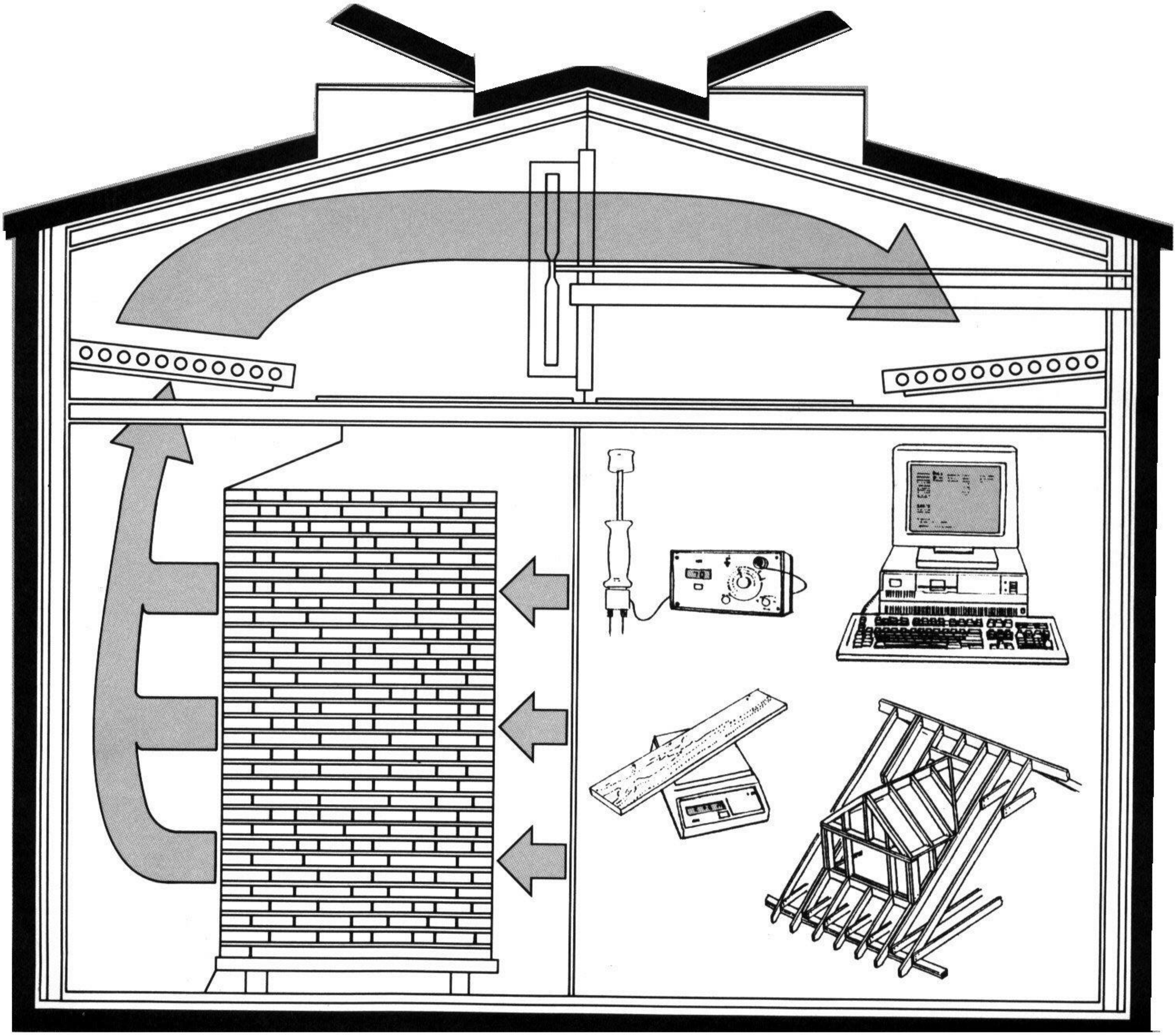
Dry Kiln Operator's Manual



Dry Kiln Operator's Manual

Edited by
William T. Simpson,
Research Forest Products Technologist

United States Department of Agriculture
Forest Service
Forest Products Laboratory[1]
Madison, Wisconsin

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Preface

The purpose of this manual is to describe both the basic and practical aspects of kiln drying lumber. The manual is intended for several types of audiences. First and foremost, it is a practical guide for the kiln operator-a reference manual to turn to when questions arise. It is also intended for mill managers, so that they can see the importance and complexity of lumber drying and thus be able to offer kiln operators the support they need to do their job well. Finally, the manual is intended as a classroom text-either for a short course on lumber drying or for the wood technology curriculum in universities or technical colleges.

This manual is a revision of the 1961 edition by Edmund F. Rasmussen. Forest Service staff who contributed to that original edition were Raymond C. Rietz, Edward C. Peck, John M. McMillen, Harvey H. Smith, and A.C. Knauss. It is a credit to these men that the 1961 edition has been in wide use and demand for the past 28 years. It is also to their credit that even though the manual is out of date in many parts, we were able to use the basic framework of the original edition to build on.

The Forest Products Laboratory staff involved in this revision were William T. Simpson (who wrote the introduction and had overall responsibility for coordination), R. Sidney Boone, James C. Ward, and John L. Tschernitz. Each person was responsible for revising certain chapters or parts of chapters. This assignment of responsibilities is indicated on the chapter-opening pages. Chapters 5 and 7 of the original manual were combined in this revision. Chapter 11, Energy in Kiln Drying, is a new chapter and was written by John L. Tschernitz. In addition to this assignment of chapters, there were many formal and informal meetings among us to exchange ideas.

Acknowledgments

Many people helped in the revision. We visited many mills to make sure we understood current and developing kiln-drying technology as practiced in industry, and we thank all the people who allowed us to visit. Professor John L. Hill of the University of New Hampshire provided the background for the section of chapter 6 on the statistical basis for kiln samples. Kiln manufacturers were also very helpful in spending time with us and providing photographs and schematics of drying equipment. In particular, we wish to thank Coe Manufacturing Company, Hemco (Harvey Engineering and Manufacturing Corp.), Irvington–Moore, Nyle Corporation, Uraken Canada, Ltd., and Wagner Electronic Products, Inc., for their help. We also thank Professor Charles J. Kozlik, retired from Oregon State University, for arranging and accompanying several of us on a plant tour in the Northwest.

Contents

Introduction

The modern dry kiln is a unique product of research, development, and experience. It is the only practical means now in wide use for rapid, high-volume drying of lumber to conditions necessary for maximum serviceability in housing, furniture, millwork, and many other wood products. As part of our charge to help further the efficient utilization of our nation's timber resource, Forest Service research and development in lumber drying has made a significant contribution to the technology. The Forest Products Laboratory (FPL) has been conducting research in lumber drying since it was established in 1910. Early work by Harry Tiemann (The Kiln Drying of Lumber: A Practical and Theoretical Treatise, J.B. Lippincott Company, Philadelphia, PA, 1917) at FPL established lumber kiln-drying technology and the first lumber dry kiln design. Tiemann's book can really he considered the first drying manual. Several other FPL drying manuals followed before the 1961 manual by Rasmussen.

A well-designed and properly operated dry kiln can in a few days or weeks turn green lumber fresh from the forest into a dry, stable material necessary for successful industrial enterprises in today's highly competitive markets. The more critical the drying requirements, the more firmly the dry kiln becomes established as an integral part of the lumber mill, the furniture factory, or the millwork plant. For many wood products, kiln-dried lumber is essential.

Dried lumber has many advantages over green lumber for producers and consumers alike. Removal of excess water reduces weight and thus shipping and handling costs. Proper drying confines shrinking and swelling of wood in use to manageable amounts under all but extreme conditions of relative humidity. Properly dried lumber can be cut to precise dimensions and machined more easily and efficiently; wood parts can he more securely fitted and fastened together with nails, screws, bolts, and adhesives; warping, splitting, checking, and other harmful effects of uncontrolled drying are largely eliminated; paint, varnish, and other finishes are more effectively applied and maintained; and decay hazards are eliminated if the wood is subsequently treated or protected from excessive moisture regain.

Efficient kiln drying of lumber is therefore of key importance in the utilization of our forest resource. On one hand, it helps to assure continued markets for wood products by increasing their service life, improving their performance, and contributing to consumer satisfaction. On the other hand, it helps to conserve our forest resource by reducing waste in manufacture and extending service life and usefulness of products. Both are essential in using timber wisely, which has long been an accepted tenet of forest management policy.

The full benefits of modern kiln-drying technology can be gained only when certain prerequisites are observed. Mill management must recognize the importance of efficient operation to quality of product, and operators must be well trained and encouraged to apply the best techniques. Quality should not be sacrificed for quantity in the production of kiln-dried lumber. The high value of our timber resource makes it uneconomical to do so.

Terms used in this manual to describe dry kilns and their components, drying characteristics of wood, and kiln operational procedures are generally accepted and used throughout the industry. For clarification and to help the newcomer with common terminology, a glossary of terms is included after the last chapter.

Chapter 1
Properties of Wood Related to Drying

Chapter 1 was revised by William T. Simpson, Supervisory Research Forest Products Technologist.

Lumber drying is one of the most time- and energy-consuming steps in processing wood products. The anatomical structure of wood limits how rapidly water can move through and out of wood. In addition, the sensitivity of the structure to stresses set up in drying limits the drying rate; rapid drying causes defects such as surface and internal checks, collapse, splits, and warp. Drying time and susceptibility to many drying defects increase at a rate that is more than proportional to wood thickness. The variability of wood properties further complicates drying. Each species has different properties, and even within species, variability in drying rate and sensitivity to drying defects impose limitations on the development of standard drying procedures. The interactions of wood, water, heat, and stress during drying are complex. The purpose of this chapter is to describe some of the fundamental properties of wood that are relevant to lumber drying. We will discuss commercial wood species, wood structure, lumber grades, water movement in wood, how wood dries, specific gravity and weight of wood, wood shrinkage, stress development during drying, and electrical and thermal properties of wood.

Commercial Wood Species

More than 100 commercially important species of trees grow in the United States. A similar number of species are imported into the United States, and the potential for additional imported species grows. The lumber produced from all of these species varies greatly in drying characteristics. The most commonly used commercial names for lumber and the corresponding species names accepted by the Forest Service for the trees from which the lumber is cut are given in table 1-1 for domestic species and table 1-2 for tropical species. Table 1-1 was adapted from the standard nomenclature of domestic hardwoods and softwoods developed by the American Society for Testing and Materials (1981). Tropical species follow the nomenclature used by Chudnoff (1984). While the commonly used lumber names are generally satisfactory for the buying and selling of lumber, they sometimes refer to lumber from a number of species that differ in green moisture content, shrinkage, or drying characteristics. In the tables and indexes of physical properties and drying schedules given in this and other chapters, the woods are arranged alphabetically by the common species names accepted by the Forest Service.

Hardwoods and Softwoods

Trees can be divided into two classes, hardwoods and softwoods. The hardwoods, such as birch, maple, and oak, have broad leaves. Some softwoods or conifers, such as the cedars, have scalelike leaves, while others, such as pine, Douglas-fir, and spruce, have needlelike leaves.

The terms hardwood and softwood are not directly associated with the hardness or softness of the wood. In fact, such hardwood trees as cottonwood, basswood, and yellow-poplar have softer wood than such softwoods as longleaf pine and Douglas-fir.

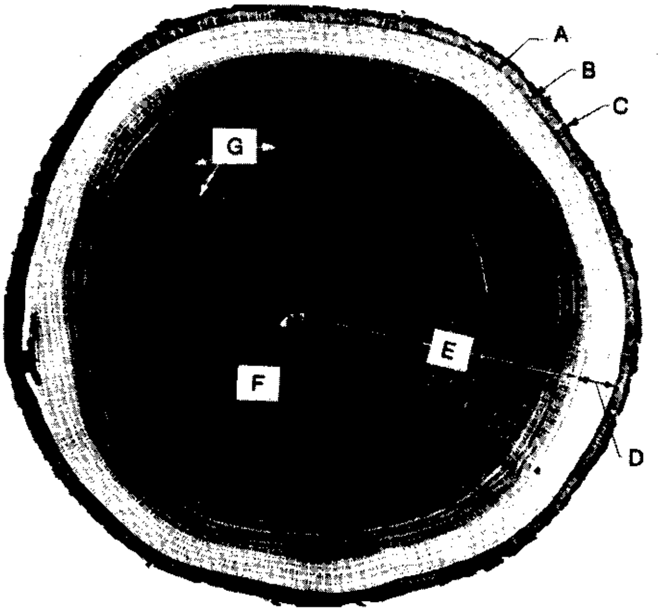

Figure 1-1—Cross section of a white oak tree trunk. A, Cambium layer (microscopic) is inside inner bark and forms wood and bark cells. B, Inner bark is moist and soft, and contains living tissue; the inner bark carries prepared food from leaves to all growing parts of tree. C, Outer bark containing corky layers is composed of dry dead tissue; it gives general protection against external injuries. Inner and outer bark are separated by a bark cambium. D, Sapwood, which contains both living and dead tissues, is the light-colored wood beneath the bark; it carries sap from roots to leaves. E, Heartwood (inactive) is formed by a gradual change in the sapwood. F, Pith is the soft tissue about which the first wood growth takes place in the newly formed twigs. G, Wood rays connect the various layers from pith to bark for storage and transfer of food. (MC88 9016)

Structural Features of Wood

The structure of wood and the location and amount of water in wood influence its drying characteristics. Wood is composed of bark, sapwood, heartwood, and pith (fig. 1-1). Each wood cell has a cavity (lumen) and walls composed of several layers arranged in different ways (fig. 1-2). The cell wall constituents are cellulose, hemicelluloses, and lignin. Most of the tubelike cells are oriented parallel to the long axis of the tree and are termed fibers, tracheids, or vessels, depending on their particular anatomical characteristics and function. Another type of cell, the wood ray, lies on radial lines from the center of the tree outward and perpendicular to the length of the tree. Figures 1-3 and 1-4 illustrate the arrangement of cells in softwoods and hardwoods, which have a similar but not identical anatomy.

One particular type of anatomical element, the pit, is important in water flow. A pit is a small, valve-like opening that connects adjacent wood cells and thus is an important pathway for the flow of water. Pits often become encrusted with substances or otherwise clogged so that water flow through them is very slow. Several types of pits are shown in figure 1-5.

Pits in softwoods often become aspirated as drying progresses. In aspiration, the torus is displaced so that it covers the pit aperture. In effect, the valves close during drying so that water flow through them is inhibited. The result is a decrease in drying rate.

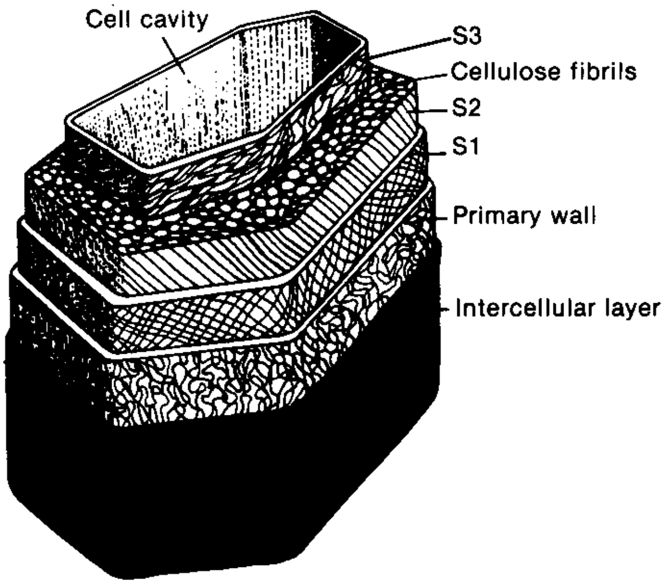

Figure 1-2—Cross section of a wood cell showing the several layers in the cell wall. (ML88 5567)

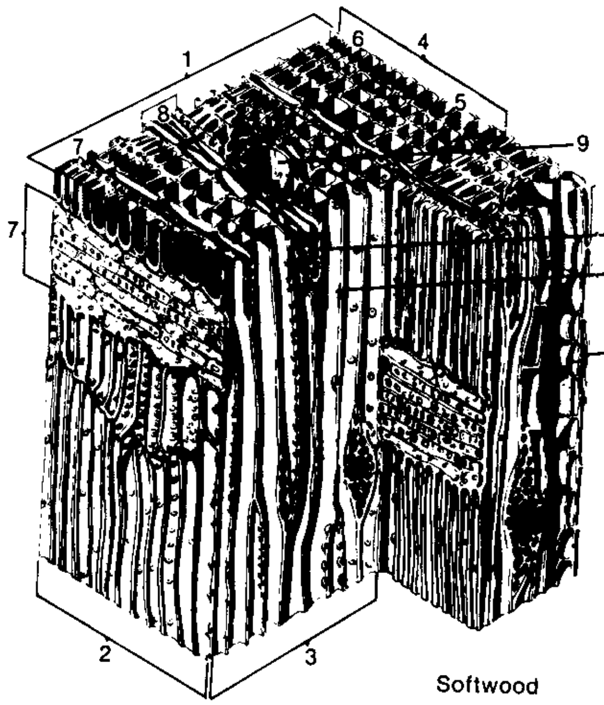

Figure 1-3—Wood structure of a softwood with resin ducts. (ML88 5568)

1. Cross-sectional face
2. Radial face
3. Tangential face
4. Growth ring
5. Earlywood
6. Latewood
7. Wood ray
8. Fusiform ray
9. Vertical resin duct
10. Horizontal resin duct
11. Bordered pit
12. Simple pit

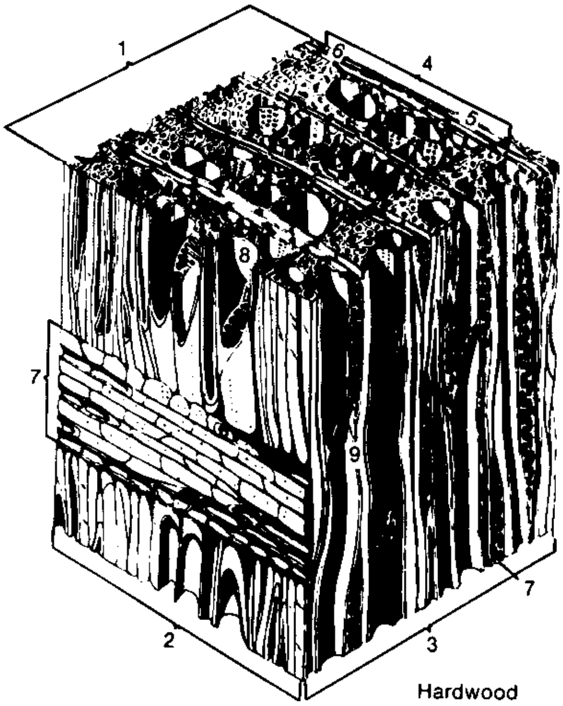

Figure 1-4—Wood structure of a hardwood. (ML88 5570)

1. Cross-sectional face
2. Radial face
3. Tangential face
4. Growth ring
5. Earlywood
6. Latewood
7. Wood ray
8. Vessel
9. Sieve plate

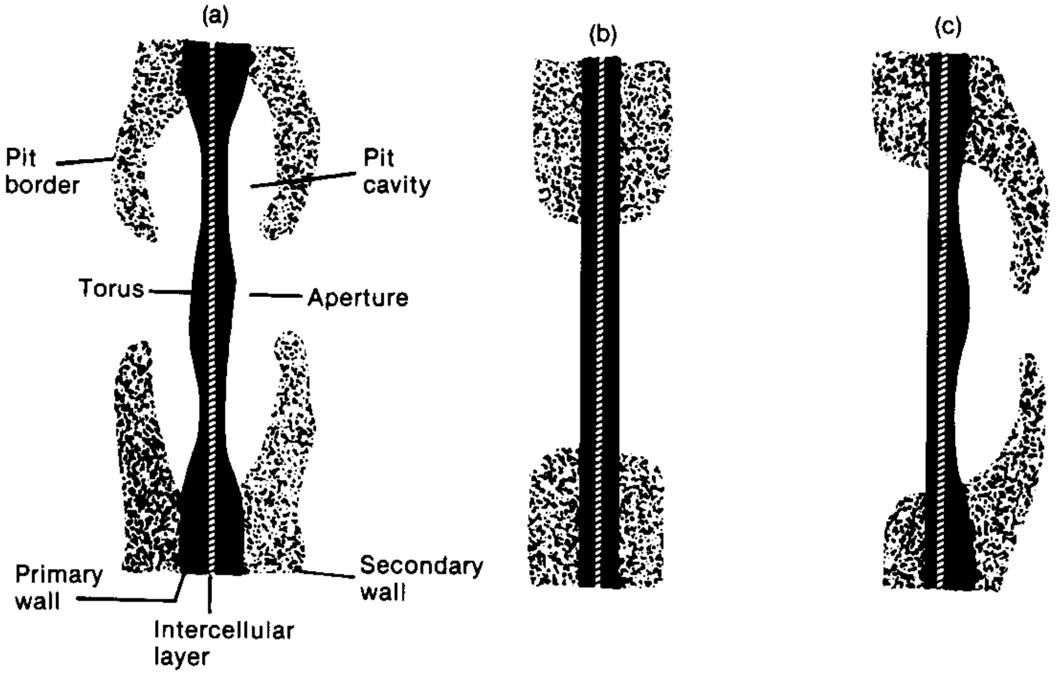

Figure 1-5—Pit cross sections. (a) Bordered pit (with torus in softwoods); (b) simple pit; and (c) half-bordered pit. (ML88 5569)

Sapwood and Heartwood

Sapwood and heartwood (fig. 1-1) affect the drying of wood. The sapwood layer next to the bark contains living cells that actively transport fluids necessary to the life of the tree. As the tree grows and increases in diameter by adding new layers of sapwood, the inner layers die. This inner wood, called heartwood, becomes infiltrated with gums, resins, and other material. Sapwood of softwood species is usually higher in moisture content than heartwood; sapwood moisture content in hardwood species is usually somewhat higher than or about equal to that of heartwood. The infiltration of gums and other material in heartwood make it more resistant to moisture flow (less permeable) than sapwood, and thus heartwood usually requires longer drying time. The lower permeability of heartwood also makes it more susceptible to certain drying defects (ch. 8), and so it requires milder drying conditions. Heartwood is usually darker than sapwood. However, because the change in color may occur slowly over a period of several years, a band of heartwood may be indistinguishable from adjacent sapwood; nevertheless, the heartwood will not dry easily because it is less permeable. Heartwood is also usually more resistant to decay and .some stains than sapwood.

Pith

The pith of a tree (fig. 1-1F) is usually near the center of the tree and is laid down by the growing tip. It is usually very small. Pith sometimes cracks during drying.

Annual Growth Rings

Diameter growth of a tree in temperate climates is represented by rings that usually can be easily seen on the end of a log as concentric circles around the pith. The closer the rings are to the pith, the smaller their radii of curvature. Each annual growth ring is composed of an inner part called earlywood (springwood), which is formed early in the growing season, and an outer part, called latewood (summerwood), which is formed later. When lumber is cut from a log, the annual rings are cut across in one direction or another and form a characteristic pattern on the broad face of the boards (fig. 1-6). In tropical woods, where there may be more than one active growing period annually, growth rings cannot be considered annual rings. In the majority of tropical species, however, there is no noticeable beginning or end of successive growth periods, so the typical pattern of rings shown in figure 1-6 does not occur.

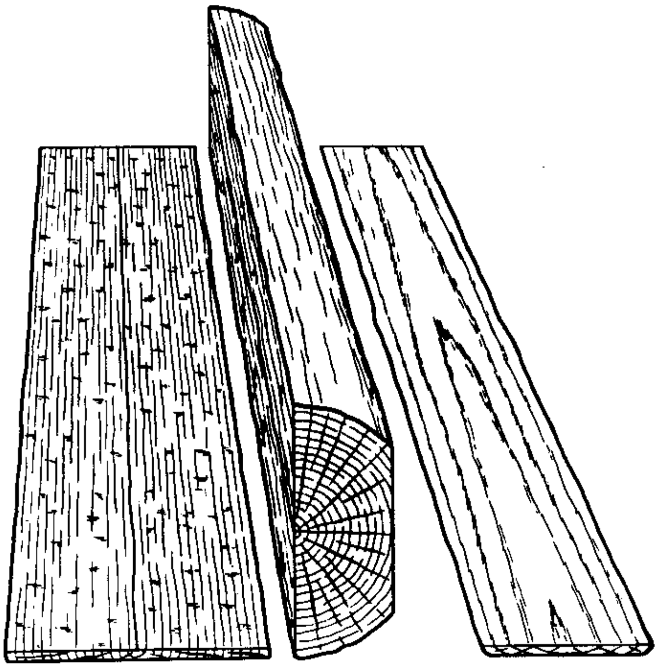

Figure 1-6—Annual growth rings. Quartersawn board (left) shows edge of annual rings on its broad face; flatsawn board (right) shows side of rings. (M 554)

The orientation of growth rings to the faces and edges of boards depends on how lumber is cut from a log. Lumber can be cut from a log in the two ways shown in figure 1-6. Sawing tangent to the annual rings produces flatsawn lumber, also called plainsawn, flat-grained, or slash-grained lumber. Sawing perpendicular to the annual rings produces quartersawn lumber, also called edge-grained or vertical-grained lumber. The angle of cut to the annual rings often lies somewhere in between. In commercial practice, lumber with rings at angles of 45° to 90° to the wide surface is called quartersawn, and lumber with rings at angles of 0° to 45° is called flatsawn. Hardwood lumber in which annual rings make angles of 30° to 60° to the wide face is sometimes called bastard sawn.

Either flatsawn or quartersawn lumber is generally suitable for most purposes. However, each type of sawn lumber responds differently in drying. Flatsawn lumber is less susceptible to collapse, shrinks and swells less in thickness, and dries faster than quartersawn. Quartersawn lumber shrinks and swells less in width, and has less twist, cup, and surface checks than flatsawn. These drying defects are discussed in chapter 8.

Wood Rays

Wood rays appear as ribbonlike strands on the face of quartersawn boards (fig. 1-6) and as short lines on the face of flatsawn boards in species with large rays. Because rays are weak and dry faster than the surrounding wood cells, surface, end, and honeycomb checks usually occur in or next to them. Species such as oak and beech, which have large rays, require special care during the early stages of drying to avoid checks.

Grain and Texture

The physical characteristics of various species that have some bearing on drying are loosely termed grain and texture. The terms fine grained and coarse grained refer to ring pattern, either the prominence of the latewood band or the width of the rings. When used in connection with wood cells, grain refers only to the direction of the cells or fibers. In straight-grained wood, the fibers run generally parallel to the length of the board, and in cross-grained or spiral-grained, they run at an angle. The terms end grain and side grain are commonly used in discussing moisture loss and drying defects. A cross section of a log or board has an end-grain surface. Any other section (radial, tangential, or intermediate) has a side-grain surface.

Texture usually refers to the diameter of individual cells. Fine-textured wood has small cells and coarse-textured, large cells. If all the cells of a wood are approximately the same size, the wood is usually called uniform textured. Uniform-textured woods in general are less likely to develop drying defects than nonuniform-textured woods. The word texture should not be used in describing hardness of wood.

Color

As a tree grows, the white or straw-colored sapwood gradually changes to heartwood, and the formation of extractives changes the color of most species. Holly, basswood, cottonwood, and magnolia, however, are examples of hardwoods in which the wood undergoes little or no change in color. Spruces and true firs are examples of softwoods that do not change color greatly.

The temperatures used in kiln drying sometimes darken wood, especially in high-temperature drying. Changes in the color of heartwood during drying are usually of little concern, but those that occur in sapwood are often significant. Chemical stains can occur when green sapwood of some species is kiln dried. The sapwood of hickory tends to turn pinkish when kiln dried (low initial temperatures must be used to preserve its whiteness) and paper birch sapwood may turn brownish. Hard maple sapwood is prone to darkening if dried at temperatures that are too high. Whiteness of the sapwood is often a very desirable feature of these species, and darkening reduces their value.

Beneficial color changes can be brought about by steaming wood before drying. Walnut, for example, is steamed in vats to darken the sapwood before drying so that it more nearly matches the color of the heartwood. Sapwood of sweetgum can be steamed to produce a salmon color that at one time was desirable for some products. Red alder is also steamed to produce a uniform honey-brown color of sapwood and heartwood.

Several other types of stain are considered drying defects, and they are discussed in chapter 8.

Variations in Structure

Lumber commonly contains variations in wood structure, such as spiral grain, knots, compression wood, tension wood, and juvenile wood.

Cross grain in lumber may result either from the way in which the log is sawed (diagonal grain) or from spiral grain that occurred in the growing tree. When spiral grain alternately runs in one direction and another in successive groups of growth rings, interlocked grain results. Lumber containing diagonal, spiral, or interlocked grain shrinks more in length than straight-grained lumber. Such lumber may bow, crook, and twist during drying.

Knots are sections of tree branches appearing in boards. Because of shrinkage, some kinds of knots may drop out during drying; more often, however, they are loosened or checked during drying and drop out of the board during handling or machining. These are called incased knots, and they result from the growth of trunk wood around dead branches. Intergrown knots, caused by the intergrowth of trunk wood and living branches, are much less likely to drop out of dried lumber.

Compression wood occurs in softwoods mainly on the lower side of leaning trees but sometimes in other parts of the tree trunk. Because this wood shrinks more along the length of boards than normal wood, boards that contain both compression and normal wood may bow, crook, and twist during drying. If this warping is restrained, the compression wood may fracture and form crossbreaks in the lumber.

Tension wood occurs in hardwoods, mainly on the upper side of leaning trees but sometimes in other parts of the trunk. Lumber containing this wood will shrink more longitudinally than normal wood, causing warp during drying.

Juvenile wood occurs in a cylinder around the pith. Once juvenile wood is formed, it does not mature-it is in the tree and lumber forever. However, as growth progresses, the new wood, as it is formed, gradually acquires more mature wood characteristics. Juvenile wood varies with species and occurs in the first 5 to 20 years of growth. The structural and physical properties of juvenile wood are considered inferior. From the standpoint of drying, the main problem is that juvenile wood shrinks more along the grain than mature wood, and warp is likely to occur during drying. Juvenile wood is more prevalent in fast-grown plantation trees than in slower grown stands. Species that are grown in volume in plantations, such as southern pine, present warp problems in drying.

Commercial Lumber Grades

When a log is sawed into lumber, the quality of the boards varies. The objective of grading is to categorize each board by quality so that it meets the requirements of the intended end uses. The grade of a board is usually based on the number, character, and location of features that may lower its strength, utility, appearance, or durability. Common visible features that affect grade are knots, checks, pitch pockets, shake, warp, and stain. Some of these features are a natural part of the tree and some can be caused by poor drying and storage practices.

Hardwood Lumber Grades

Most hardwood lumber is graded according to rules adopted by the National Hardwood Lumber Association. The grade of a board is determined by the proportion that can be cut into a certain number and size of smaller pieces clear of defects on at least one side. The grade is based on the amount of usable cuttings in the board rather than on the number or size of grade-determining features that characterize most softwood grades.

The highest cutting grade is termed Firsts and the next grade Seconds. Firsts and Seconds are usually combined into one grade, FAS. The third grade is termed Selects, followed by No. 1 Common, No. 2 Common, Sound Wormy, No. 3A Common, and No. 3B Common. Standard grades are described in table 1-3, which illustrates the grade-determining criteria of board length and width, surface measure of clear cuttings, percentage of board that must yield clear cuttings, and maximum number and size of cuttings allowed.

Hardwood lumber is usually manufactured to standard sizes. Standard lengths are in 1-ft increments from 4 to 16 ft. Hardwood lumber is usually manufactured to random width, but there are minimum widths for each grade as follows:

Firsts	6 in
Seconds	6 in
Selects	4 in
Nos. 1, 2, 3A, 3B Common	3 in

Standard thicknesses for rough and surfaced-two-sides (S2S) lumber are given in table 1-4.

This brief summary of grades is not complete and is only intended to offer a general view of how hardwood lumber is graded. The official grading rules of the National Hardwood Lumber Association should be consulted for complete details. There are also grading rules for dimension stock and special finished products such as flooring.

Softwood Lumber Grades

Softwood lumber grades can be divided into two categories based on use: for construction and for remanufacture. Construction lumber is expected to function as graded and sized after the primary processing steps of sawing, drying, and planing. Lumber for remanufacture is further modified in size and/or shape before use. There are many individual grading rules for different softwood species. The U.S. Department of Commerce has published the American Softwood Lumber Standard PS-20-70, which is an optional standard, in an attempt to reduce the differences in grading rules.

Construction lumber can be divided into three general categories: stress-graded, non-stress-graded, and appearance lumber. Stress-graded and non-stress-graded lumber are used where structural integrity is the prime concern; structural integrity is of secondary importance in appearance lumber. Almost all softwood lumber nominally 2 to 4 in thick is stress graded. This is the lumber that is typically used as 2 by 4 studs, joists, rafters, and truss members. Grading is based on the premise that lumber has lower strength than clear wood; characteristics used for grading are density (usually judged by ring count), decay, slope of grain, knots, shake, checks and splits, wane, and pitch pockets. These characteristics can be visually assessed.

Lumber intended for general building and utility purposes with little or no remanufacture is typically non-stress graded. Boards are one of the most common non-stress-graded products. The common grades are separated into several different categories that vary with species and grading associations. First-grade boards are usually graded primarily for serviceability, although appearance is also a consideration. Typical uses are siding, cornice, shelving, and paneling. Second- and lower-grade boards are permitted more and larger knots and are suitable for such products as subfloors, sheathing, and concrete forms.

Appearance lumber is often nonstress graded but forms a separate category because of the importance of appearance. Secondary manufacture is usually restricted to onsite fitting and cutting. Typical products are trim, siding, flooring, casing, and steps. Most appearance grades are described by combinations of letters such as B&BTR and C&BTR, although such terms as select and clear are used for some species. The upper grades allow a few minor imperfections such as small planer skips, checks, stain, and pin knots. The number and size of imperfections increase as the grade drops.

Lumber intended for further manufacture in plants as opposed to onsite modifications is usually graded as factory or shop lumber. It forms the basic raw material for many secondary operations such as furniture and mill work. Factory Select and Select Shop are typically the highest grades, followed by No. 1, No. 2, and No. 3. Grade characteristics are influenced by the width, length, and thickness of the piece and are based on the amount of high-quality material that can be cut from it.

There are several other grading systems for specialty products such as ladders, pencils, tanks, laminating stock, and industrial clears.

Moisture content is often specified in softwood lumber grades. For many products, the moisture content must be within certain limits and the grade stamp must include the moisture content at the time of surfacing. Lumber surfaced green is usually required to be stamped S-GRN. Most softwood lumber is dried to below 19 percent moisture content, and when surfaced at this moisture content it is stamped S-DRY. Sometimes the maximum allowable moisture content is 15 percent, and this is stamped as MC-15 or KD.

Wood-Moisture Relations

All wood in growing trees contains a considerable quantity of water, commonly called sap. Although sap contains some materials in solution, from the drying standpoint sap can be considered plain water. Most of this water should be removed to obtain satisfactory service for most uses of wood. All wood loses or gains moisture in an attempt to reach a state of balance or equilibrium with the conditions of the surrounding air. This state of balance depends on the relative humidity and temperature of the surrounding air. Therefore, some knowledge of wood-moisture relations is helpful in understanding what happens to wood during drying, storage, fabrication, and use.

The amount of moisture in wood is termed the moisture content. It can be expressed as a percentage of either dry or wet weight. For most purposes, the moisture content of lumber is based on dry weight, but the moisture content of wood fuel is usually based on wet weight. Moisture content on dry and wet basis is defined as follows:

On dry basis,

$$\text{Moisture content (percent)} = \frac{\text{Weight of water in wood}}{\text{Weight of totally dry wood}} \times 100$$

On wet basis,

$$\text{Moisture content (percent)} = \frac{\text{Weight of water in wood}}{\text{Weight of dry wood and water}} \times 100$$

These two ways of expressing moisture content can be related by

$$\text{Moisture content (dry)} = \frac{\text{Moisture content (wet)}}{100 - \text{Moisture content (wet)}} \times 100$$

In this manual we will deal only with the dry basis. For most species, the common and accurate method of determining moisture content is the ovendrying method, or oven test. This method is inaccurate for species with a high extractives content. In ovendrying (described in ch. 6), all the water is evaporated from a wood section by heating. Knowing the wood weight before and after ovendrying allows calculation of moisture content.

The amount of water in green or wet wood varies greatly, depending mainly on species. The moisture content of some species may be as low as 30 percent, whereas that of others may be as high as 200 percent. Large variations may occur not only between species but also within the same species and even in the same tree. In softwood species, sapwood usually contains more water than heartwood. In species such as redwood, the butt logs of trees may contain more water than the top logs. Some species contain an abnormal type of heartwood, called wetwood or sometimes sinker stock, that is sometimes higher in green moisture content than normal wood of the species. In addition to the higher moisture content, wetwood is slower to dry than normal wood and often more susceptible to such drying defects as honeycomb and collapse.

Contrary to popular belief, the amount of water in green wood does not vary greatly with the season of the year in which the trees are cut. Moisture content values for green wood of various species is given in table 1-5.

Free and Bound Water

Water is held in wood as free water or bound water. Free water is contained in the cell cavities (fig. 1-2); bound water is held within the cell walls. Free water is held within the cell cavities less tightly than the bound water is held within the cell walls. Consequently, slightly more energy is required to remove bound water than free water. Free water does not affect as many wood properties as bound water, but does affect thermal conductivity and permeability. Bound water affects many physical and mechanical properties, and its removal causes changes that affect the use of the wood.

Fiber Saturation Point

The fiber saturation point is defined as the moisture content at which the cell walls are saturated but no free water remains in the cell cavities. Moisture content of the individual cell walls at the fiber saturation point is usually about 30 percent, but may be lower for some species. Care must be used in judging whether a piece of wood is at the fiber saturation point. The term really refers to individual cells rather than boards or other pieces of wood. The mechanisms of how wood dries will be discussed later, but basically wood dries from the outside to the inside. Thus, during drying, the outside part of a board might be at 15 percent moisture content while the inside might still be at 45 percent. The average moisture content of the entire board might be 30 percent, but it is erroneous to consider the board to be at the fiber saturation point. There will be a continuous variation or gradient of moisture content from the outside to the inside of the board from 15 to 45 percent, and only some cells will be exactly at the fiber saturation point of 30 percent.

The fiber saturation point is important in the drying of wood for the following reasons: (1) more energy is required to evaporate water from a cell wall than from the cell cavity (approximately 5 percent more at 15 percent moisture content and 15 percent more at 6 percent moisture content); (2) a wood cell will not shrink until it reaches the fiber saturation point; and (3) large changes in many physical and mechanical properties of wood begin to take place at the fiber saturation point.

Equilibrium Moisture Content

Wood loses or gains moisture until the amount it contains is in balance with that in the surrounding atmosphere. The amount of moisture at this point of balance is called the equilibrium moisture content (EMC). The EMC depends mainly on the relative humidity and temperature of the surrounding air, although species and previous moisture history have a slight effect on EMC. The relationship of EMC to relative humidity and temperature is shown in figure 1-7. If, for example, wood is kept in air at 141 °F and 65 percent relative humidity, it will eventually either gain or lose moisture until it reaches approximately 10 percent moisture content.

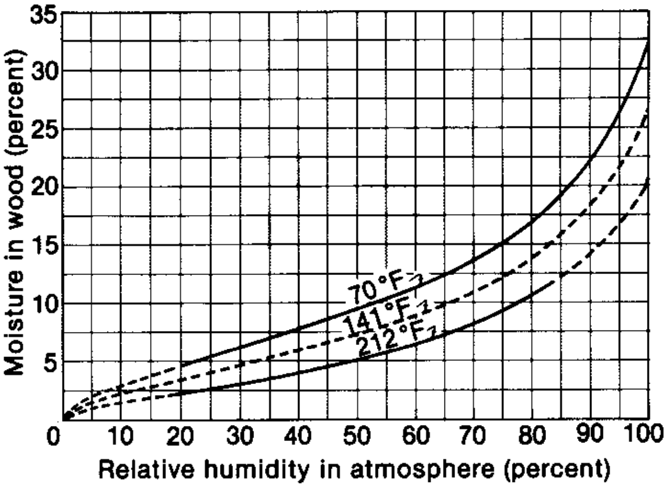

Figure 1-7—Relation of the equilibrium moisture content of wood to the relative humidity of the surrounding atmosphere at three temperatures. (ML88 5572)

Kiln drying usually requires control of EMC conditions, that is, temperature and relative humidity, in the kiln. Thus both temperature and relative humidity have to be measured. Two thermometers-dry bulb and wet bulb--are used to obtain temperature and relative humidity. The dry-bulb thermometer measures temperature in the usual way, and the result is called the dry-bulb temperature. The sensor of the wet-bulb thermometer is kept wet with a wick cover, from which water evaporates at a rate determined by the relative humidity and temperature of the air. The drier the air, the faster the rate of evaporation. This evaporation has a cooling effect that increases as the rate of evaporation increases. Thus, the drier the air, the greater the cooling effect and the lower the temperature indicated by the wet-bulb thermometer. The difference between dry- and wet-bulb temperatures, called the wet-bulb depression, is thus a measure of the relative humidity of the air.

The relationship between relative humidity, temperature, and EMC is shown in table 1-6 for temperatures below 212 °F, and in table 1-7 for temperatures above 212 °F. For example, assume that the dry-bulb temperature in a kiln is 150 °F and the wet-bulb temperature 130 °F. The wet-bulb depression then is 20 °F. Wet-bulb depression temperatures are shown across the top of tables 1-6 and 1-7 and dry-bulb temperatures on the extreme left of the table. To find the EMC at the assumed conditions, (1) locate 20 °F wet-bulb depression column and (2) follow this column downward until it intersects the 150 °F dry-bulb temperature line. The EMC value, 8 percent, is the underscored value. Note that the relative humidity value (not underscored), 57 percent, is given directly above the EMC value. Wet- and dry-bulb temperatures, EMC, and psychrometric relations are further discussed in the appendix to this chapter.

How Wood Dries

Water in wood normally moves from higher to lower zones of moisture content. This fact supports the common statement that "wood dries from the outside in," which means that the surface of the wood must be drier than the interior if moisture is to be removed. Drying can be broken down into two phases: movement of water from the interior to the surface of wood, and removal of water from the surface. Moisture moves to the surface more slowly in heartwood than in sapwood, primarily because extractives plug the pits of heartwood. In drying, the surface fibers of heartwood of most species reach moisture equilibrium with the surrounding air soon after drying begins. This is the beginning of the development of a typical moisture gradient (fig. 1-8), that is, the difference in moisture content between the inner and outer portions of a board. The surface fibers of sapwood also tend to reach moisture equilibrium with the surrounding air if the air circulation is fast enough to evaporate water from the surface as fast as it comes to the surface. If the air circulation is too slow, a longer time is required for the surfaces of sapwood to reach moisture equilibrium. This is one reason why air circulation is so important in kiln drying. If it is too slow, drying is also slower than necessary and mold might even develop on the surface of lumber. If it is too fast, electrical energy in running the fans is wasted, and in certain species surface checking may develop if wet-bulb depression and air velocity are not coordinated.

Water moves through wood as liquid or vapor through several kinds of passageways. These are the cavities of fibers and vessels, ray cells, pit chambers and their pit membrane openings, resin ducts of certain softwoods, other intercellular spaces, and transitory cell wall passageways (Panshin and de Zeeuw 1980). Most water lost by wood during drying moves through cell cavities and pits. It moves in these passageways in all directions, both along and with the grain. Lighter species in general dry faster than heavier species because their structure contains more openings per unit volume.

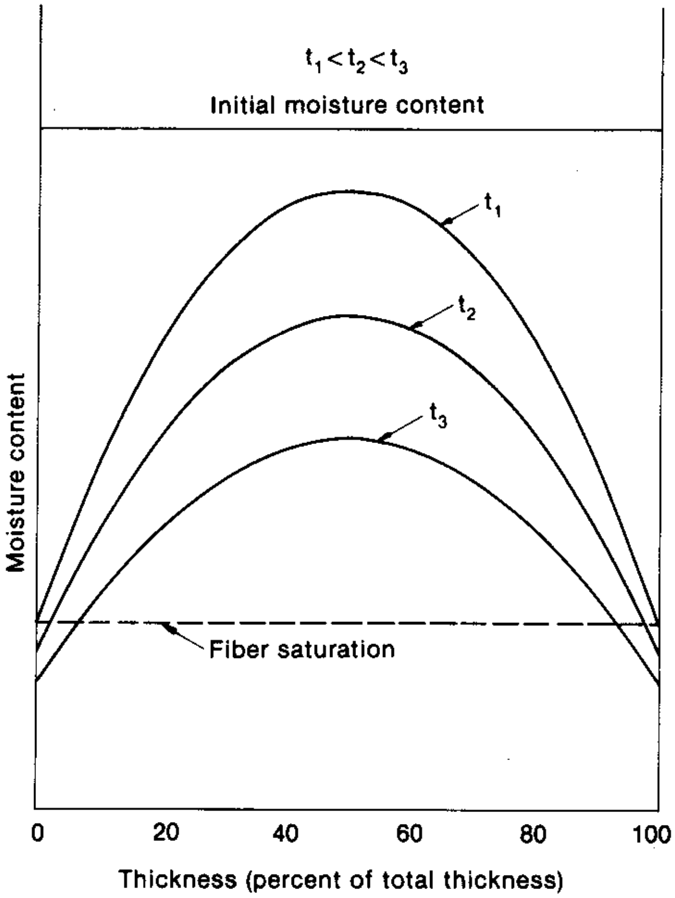

Figure 1-8—Typical moisture gradient in lumber during drying at times increasing from t_1 to t_3. (ML88 5571)

Forces That Move Water

When wood is drying, several forces may be acting simultaneously to move water (Siau 1984):

1. Capillary action causes free water to flow through the cell cavities and pits.
2. Differences in relative humidity cause water vapor to move through the cell cavities by diffusion, which moves water from areas of high to areas of low relative humidity. Cell walls are the source of water vapor; that is, water evaporates from the cell walls into the cell cavities.
3. Differences in moisture content cause bound water to move through the cell walls by diffusion, which moves water from area of high to areas of low moisture content. Generally, any water molecule that moves through wood by diffusion moves through both cell walls and cell cavities. Water may evaporate from a cell wall into a cell cavity, move across the cell cavity, be readsorbed on the opposite cell wall, move through the cell wall by diffusion, and so on until it reaches the surface of the board.

When green wood starts to dry, evaporation of water from the surface cells sets up capillary forces that exert a pull on the free water in the zones of wood beneath the surface, and a flow results. This is similar to the movement of water in a wick. Much free water in sapwood moves in this way. In comparison to diffusion, capillary movement is fast.

Longitudinal diffusion is about 10 to 15 times faster than lateral (radial or tangential) diffusion. Radial diffusion, perpendicular to the growth rings, is somewhat faster than tangential diffusion, parallel to the rings. This explains why flatsawn lumber dries faster than quartersawn lumber. Although longitudinal diffusion is 10 to 15 times faster than lateral diffusion, it is of practical importance only in short items. Common lumber is so much longer than it is thick that most of the water removed during drying does so through the thickness direction, leaving from the wide face of a board. In lumber where width and thickness are not greatly different, such as in squares, significant drying occurs in both the thickness and width directions.

The rate ʻof diffusion depends to a large extent upon the permeability of the cell walls and their thickness. Thus permeable species dry faster than impermeable ones, and the rate of diffusion decreases as the specific gravity increases.

Because moisture moves more freely in sapwood than heartwood, both by diffusion and by capillary flow, sapwood generally dries faster than heartwood under the same drying conditions. The heartwood of many species, however, is lower in moisture content than sapwood, and may reach final moisture content faster.

Factors That Influence Drying Rate

The rate at which moisture moves in wood depends on the relative humidity of the surrounding air, the steepness of the moisture gradient, and the temperature of the wood. The lower the relative humidity, the greater the capillary flow. Low relative humidity also stimulates diffusion by lowering the moisture content at the surface, thereby steepening the moisture gradient and increasing diffusion rate. The higher the temperature of the wood, the faster moisture will move from the wetter interior to the drier surface. If relative humidity is too low in the early stages of drying, excessive surface and end checking may result. And if the temperature is too high, collapse, honeycomb, or strength reduction may occur (see ch. 8).

Lumber Thickness

Drying rate is also affected by thickness. Drying time increases with thickness and at a rate that is more than proportional to thickness. For example, if thickness is doubled, drying time is more than doubled. Theoretically, if drying were controlled completely by diffusion, drying time would increase by a factor of four if thickness were doubled. But because of the other mechanisms involved in drying, drying time increases between three and four times. Thickness variation in lumber caused by poor sawing can lead to excessive moisture content variation after drying or excessive kiln time to equalize the variation. For example, the kiln-drying time for l-in-thick red oak will vary by about 4 percent for each 1/32-in variation in thickness.

Specific Gravity and Weight of Wood

Specific gravity is a physical property of wood that is a guide to ease of drying as well as an index of weight (table 1-8). In general, the heavier the wood, the slower the drying rate and the greater the likelihood of developing defects during drying. Specific gravity is defined as the ratio of the weight of a body to the weight of an equal volume of water. The specific gravity of wood is usually based on the volume of the wood at some specified moisture content and its weight when ovendry:

$$\text{Specific gravity} = \frac{\text{Ovendry weight of wood}}{\text{Weight of equal volume of water}}$$

Thus, if the specific gravity of a piece of green wood is 0.5, the ovendry weight of the wood substance in a cubic foot of the green wood is one-half the weight of a cubic foot of water. The higher the specific gravity of wood, the greater the amount of ovendry wood per unit volume of green wood. Thus, at the same moisture content, high specific gravity species contain more water than low specific gravity species. The green weight of 1 ft^3 of wood can be calculated from the following formula:

$$\text{Green weight} = \text{Specific gravity} \times (\text{Moisture content} + 100) \times 62.4/100 \text{ lb}$$

For example, the green weight of 1 ft^3 of a species of specific gravity 0.4 at 75 percent moisture content is 43.7 lb. The ovendry weight (by substituting 0 for moisture content in the formula) is 25 lb, and thus 18.7 lb of water are present. At a specific gravity of 0.6 at 75 percent moisture content, the green weight is

65.5 lb, the ovendry weight 37.4 lb, and the weight of water 28.1 lb. Thus, there are 9.4 lb more water at a specific gravity of 0.6 than at 0.4.

As the above formula indicates, weight of wood depends on its specific gravity and moisture content. Calculated weights for lumber are given in table 1-9. The values for weights per thousand board feet apply to a thousand feet, surface measure, of boards exactly 1 in thick (actual board feet) and not to a thousand board feet lumber scale. These weights were determined in the way described by Panshin and de Zeeuw (1980) and the resulting weight per cubic foot at the given moisture content multiplied by 83.3, the number of cubic feet in a thousand board feet. Note that two correction factors are given for calculating weights at moisture contents not shown in table 1-9. These factors are simply added to table values to calculate weights between table values. The correction factor for below 30 percent moisture content takes into account the volumetric shrinkage that occurs below 30 percent moisture content. The correction factor above 30 percent moisture content does not require a shrinkage correction component.

Since the weights in table 1-9 are based on actual board feet-a thousand lineal feet of lumber exactly 1 in thick and 12 in wide-they must be adjusted upward for rough lumber greater than 1 in thick and downward for surfaced lumber less than 1 in thick.

Example: What is the weight of 1,000 fbm of nominal 1 by 8 ponderosa pine lumber at 6 percent moisture content dressed to 25/32 in thick by 7-1/2 in wide?

The downward adjustment factor is calculated as follows:

$$\frac{25/32 \times 7\frac{1}{2}}{1 \times 8} = 0.732$$

From table 1-9, the weight of 1,000 fbm, actual, of this size ponderosa pine is 2,271 lb. With the downward adjustment the weight is

$$2{,}271 \times 0.732 = 1{,}662 \text{ lb}$$

Example: What is the weight of 1,000 fbm of nominal 4/4 rough, random width, northern red oak lumber at 75 percent moisture content? Assume the target sawing thickness is 37/32 in.

The upward adjustment factor is calculated as follows:

$$\frac{37/32}{1} = 1.156$$

Table 1-9 does not have a column for 75 percent moisture content, so the correction factor in column 2 must be used. The weight at 60 percent moisture content in table 1-9 is 4,666 lb. Using the correction factor of 29.1 lb per 1 percent moisture content, the weight of 1,000 fbm, actual, is

$$(75 - 60) \times 29.1 + 4{,}666 = 5{,}103 \text{ lb}$$

And with the upward adjustment factor, the weight of the nominal 4/4 lumber is

$$5{,}103 \times 1.156 = 5{,}899 \text{ lb}$$

Shrinkage of wood

Shrinkage of wood is the basic cause of many problems that occur in wood during drying and also in service. When water begins to leave the cell walls at 25 to 30 percent moisture content, the walls begin to shrink. Even after drying, wood will shrink and swell in service as relative humidity varies (table 1-6). Drying stresses develop because wood shrinks by different amounts in the radial, tangential, and longitudinal directions and because during drying, shrinkage starts in the outer fibers before it starts in the inner fibers. These stresses can cause cracks and warp to develop.

When wood is dried to 15 percent moisture content, about one-half of the total possible shrinkage has occurred; when dried to 8 percent, nearly three-fourths of the possible shrinkage has occurred. Figure 1-9 illustrates how Douglas-fir shrinks with loss of moisture. While these curves are not straight, the relationship between moisture content and shrinkage is generally approximated a a straight-line relationship.

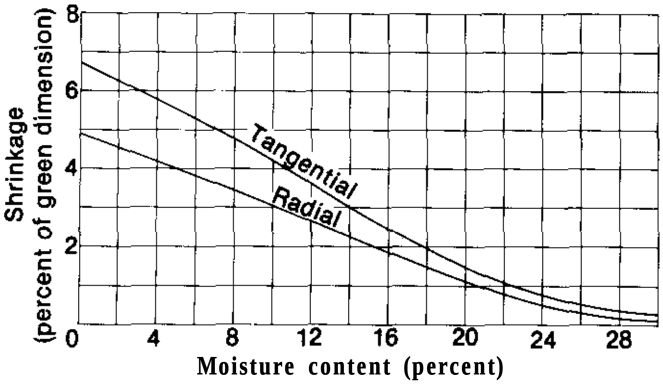

Figure 1-9—Typical relation of moisture content to shrinkage of Douglas-fir. Although the curves are not straight lines, they may be considered as such for practical shrinkage calculations. (ML88 5573)

Average Shrinkage Values

Table 1-10 gives average shrinkage values for various species of wood. These values are given in percentages of the green dimension.

$$\text{Shrinkage (percent)} = \frac{\text{Green dimension} - \text{Dry dimension}}{\text{Green dimension}} \times 100$$

Wood shrinks about 1.5 to 2 times as much parallel to the growth rings (tangential) as it does at a right angle to the growth rings (radial). The shrinkage along the grain (longitudinal) is small (0.2 percent or less for normal wood). Characteristic shrinkage patterns of boards are shown in figure 1-10.

Table 1-10 gives shrinkage values at only 20, 6, and 0 percent moisture content. Knowing the total shrinkage of a species at 0 percent moisture content, the percent shrinkage at any moisture content below 30 percent can be calculated. Since shrinkage curves are reasonably close to straight lines from 30 percent (approximate fiber saturation point) to 0 percent moisture content, each 1 percent change in moisture contact below 30 percent is equal to 1/30 of the total shrinkage from 30 to 0 percent.

$$S_M = \frac{S_0(30 - M)}{30}$$

where S_M is percent shrinkage from green to moisture content M and S_0 is total shrinkage to 0 percent moisture content from table 1-10.

Example: What is the tangential shrinkage of western hemlock from green to 12 percent moisture content?

From table 1-10, the shrinkage of western hemlock to 0 percent moisture content is 7.8 percent. From the above equation

$$S_M = \frac{7.8(30 - 12)}{30} = 4.7 \text{ percent}$$

Shrinkage Variability

Shrinkage differs not only with respect to the length, width, and thickness of a board, but even in material cut from the same species and from the same tree. The values listed in table 1-10 are only representative values for the species, and individual observations of shrinkage may differ from them.

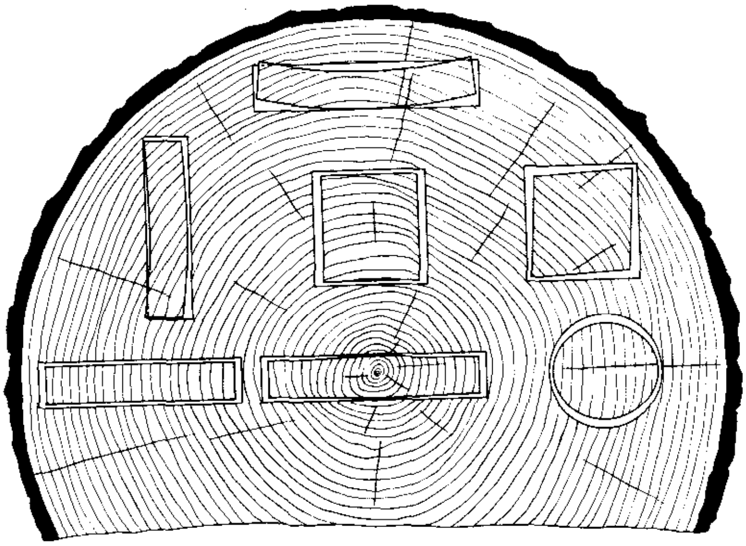

Figure 1-10—Characteristic shrinkage and distortion of flats, squares, and rounds as affected by the direction of annual growth rings. The dimensional changes shown are somewhat exaggerated. (M 12494)

On the average, hardwoods shrink more than softwoods. In general, species of high specific gravity shrink more than ones of low specific gravity, but there are exceptions. Basswood, a light species, has high shrinkage, while the heavier black locust has more moderate shrinkage. The amount of shrinkage and the difference between radial and tangential shrinkage have a direct influence on the development of drying defects. Species that are high in extractive content–like tropical species such as true mahogany-have relatively low shrinkage.

Longitudinal shrinkage is variable. While it is usually less than 0.2 percent from green to ovendry, reaction wood and juvenile wood can shrink as much as 1 to 1.5 percent. As an increasing amount of young-growth plantation trees with juvenile wood is harvested, the variability of longitudinal shrinkage and its influence on warp become more of a problem.

Drying Stresses

The effect of drying stresses on the development of drying defects is discussed in chapter 8. Drying stresses are the main cause of nonstain-related drying defects. Understanding these stresses provides a means for preventing them. There are two causes of drying stresses: hydrostatic tension and differential shrinkage. Hydrostatic tension forces develop during the flow of capillary water. As water evaporates from cell cavities near the surface, it exerts a pull on water deeper in the wood. This tension pull is inward on the walls of cells whose cavities are full of water, and the result can be an in-

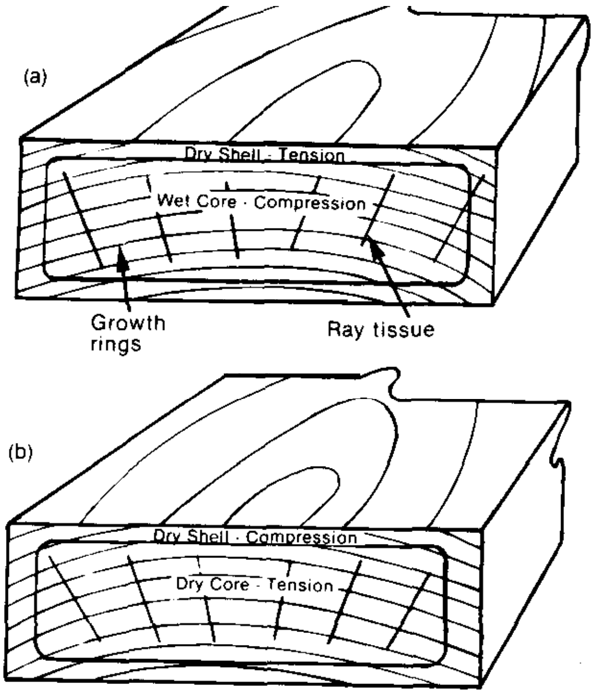

Figure 1-11—End view of board showing development of drying stresses early (a) and later (b) in drying. (ML88 5574)

ward collapse of the cell wall. The danger of collapse is greatest early in drying when many cell cavities are full of water, and if the temperature is high, collapse is more likely to occur.

Differential shrinkage between the shell and core of lumber also causes drying defects. Early in the drying process, the fibers in the shell (the outer portion of the board) dry first and begin to shrink. However, the core has not yet begun to dry and shrink, and consequently the core prevents the shell from shrinking. Thus, the shell goes into tension and the core into compression, as illustrated in figure 1-11. If the shell dries too rapidly, it is stressed beyond the elastic limit and dries in a permanently stretched (set) condition without attaining full shrinkage. Sometimes surface checks occur during this early stage of drying, and they can be a serious defect for many uses. As drying progresses, the core begins to dry and attempts to shrink. However, the shell is set in a permanently expanded condition and prevents normal shrinkage of the core. This causes the stresses to reverse-the core goes into tension and the shell into compression. The change in the shell and core stresses and moisture content during drying is shown in figure 1-12. These internal tension stresses may be severe enough to cause internal cracks (honeycomb) to occur.

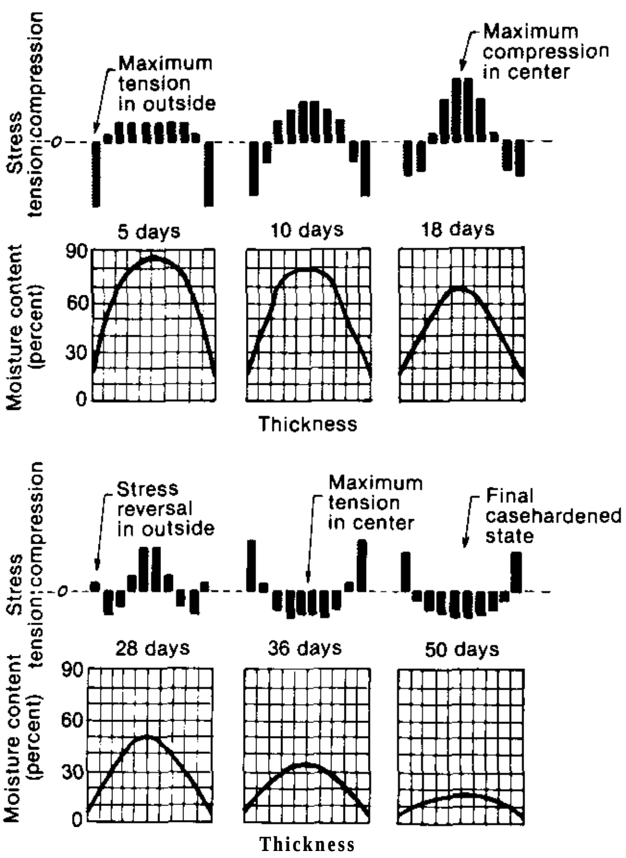

Figure 1-12—Moisture–stress relationship during six stages of kiln drying 2-in red oak. (ML88 5575)

Differential shrinkage caused by differences in radial, tangential, and longitudinal shrinkage is a major cause of warp. The distortions shown in figure 1-10 are due to differential shrinkage. When juvenile or reaction wood is present on one side or face of a board and normal wood is present on the opposite face, the difference in their longitudinal shrinkage will also cause warp.

Electrical Properties

Electrical properties of wood vary enough with moisture content that they can be used to measure moisture content reasonably accurately and very quickly. Those electrical properties of wood that indicate level of moisture content are resistance to the flow of electrical current and dielectric properties. These properties are utilized in electric moisture meters to estimate the moisture content of wood (James 1988).

The direct current electrical resistance of wood varies greatly with moisture content, especially below the fiber saturation point. It decreases greatly as moisture content increases (table 1-11). Resistance also varies with species, is greater across the grain than

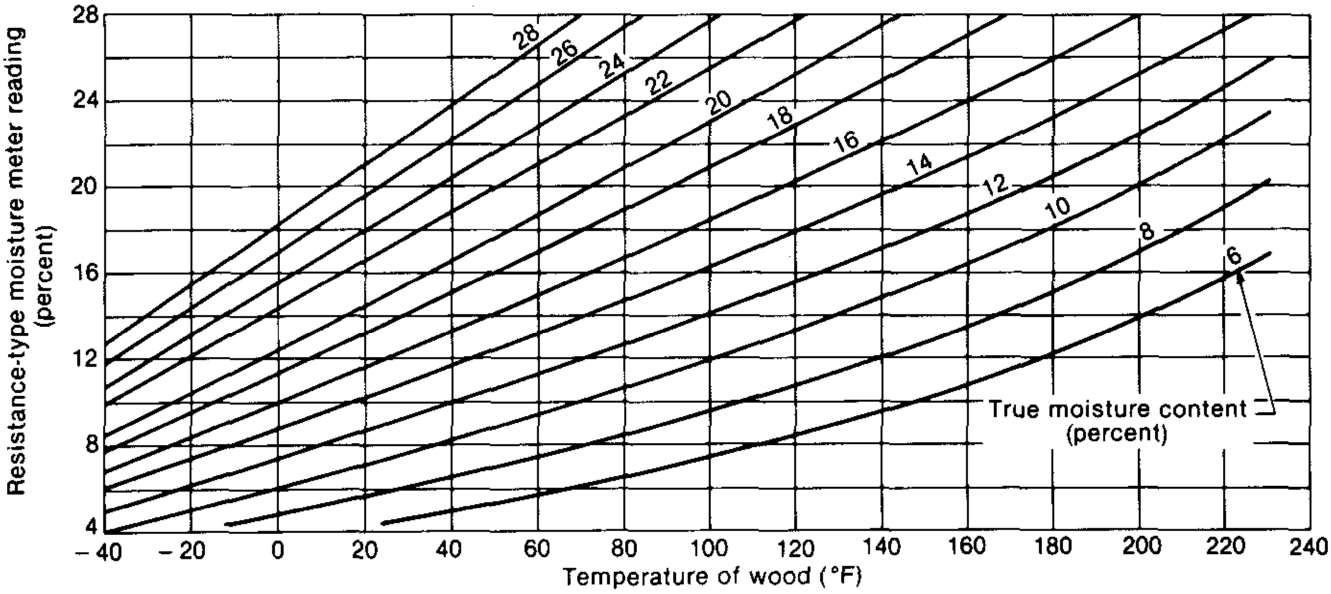

Figure 1-13—Temperature corrections for reading of resistance-type moisture meters, based on combined data from several investigators. Find meter reading on vertical axis, follow horizontally to vertical line corresponding to the temperature of the wood, and interpolate corrected reading from family of curves. Example: If meter indicated 18 percent on wood at 120 °F, corrected reading would be 14 percent. This chart is based on a calibration temperature of 70 °F. For other calibration temperatures near 70 °F, adequate corrections can be obtained simply by shifting the temperature scale so that the true calibration temperature coincides with 70 °F on the percent scale. For example, for meters calibrated at 80 °F, add 10 °F to each point on the temperature scale (shift the scale 10 °F toward the left), and use the chart as before. After temperature correction, apply the appropriate species correction. (ML88 5576)

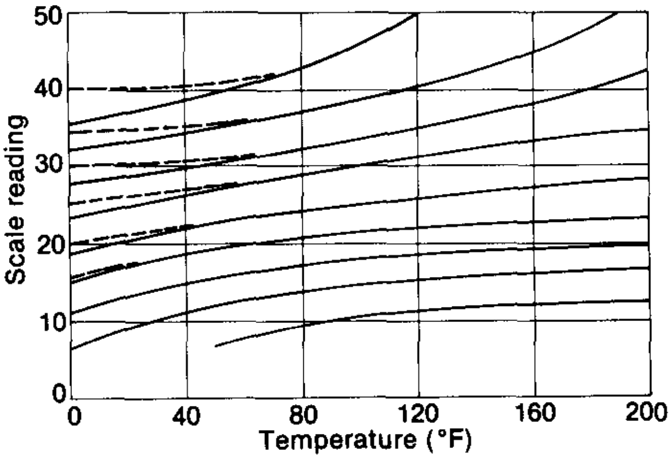

Figure 1-14—Approximate temperature corrections for capacitive admittance meter; data taken using a "Sentry" hand meter with calibration setting of 20 or greater. Solid lines are for the meter itself at room temperature; broken lines are for the meter at the same temperature as the lumber. (ML88 5578)

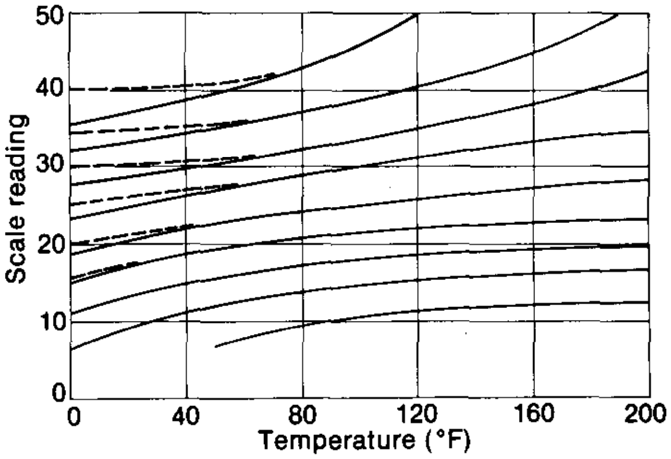

Figure 1-15—Approximate temperature corrections for readings of power-loss type moisture meters; data taken using a Moisture Register model L. Locate the point whose coordinates are the observed scale reading and the specimen temperature, and trace back parallel to the curves to the calibration temperature of the meter (usually 80°F). The vertical coordinate here is the corrected scale reading, which is then converted to moisture content using the usual species conversion tables. Solid lines are for the meter itself at room temperature; broken lines are for the meter at the same temperature as the lumber. (ML88 5579)

along it, and is affected by temperature. Resistance is not greatly affected by specific gravity. Commercial resistance moisture meters are often calibrated for one species, but are supplied with a species correction table. The meters are usually calibrated for 70 °F and also require a temperature correction chart (fig. 1-13). Resistance meters use probes that must be driven into the wood for measurement.

Meters that use the dielectric properties of wood are classified as one of two types-capacitance and power-loss (James 1988). With these instruments, electrodes are pressed against the wood, and high-frequency electric energy is applied. The electrodes do not penetrate the wood. The amount of power absorbed depends on the moisture content of the wood. Species correction tables and temperature correction charts (figs. 1-14 and l-15) are also necessary.

Thermal Properties

Thermal properties are relevant to wood drying because they are related to energy requirements and the time required to heat wood to drying temperature. Specific heat of a material is the ratio of the heat capacity of the material to that of water. It is a measure of the energy required to raise the temperature of the material. Thermal conductivity is a measure of the rate of heat flow through a material. The coefficient of thermal expansion is a measure of the change of dimension caused by temperature change.

Specific Heat

The specific heat of wood depends on the temperature and moisture content of the wood, but is practically independent of density or species. Specific heat of dry wood can be approximately related to temperature T, in degrees Fahrenheit, by the following formula:

$$\text{Specific heat} = 0.25 + 0.0006T$$

When wood contains water, the specific heat increases because the specific heat of water is larger than that of dry wood. If the specific heat of water is taken as one, the specific heat of wood at moisture content m, where m is percent moisture content divided by 100, is

$$\text{Specific heat} = \frac{0.25 + 0.0006T + m}{1 + m}$$

Example: Estimate the energy in British thermal units (Btu) required to raise the temperature of 50,000 fbm of nominal 4/4 northern red oak at 75 percent moisture content from 60 to 110 °F.

This is a continuation of the earlier example on weight of wood, where the weight of 1,000 fbm of 4/4 northern red oak at 75 percent was 5,103 lb. Thus 50,000 fbm weigh 255,150 lb. The specific heat over the interval between 60 and 110 °F can be approximated by using the average temperature as follows:

$$T = \frac{60 + 110}{2} = 85\,^\circ\text{F}$$

Thus, the specific heat is

$$\frac{0.25 + 0.0006 \times 85 + 0.75}{1 + 0.75} = 0.601 \frac{\text{Btu}}{\text{lb} \times {}^\circ\text{F}}$$

The energy required is the product of the weight, the specific heat, and the temperature rise as follows:

$$\begin{aligned} \text{Energy} &= 255{,}150 \text{ lb} \times 0.601 \frac{\text{Btu}}{\text{lb} \times {}^\circ\text{F}} \\ &\quad \times (110 - 60)^\circ\text{F} \\ &= 7{,}667 \text{ million Btu} \end{aligned}$$

Thermal Conductivity

The thermal conductivity of wood is affected by density, moisture content, extractive content, grain direction, temperature, and structural irregularities such as knots. It is nearly the same in the radial and tangential directions but two to three times greater parallel to the grain. It increases as the density, moisture content, temperature, and extractive content increase. Thermal conductivity below 40 percent moisture content can be approximated by

$$k = G \times (1.39 + 0.028 \times M) + 0.165$$

and above 40 percent moisture content by

$$k = G \times (1.39 + 0.038 \times M) + 0.165$$

where k is thermal conductivity in Btu·in/h·ft^2. °F and G is specific gravity based on volume at M percent moisture content and ovendry weight.

Thermal Expansion

The thermal expansion of wood is so small that it is overshadowed by shrinkage and swelling. It is far less than dimensional changes associated with changes in moisture content, and conditions that would cause thermal expansion would also cause moisture-related shrinkage. The coefficient of thermal expansion is defined as the unit increase in dimension per degree increase in temperature. The coefficient of ovendry wood in the longitudinal direction is apparently independent of specific gravity and species. In both hardwoods and softwoods, it ranges from 0.0000017 to 0.0000025 inch per inch per degree Fahrenheit.

The coefficients of thermal expansion in the radial and tangential directions are 5 to 10 times greater than in the longitudinal direction and are thus of more practical interest. They depend on specific gravity, and for ovendry wood can be approximated by the following equations over the specific gravity range of 0.1 to 0.8:

$$\text{Radial coefficient} = (18G + 5.5) \times 10^{-6} \text{ per } ^\circ\text{F}$$

$$\text{Tangential coefficient} = (18G + 10.2) \times 10^{-6} \text{ per } ^\circ\text{F}$$

where G is specific gravity. Thermal expansion coefficients can be considered independent of temperature over the range of –60° to 130°F.

The thermal expansion properties of wood containing water are difficult to define. When wood with moisture is heated, it tends to expand because of normal thermal expansion and at the same time to shrink because of drying that occurs with the rise in temperature. Unless wood is below about 3 to 4 percent moisture content, the shrinkage will be greater than the thermal expansion. The question is sometimes asked if thermal expansion can cause checking in lumber. Because thermal expansion is so small, it is doubtful that it can cause checking.

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Table 1-1—Commercial species grown in the United States

Commercial name for lumber	Common tree name	Botanical name
	HARDWOODS	
Alder		
Red alder	red alder	*Alnus rubra*
Apple	apple	*Malus* spp.
Ash		
Black ash[1]	black ash	*Fraxinus nigra*
Oregon ash	Oregon ash	*F. latifolia*
White ash	blue ash	*F. quadrangulata*
	green ash	*F. pennsylvanica*
	white ash	*F. americana*
Aspen[2]	bigtooth aspen	*Populus grandidentata*
	quaking aspen	*P. tremuloides*
Basswood[3]	American basswood	*Tilia americana*
	white basswood	*T. heterophylle*
Beech	beech, American	*Fagus grandifolia*
Birch[4]	gray birch	*Betula populifolia*
	paper birch	*B. papyrifera*
	river birch	*B. nigra*
	sweet birch	*B. lenta*
	yellow birch	*B. alleghaniensis*
Box elder	boxelder	*Acer negundo*
Buckeye	Ohio buckeye	*Aesculus glabra*
	yellow buckeye	*A. octandra*
Butternut	butternut	*Juglans cinerea*
Cherry	black cherry	*Prunus serotina*
Chestnut	American chestnut	*Castanea dentata*
	balsam poplar	*Populus balsamifera*
Cottonwood	black cottonwood	*P. trichocarpa*
	eastern cottonwood	*P. deltoides*
	plains cottonwood	*P. sargentii*
	swamp cottonwood	*P. heterophylla*
Dogwood	flowering dogwood	*Cornus florida*
	Pacific dogwood	*C. nuttallii*
Elder, see Box elder		
Elm		
Rock elm	cedar elm	*Ulmus crassifolia*
	rock elm	*U. thomasii*
	September elm	*U. serotina*
	winged elm	*U. alata*
Soft elm[5]	American elm	*U. americana*
	slippery elm	*U. rubra*
Gum[6]	sweetgum	*Liquidambar styraciflua*
Hackberry	hackberry	*Celtis occidentalis*
	sugarberry	*C. laevigata*
Hickory[7]	mockernut hickory	*Carya tomentosa*
	pignut hickory	*C. glabra*
	sand hickory	*C. pallida*
	shagbark hickory	*C. ovata*
	shellbark hickory	*C. laciniosa*
Holly	American holly	*Ilex opaca*
Ironwood	eastern hophornbeam	*Ostyra virginiana*
Locust	black locust	*Robinia pseudoacacia*
	honeylocust	*Gleditsia triacanthos*
Madrone	Pacific madrone	*Arbutus menziesii*
Magnolia	southern magnolia	*Magnolia grandiflora*
	sweetbay	*M. virginiana*
	cucumber tree	*M. acuminata*
Maple		
Hard maple[8]	black maple	*Acer nigrum*
	sugar maple	*A. saccharum*
Oregon maple	bigleaf maple	*A. macrophyllum*
Soft maple[8]	red maple	*A. rubrum*
	silver maple	*A. saccharinum*

Table 1-1—Commercial species grown in the United States—continued

Commercial name for lumber	Common tree name	Botanical name
	HARDWOODS—continued	
Myrtle, *see* Oregon myrtle		
Oak		
Red oak	black oak	*Quercus velutina*
	blackjack oak	*Q. marilandica*
	California black oak	*Q. kellogii*
	cherrybark oak	*Q. falcata var. pagodaefolia*
	laurel oak	*Q. laurifolia*
	northern pin oak	*Q. ellipsoidalis*
	northern red oak	*Q. rubra*
	Nuttall oak	*Q. nuttalli*
	pin oak	*Q. palustris*
	scarlet oak	*Q. coccinea*
	shingle oak	*Q. imbricaria*
	Shumard oak	*Q. shumardii*
	southern red oak	*Q. falcata*
	turkey oak	*Q. laevis*
	willow oak	*Q. phellos*
White oak	Arizona white oak	*Q. arizonica*
	blue oak	*Q. douglasii*
	bur oak	*Q. macrocarpa*
	California white oak	*Q. lobata*
	chestnut oak	*Q. prinus*
	chinkapin oak	*Q. muehlenbergii*
	Emory oak	*Q. emoryi*
	Gambel oak	*Q. gambelii*
	Mexican blue oak	*Q. oblongifolia*
	live oak	*Q. virginiana*
	Oregon white oak	*Q. garryana*
	overcup oak	*Q. lyrata*
	post oak	*Q. stellata*
	swamp chestnut oak	*Q. michauxii*
	swamp white oak	*Q. bicolor*
	white oak	*Q. alba*
Oregon myrtle	California-laurel	*Umbellularia californica*
Osage orange	Osage-orange	*Maclura pomifera*
Pecan[7]	bitternut hickory	*Carya cordiformis*
	nutmeg hickory	*C. myristicaeformis*
	water hickory	*C. aquatica*
	pecan	*C. illinoensis*
Persimmon	common persimmon	*Diospyros virginiana*
Sassafras	sassafras	*Sassafras albidum*
Sycamore	American sycamore	*Platanus occidentalis*
Tanoak	tanoak	*Lithocarpus densiflorus*
Tupelo[9]	black tupelo	*Nyssa sylvatica*
	Ogeechee tupelo	*N. ogeche*
	swamp tupelo	*N. silvatica var. biflora*
	water tupelo	*N. aquatica*
Walnut	black walnut	*Juglans nigra*
Willow	black willow	*Salix nigra*
	peachleaf willow	*S. amygdaloides*
Yellow poplar	yellow-poplar	*Liriodendron tulipifera*
	SOFTWOODS	
Cedar		
Alaska cedar	Alaska-cedar	*Chamaecyparis nootkatensis*
Incense cedar	incense-cedar	*Libocedrus decurrens*
Port Orford cedar	Port-Orford-cedar	*Chamaecyparis lawsoniana*
Eastern red cedar	eastern redcedar	*Juniperus virginiana*
	southern redcedar	*J. silicicola*
Western red cedar	western redcedar	*Thuja plicata*
Northern white cedar	northern white-cedar	*T. occidentalis*
Southern white cedar	Atlantic white-cedar	*Chamaecyparis thyoides*
Cypress[10]	baldcypress	*Taxodium distichum*
	pondcypress	*T. distichum var. nutans*
Fir		
Balsam fir[11]	balsam fir	*Abies balsamea*
	Fraser fir	*A. fraseri*
Douglas fir[12]	Douglas-fir	*Pseudotsuga menziesii*
	Inland Douglas-fir	*P. menziesii var. glauca*
Noble fir	noble fir	*Abies procera*

Table 1-1—Commercial species grown In the United States—concluded

Commercial name for lumber	Common tree name	Botanical name
	SOFTWOODS—continued	
Fir (continued)		
White fir	California red fir	*A. magnifica*
	grand fir	*A. grandis*
	noble fir	*A. procera*
	Pacific silver fir	*A. amabilis*
	subalpine fir	*A. lasiocarpa*
	white fir	*A. concolor*
Hemlock		
Eastern hemlock	Carolina hemlock	*Tsuga caroliniana*
	eastern hemlock	*T. canadensis*
Mountain hemlock	mountain hemlock	*T. medensiana*
West coast hemlock	western hemlock	*T. heterophylla*
Juniper		
Western juniper	alligator juniper	*Juniperus deppeana*
	Rocky Mountain juniper	*J. scopulorum*
	Utah juniper	*J. osteosperma*
	western juniper	*J. occidentalis*
Larch		
Western larch	western larch	*Larix occidentalis*
Pine		
Jack pine	jack pine	*Pinus banksiana*
Lodgepole pine	lodgepole pine	*P. contorta*
Norway pine	red pine	*P. resinosa*
Ponderosa pine	ponderosa pine	*P. ponderosa*
Sugar pine	sugar pine	*P. lambertiana*
Idaho white pine	western white pine	*P. monticola*
Northern white pine	eastern white pine	*P. strobus*
Longleaf pine[13]	longleaf pine	*P. palustris*
	slash pine	*P. elliottii*
Southern pine	loblobbly pine	*Pinus taeda*
	longleaf pine	*P. palustris*
	pitch pine	*P. rigida*
	pond pine	*P. serotina*
	shortleaf pine	*P. echinata*
	slash pine	*P. elliottii*
	Virginia pine	*P. virginiana*
Redwood	redwood	*Sequoia sempervirens*
Spruce		
Eastern spruce	black spruce	Picea mariana
	red spruce	P. rubens
	white spruce	P. glauca
Engelmann spruce	blue spruce	P. pungens
	Engelmann spruce	P. engelmannii
Sitka spruce	Sitka spruce	P. sitchensis
Tamarack	tamarack	Larix laricina
Yew		
Pacific yew	Pacific yew	Taxus brevifolia

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[1] Black ash is known commercially in some consuming centers as brown ash, and is also sometimes designated as such in specifications.

[2] Aspen lumber is sometimes designated as popple.

[3] For some commercial uses where a white appearance is required, the sapwood of American basswood (*Tilia americana*) is specified under the designation "white basswood." This commercial-use designation should not be confused with the species (*T. heterophylla*) having the common name white basswood.

[4] The principal lumber species is yellow birch. It may be designated either sap birch (all sapwood) or red birch (all hardwood) or it may be unselected. Sweet birch is sold without distinction from yellow birch. Paper birch is a softer wood used principally for turnings and novelties and is widely know as white birch. The remaining birches are of minor commercial importance.

[5] Soft elm lumber is sometimes designated as white elm. A special type of slowly grown material is sometimes designated commercially as gray elm. Slippery elm is called red elm in some localities, although that term is also used for two other elms.

[6] Usually designated either as red gum or as sap gum, as the case may be, or as gum or sweetgum when not selected for color. (For black gum, *see* tupelo, footnote 9.)

[7] The impossibility of distinguishing between hickory ad pecan lumber for accurate species identification is recognized. Three of the four major *Carya* species in the pecan group have the word "hickory" in their name.

[8] When hard maple or soft maple is specified to be white, the specification generally is interpreted as being a requirement for sapwood, although it sometimes may take on the special meaning of being all sapwood with a minimum of natural color.

[9] The impossibility of distinguishing between black tupelo (blackgum), swamp tupelo, and water tupelo lumber for accurate species identification is recognized.

[10] Cypress includes types designated as red cypress, white cypress, and yellow cypress. Red cypress is frequently classified and sold separately from the other types.

[11] Balsam fir lumber is sometimes designated either as eastern fir or as balsam.

[12] Douglas fir may be specified either as Coast Region Douglas for or as Inland Region Douglas for, but if the particular type is not so specified or is not otherwise indicated through the grade specifications, either or both types will be allowed.

[13] The commercial requirements for longleaf pine lumber are that not only must it be produced from trees of the botanical species of *Pinus elliottii* and *P. palustris,* but each piece in addition must average either on one end or the other not less than six annual rings per inch and not less than one-third summerwood. Longleaf pine lumber is sometimes designated as pitch pine in the export trade.

Table 1-2—Tropical wood species

Common name (other common names)[1]	Botanical name[2]
Afrormosia (kokrodua, assamela)	*Pericopsis elata* (Af)
Albarco (jequitiba, abarco, bacu, cerú, tauary)	*Cariniana* spp. (LA)
Andiroba (crabwood, cedro macho, carapa)	*Carapa guianensis* (LA]
Angelique (basralocus)	*Dicorynia guianensis* (LA)
Apitong (keruing, eng, in, yang, heng, keroeing)	*Dipterocarpus* spp. (As)
Avodire (blimah-pu, apapaye, lusamba, apaya)	*Turraeanthus africanus* (Af)
Balata (bulletwood, chicozapote, ausubo)	*Manilkara bidentata* (LA)
Balsa (corcho, gatillo, enea, pung, lana)	*Ochroma pyramidale (LA)*
Banak (baboen, sangre, palo de sangre)	*Virola* spp. (LA)
Benge (mutenye, mbenge)	*Guibourtia arnoldiana* (Af)
Bubinga (essingang, ovang, kevazingo, waka)	*Guibourtia* spp. (Af)
Caribbean pine (pino, ocote)	*Pinus caribaea* (LA)
Cativo (amansamujer, camibar, muramo, curucai)	*Prioria copaifera* (LA)
Ceiba (silk-cotton-tree, kapok-tree)	*Ceiba pentandra* (LA)
Cocobolo (granadillo, funera, palo negro)	*Dalbergia retusa* (LA)
Courbaril (cuapinol, guapinol, locust)	*Hymenaea courbaril* (LA)
Cuangare (virola, fruta dorado, miguelario)	*Dialyanthera* spp. (LA)
Cypress, Mexican (cipres)	*Cupressus lusitanica* (LA)
Degame (lemonwood, camarón, palo camarón, surr,a)	*Calycophyllum candidissium* (LA)
Determa (red louro, wana, wane, grignon rouge)	*Ocotea rubra* (LA)
Ebony, East Indian (kaya malam, kaya arang)	*Diospyros ebenum* (As)
Ebony, African (mgiriti, msindi, omenowa)	*Diospyros* spp. (Af)
Gmelina (gumhar, yemane)	*Gmelina arborea* (As)
Goncalo alves (palo de cera, palo de culebra)	*Astronium graveolens* (LA)
Greenheart (demerara greenheart, bibiru)	*Ocotea rodiaei* (LA)
Hura (possumwood, arbol del diablo, haba)	*Hura crepitans* (LA)
Ilomba (gboyei, qualele, walele, otie, akomu)	*Pycanthus angolensis* (Af)
Imbuia (Brazilian walnut, canella imbuia)	*Phoebe porosa* (LA)
Ipe (bethabara, lapacho, amapa, cortez)	*Tabebuia* spp. (lapacho group) (LA)
Iroko (semli, odoum, rokko, oroko, abang)	*Chlorophora excelsa* and *regia* (Af)
Jarrah	*Eucalyptus marginata (As)*
Jelutong (jelutong bukit)	*Dyera costulate* (As)
Kapur (keladan, kapoer, Borneo camphorwood)	*Drybalanops* spp. (As)
Karri	*Eucalyptus diversicolor* (As)
Kempas (impas, mengris)	*Koompassia malaccensis* (As)
Keruing (apitong, eng, in, yang, heng, keroeing)	*Dipterocarpus* spp. (As)
Lauan, red, light red, and white (maranti)	*Shorea* spp. (As)
Lignumvitae (guayacán, palo santo)	*Guaiacum* spp. (LA)
Limba (afara, ofram, fraké, akom, korina)	*Terminalia superba* (Af)
Mahogany, African	*Khaya* spp. (Af)
Mahogany, true (Honduras mahogany. caoba)	*Swietenia macrophylla* (LA)
Manni (chewstick, barillo, cerillo, machare)	*Symphonia globulifera* (LA)
Merbau (ipil, tat-talun, lumpha, lumpho, kwila)	*Intsia bijuga* and *palembanica* (As)
Mersawa (palosapis, pengiran)	*Anisoptera* spp. (As)
Mora (nato, nato rojo, mora de Guayana)	*Mora* spp. (LA)
Obeche (arere, samba, ayous, wawa, abachi)	*Triplochiton scleroxylon* (Af)
Ocote pine (pino, ocote)	*Pinus oocarpa* (LA)
Okoume (gaboon, angouma, moukoumi, N’Koumi)	*Aucoumea klaineana* (Af)
Opepe (kusia, badi, bilinga, akondoc, kilingi)	*Nauclea* spp. (Af)
Parana pine (pinheiro do paraná)	*Araucaria angustifolia* (LA)
Pau Marfim (marfim, pau liso, guatambú)	*Balfourodendron riedelianum* (LA)
Peroba de campos (white peroba, ipe peroba)	*Paratecoma peroba* (LA)
Peroba rosa (amarello, amargoso, ibira-romí)	*Aspidosperma* spp. (LA)
Primavera (duranga, San Juan, palo blanca)	*Cybistax donnell-smithii* (LA)
Purpleheart (amaranth, palo morado, morado)	*Peltogyne* spp. (LA)
Ramin (melawis, garu buaja, lanutan-bagio)	*Gonystylus* spp. (As)
Roble (encino, oak, ahuati, cucharillo)	*Quercus* spp. (LA)
Roble (mayflower, amapa, roble blanco)	*Tabebuia* spp. Roble group (LA)
Rosewood, Indian (shisham)	*Dalbergia latifolia* (As)
Rosewood, Brazilian (jacarandá)	*Dalbergia nigra* (LA)
Rubberwood (árbol de caucho, sibi-sibi)	*Hevea brasilliensis* (LA, As)
Sande (cow-tree, mastate, avichuri)	*Brosimum* spp. Utile group (LA)
Santa Maria (jacareuba, barí)	*Calophyllum brasiliense* (LA)
Sapele (aboudikro, penkwa, muyovu)	*Entandrophragma cylindricum* (Af)
Sepetir (sindur, supa, kayu galu, makata)	*Pseudosindora and Sindora* spp. (As)
Spanish cedar (cedro, acajou rouge)	*Cedrela* spp. (LA)
Sucupira (alcornoque, sapupira)	*Bowdichia* spp. (LA)
Sucupira (botonallare, peonía, tatabu)	*Diplotropis purpurea* (LA)
Teak (kyun, teck, teca)	*Tectona grandis* (As]
Wallaba (palo machete, bijlhout, wapa, apá)	*Eperua* spp. (LA)

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[1] Additional common names are listed in Chudnoff (1984).

[2] Af is Africa; As, Asia and Oceania; and LA, Latin America.

Table 1-3—Standard hardwood cutting grades[1]

Grade and length (ft) allowed	Width allowed (in)	Surface measure of pieces (ft²)	Amount of each piece that must work into clear-face cuttings (percent)	Maximum cutting allowed (number)	Minimum size of cuttings required
Firsts[2] 8 to 16 (will admit 30 percent of 8- to 11-foot, 1/2 of which may be 8- and 9-foot)	6+	4 to 9	91-2/3	1	4 inches by 5 feet, or 3 inches by 7 feet
		10 to 14	91-2/3	2	
		15+	91-2/3	3	
Seconds[2] 8 to 16 (will admit 30 percent of 8- to 11-foot, 1/2 of which may be 8- and 9-foot)	6+	4 and 5	83-1/3	1	4 inches by 5 feet, or 3 inches by 7 feet
		6 and 7	83-1/3	1	
		6 and 7	91-2/3	2	
		8 to 11	83-1/3	2	
		8 to 11	91-2/3	3	
		12 to 15	83-1/2	3	
		12 to 15	91-2/3	4	
		16+	83-1/3	4	
Selects 6 to 16 (will admit 30 percent of 6- to 11-foot, 1/6 of which may be 6- and 7-foot)	4+	2 and 3	91-2/3	1	4 inches by 5 feet, or 3 inches by 7 feet
		4+	(3)		
No. 1 Common 4 to 16 (will admit 10 percent of 4- to 7-foot, 1/2 of which may be 4- and 5-foot)	3+	1	100	0	4 inches by 2 feet, or 3 inches by 3 feet
		2	75	1	
		3 and 4	66-2/3	1	
		3 and 4	75	2	
		5 to 7	66-2/3	2	
		5 to 7	75	3	
		8 to 10	66-2/3	3	
		11 to 13	66-2/3	4	
		14+	66-2/3	5	
No. 2 Common 4 to 16 (will admit 30 percent of 4- to 7-foot, 1/3 of which may be 4- and 5-foot) 4 to 16 (will admit 30 percent of 4- to 7-foot, 1/3 of which may be 4- and 5-foot)	3+	1	66-2/3	1	3 inches by 2 feet
		2 and 3	50	1	
		2 and 3	66-2/3	2	
		4 and 5	50	2	
		4 and 5	66-2/3	3	
		6 and 7	50	3	
		6 and 7	66-2/3	4	
		8 and 9	50	4	
		10 and 11	50	5	
		12 and 13	50	6	
		14+	50	7	
No. 3A Common 4 to 16 (will admit 50 percent of 4- to 7-foot, 1/2 of which may be 4- and 5-foot)	3+	1+	[4]33-1/3	(5)	3 inches by 2 feet
No. 3B Common 4 to 16 (will admit 50 percent of 4- to 7-foot, 1/2 of which may be 4- and 5-foot)	3+	1+	[6]25	(5)	1-1/2 inches by 2 feet

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[1] Inspection to be made on the poorer side of the piece, except in Selects.

[2] Firsts and Seconds are combined as 1 grade (FAS). The percentage of Firsts required in the combined grade varies from 20 to 40 percent, depending on the species.

[3] Same as Seconds with reverse side of board not below No. 1 Common or reverse side of cuttings sound.

[4] This grade also admits pieces that grade not below No. 2 Common on the good face and are sound on the reverse face.

[5] Unlimited.

[6] The cuttings must be sound; clear face not required.

Table 1-4—Standard thickness for rough and surfaced (S2S) hardwood lumber

Nominal rough thickness (in)	S2S thickness (in)	Nominal rough thickness (in)	S2S thickness (in)
3/8	3/16	1-3/4 (7/4)	1-1/2
1/2	5/16	2 (8/4)	1-3/4
5/8	7/16	2-1/2 (10/4)	2-1/4
3/4	9/16	3 (12/4)	2-3/4
1 (4/4)	3/4	3-1/2 (14/4)	3-1/4
1-1/4 (5/4)	1-1/16	4 (16/4)	3-3/4
1-1/2 (6/4)	1-5/16		

S2S refers to lumber that is surfaced on two sides.

Table 1-5—Average moisture content of green wood

	Moisture content[1] (percent)		
Species	Heartwood	Sapwood	Mixed heartwood and sapwood
	SOFTWOODS		
Baldcypress	121	171	—
Cedar			
Alaska	32	166	—
Atlantic white	—	—	35
Eastern redcedar	33	—	—
Incense	40	213	—
Northern white	32	240	93
Port-Orford	50	98	—
Western redcedar	58	249	62
Douglas-fir			
Coast type	37	115	45
Intermediate type	34	154	—
Rocky Mountain type	30	112	43
Fir			
Balsam	88	173	117
California red	—	—	108
Grand	91	136	—
Noble	34	115	—
Pacific silver	55	164	—
Subalpine	—	—	47
White	98	160	—
Hemlock			
Eastern	97	119	—
Western	85	170	—
Larch, western	54	119	—
Pine			
Eastern white	50	175	90
Lodgepole	41	120	—
Ponderosa	40	148	—
Red	32	134	—
Southern			
Loblolly	33	110	—
Longleaf	31	106	—
Shortleaf	32	122	—
Sugar	98	219	—
Western white	62	148	—
Redwood			
Old-growth	86	210	—
Second-growth	—	—	127
Spruce			
Black	52	113	77
Engelmann	51	173	—
Sitka	41	142	43
Tamarack	49	—	—
	HARDWOODS		
Alder, red	—	97	—
Apple	81	74	—
Ash			
Black	95	—	—
Green	—	58	—
White	46	44	—
Aspen	95	113	—
	HARDWOODS—continued		
Basswood, American	81	133	—
Beech, American	55	72	—
Birch			
Paper	89	72	—
Sweet	75	70	—
Yellow	74	72	—
Buckeye, yellow	—	—	141
Butternut	—	—	104
Cherry, black	58	—	—
Chestnut, American	120	—	—
Cottonwood, black	162	146	—
Dogwood, flowering	—	—	62
Elm			
American	95	92	—
Cedar	66	61	—
Rock	44	57	—
Hackberry	61	65	—
Hickory			
Bitternut	80	54	—
Mockernut	70	52	—
Pignut	71	49	—
Red	69	52	
Sand	68	50	—
Water	97	62	—
Holly, American	—	—	82
Hophornbeam, eastern	—	—	52
Laurel, California	—	—	65
Locust, black	—	—	40
Madrone, Pacific	—	—	81
Magnolia	80	104	—
Maple			
Silver (soft)	58	97	—
Sugar (hard)	65	72	—
Oak			
California black	76	75	—
Live	—	—	50
Northern red	80	69	—
Southern red	83	75	—
Southern swamp	79	66	—
Water	81	81	—
White	64	78	—
Willow	82	74	—
Osage-orange	—	—	31
Persimmon, common	—	—	58
Sweetgum	79	137	—
Sycamore, American	114	130	—
Tanoak	—	—	89
Tupelo			
Black	87	115	—
Swamp	101	108	—
Water	150	116	—
Walnut, black	90	73	—
Willow, black	—	—	139
Yellow-poplar	83	106	—

[1] Based **on ovendry weight.**

Table 1-6—Relative humidity and equilibrium moisture content at various dry-bulb temperatures and wet-bulb depressions below 212°F.

Dry-bulb temperature (°F)	Relative humidity’ and equilibrium moisture content[2] (%) at various wet-bulb depression temperatures (°F)																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
30	89	78	67	57	46	36	27	17	6	—	—	—	—	—	—	—	—	—
	—	*15.9*	*12.9*	*10.8*	*9.0*	*7.4*	*5.7*	*3.9*	*1.6*	—	—	—	—	—	—	—	—	—
35	90	81	72	63	54	45	37	28	19	11	3	—	—	—	—	—	—	—
	—	*16.8*	*13.9*	*11.9*	*10.3*	*8.8*	*7.4*	*6.0*	*4.5*	*2.9*	*0.8*	—	—	—	—	—	—	—
40	92	83	75	68	60	52	45	37	29	22	15	8	—	—	—	—	—	—
	—	*17.6*	*14.8*	*12.9*	*11.2*	*9.9*	*8.6*	*7.4*	*6.2*	*5.0*	*3.5*	*1.9*	—	—	—	—	—	—
45	93	85	78	72	64	58	51	44	37	31	25	19	12	6	—	—	—	—
	—	*18.3*	*15.6*	*13.7*	*12.0*	*10.7*	*9.5*	*8.5*	*7.5*	*6.5*	*5.3*	*4.2*	*2.9*	*1.5*	—	—	—	—
50	93	86	80	74	68	62	56	50	44	38	32	27	21	16	10	5	—	—
	—	*19.0*	*16.3*	*14.4*	*12.7*	*11.5*	*10.3*	*9.4*	*8.5*	*7.6*	*6.7*	*5.7*	*4.8*	*3.9*	*2.8*	*1.5*	—	—
55	94	88	82	76	70	65	60	54	49	44	39	34	28	24	19	14	9	5
	—	*19.5*	*16.9*	*15.1*	*13.4*	*12.2*	*11.0*	*10.1*	*9.3*	*8.4*	*7.6*	*6.8*	*6.0*	*5.3*	*4.5*	*3.6*	*2.5*	*1.3*
60	94	89	83	78	73	68	63	58	53	48	43	39	34	30	26	21	17	13
	—	*19.9*	*17.4*	*15.6*	*13.9*	*12.7*	*11.6*	*10.7*	*9.9*	*9.1*	*8.3*	*7.6*	*6.9*	*6.3*	*5.6*	*4.9*	*4.1*	*3.2*
65	95	90	84	80	75	70	66	61	56	52	48	44	39	36	32	27	24	20
	—	*20.3*	*17.8*	*16.1*	*14.4*	*13.3*	*12.1*	*11.2*	*10.4*	*9.7*	*8.9*	*8.3*	*7.7*	*7.1*	*6.5*	*5.8*	*5.2*	*4.5*
70	95	90	86	81	77	72	68	64	59	55	51	48	44	40	36	33	29	25
	—	*20.6*	*18.2*	*16.5*	*14.9*	*13.7*	*12.5*	*11.6*	*10.9*	*10.1*	*9.4*	*8.8*	*8.3*	*7.7*	*7.2*	*6.6*	*6.0*	*5.5*
75	95	91	86	82	78	74	70	66	62	58	54	51	47	44	41	37	34	31
	—	*20.9*	*18.5*	*16.8*	*15.2*	*14.0*	*12.9*	*12.0*	*11.2*	*10.5*	*9.8*	*9.3*	*8.7*	*8.2*	*7.7*	*7.2*	*6.7*	*6.2*
80	96	91	87	83	79	75	72	68	64	61	57	54	50	47	44	41	38	35
	—	*21.0*	*18.7*	*17.0*	*15.5*	*14.3*	*13.2*	*12.3*	*11.5*	*10.9*	*10.1*	*9.7*	*9.1*	*8.6*	*8.1*	*7.7*	*7.2*	*6.8*
85	96	92	88	84	80	76	73	70	66	63	59	56	53	50	47	44	41	38
	—	*21.2*	*18.8*	*17.2*	*15.7*	*14.5*	*13.5*	*12.5*	*11.8*	*11.2*	*10.5*	*10.0*	*9.5*	*9.0*	*8.5*	*8.1*	*7.6*	*7.2*
90	96	92	89	85	81	78	74	71	68	65	61	58	55	52	49	47	44	41
	—	*21.3*	*18.9*	*17.3*	*15.9*	*14.7*	*13.7*	*12.8*	*12.0*	*11.4*	*10.7*	*10.2*	*9.7*	*9.3*	*8.8*	*8.4*	*8.0*	*7.6*
95	96	92	89	85	82	79	75	72	69	66	63	60	57	55	52	49	46	44
	—	*21.3*	*19.0*	*17.4*	*16.1*	*14.9*	*13.9*	*12.9*	*12.2*	*11.6*	*11.0*	*10.5*	*10.0*	*9.5*	*9.1*	*8.7*	*8.2*	*7.9*

Table 1-6—Relative humidity and equilibrium moisture content at various dry-bulb temperatures and wet-bulb depressions below 212°F—continued

Dry-bulb temperature (°F)	Relative humidity[1] and equilibrium moisture content[2] (%) at various wet-bulb depression temperatures (°F)																		
	19	20	21	22	23	24	25	26	27	28	29	30	32	34	36	38	40	45	50
30	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
35	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
40	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
45	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
50	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
55	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
60	9	5	1	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	2.3	*1.3*	*0.2*	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
65	16	13	8	6	2	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	3.8	*3.0*	*2.3*	*1.4*	*0.4*	—	—	—	—	—	—	—	—	—	—	—	—	—	—
70	22	19	15	12	9	6	3	—	—	—	—	—	—	—	—	—	—	—	—
	4.9	*4.3*	*3.7*	*2.9*	*2.3*	*1.5*	*0.7*	—	—	—	—	—	—	—	—	—	—	—	—
75	28	24	21	18	15	12	10	7	4	1	—	—	—	—	—	—	—	—	—
	5.6	*5.1*	*4.7*	*4.1*	*3.5*	*2.9*	*2.3*	*1.7*	*0.9*	*0.2*	—	—	—	—	—	—	—	—	—
80	32	29	26	23	20	18	15	12	10	7	5	3	—	—	—	—	—	—	—
	6.3	*5.8*	*5.4*	*5.0*	*4.5*	*4.0*	*3.5*	*3.0*	*2.4*	*1.8*	*1.1*	*0.3*	—	—	—	—	—	—	—
85	36	33	30	28	25	23	20	18	15	13	11	9	4	—	—	—	—	—	—
	6.7	*6.3*	*6.0*	*5.6*	*5.2*	*4.8*	*4.3*	*3.9*	*3.4*	*3.0*	*2.4*	*1.7*	*0.9*	—	—	—	—	—	—
90	39	36	34	31	29	26	24	22	19	17	15	13	9	5	1	—	—	—	—
	7.2	*6.8*	*6.5*	*6.1*	*5.7*	*5.3*	*4.9*	*4.6*	*4.2*	*3.8*	*3.3*	*2.8*	*2.1*	*1.3*	*0.4*	—	—	—	—
95	42	39	37	34	32	30	28	26	23	22	20	17	14	10	6	2	—	—	—
	7.5	*7.1*	*6.8*	*6.4*	*6.1*	*5.7*	*5.3*	*5.1*	*4.8*	*4.4*	*4.0*	*3.6*	*3.0*	*2.3*	*1.5*	*0.6*	—	—	—

Table 1-6—Relative humidity and equilibrium moisture content at various dry-bulb temperatures and wet-bulb depressions below 212°F—continued

Dry-bulb temperature (°F)	Relative humidity[1] and equilibrium moisture content[2] (%) at various wet-bulb depression temperature (°F)																	
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
100	96	93	89	86	83	80	77	73	70	68	65	62	59	56	54	51	49	46
	—	*21.3*	*19.0*	*17.5*	*16.1*	*15.0*	*13.9*	*13.1*	*12.4*	*11.8*	*11.2*	*10.6*	*10.1*	*9.6*	*9.2*	*8.9*	*8.5*	*8.1*
105	96	93	90	87	83	80	77	74	71	69	66	63	60	58	55	53	50	48
	—	*21.4*	*19.0*	*17.5*	*16.2*	*15.1*	*14.0*	*13.3*	*12.6*	*11.9*	*11.3*	*10.8*	*10.3*	*9.8*	*9.4*	*9.0*	*8.7*	8.3
110	97	93	90	87	84	81	78	75	73	70	67	65	62	60	57	55	52	50
	—	*21.4*	*19.0*	*17.5*	*16.2*	*15.1*	*14.1*	*13.3*	*12.6*	*12.0*	*11.4*	*10.8*	*10.4*	*9.9*	*9.5*	*9.2*	*8.8*	8.4
115	97	93	90	88	85	82	79	76	74	71	68	66	63	61	58	56	54	52
	—	*21.4*	*19.0*	*17.5*	*16.2*	*15.1*	*14.1*	*13.4*	*12.7*	*12.1*	*11.5*	*10.9*	*10.4*	*10.0*	*9.6*	*9.3*	*8.9*	8.6
120	97	94	91	88	85	82	80	77	74	72	69	67	65	62	60	58	55	53
	—	*21.3*	*19.0*	*17.4*	*16.2*	*15.1*	*14.1*	*13.4*	*12.7*	*12.1*	*11.5*	*11.0*	*10.5*	*10.0*	*9.7*	*9.4*	*9.0*	*8.7*
125	97	94	91	88	86	83	80	77	75	73	70	68	65	63	61	59	57	55
	—	*21.2*	*18.9*	*17.3*	*16.1*	*15.0*	*14.0*	*13.4*	*12.7*	*12.1*	*11.5*	*11.0*	*10.5*	*10.0*	*9.7*	*9.4*	*9.0*	*8.7*
130	97	94	91	89	86	83	81	78	76	73	71	69	67	64	62	60	58	56
	—	*21.0*	*18.8*	*17.2*	*16.0*	*14.9*	*14.0*	*13.4*	*12.7*	*12.1*	*11.5*	*11.0*	*10.5*	*10.0*	*9.7*	*9.4*	*9.0*	*8.7*
140	97	95	92	89	87	84	82	79	77	75	73	70	68	66	64	62	60	58
	—	*20.7*	*18.6*	*16.9*	*15.8*	*14.8*	*13.8*	*13.2*	*12.5*	*11.9*	*11.4*	*10.9*	*10.4*	*10.0*	*9.6*	*9.4*	*9.0*	*8.7*
150	98	95	92	90	87	85	82	80	78	76	74	72	70	68	66	64	62	60
	—	*20.2*	*18.4*	*16.6*	*15.4*	*14.8*	*13.7*	*13.0*	*12.4*	*11.8*	*10.2*	*10.8*	*10.3*	*9.9*	*9.5*	*9.2*	*8.9*	*8.6*
160	98	95	93	90	88	86	83	81	79	77	75	73	71	69	67	65	64	62
	—	*19.8*	*18.1*	*16.2*	*15.2*	*14.2*	*13.4*	*12.7*	*12.1*	*11.5*	*11.0*	*10.6*	*10.1*	*9.7*	*9.4*	*9.1*	*8.8*	*8.5*
170	98	95	93	91	89	86	84	82	80	78	76	74	72	70	69	67	65	63
	—	*19.4*	*17.7*	*15.8*	*14.8*	*13.9*	*13.2*	*12.4*	*11.8*	*11.3*	*10.8*	*10.4*	*9.9*	*9.6*	*9.2*	*9.0*	*8.6*	*8.4*
180	98	96	94	91	89	87	85	83	81	79	77	75	73	72	70	68	67	65
	—	*18.9*	*17.3*	*15.5*	*14.5*	*13.7*	*12.9*	*12.2*	*11.6*	*11.1*	*10.6*	*10.1*	*9.7*	*9.4*	*9.0*	*8.8*	*8.4*	*8.1*
190	98	96	94	92	90	88	85	84	82	80	78	76	75	73	71	69	68	66
	—	*18.5*	*16.9*	*15.2*	*14.2*	*13.4*	*12.7*	*12.0*	*11.4*	*10.9*	*10.5*	*10.0*	*9.6*	*9.2*	*8.9*	*8.6*	*8.2*	*7.9*
200	98	96	94	92	90	88	86	84	82	80	79	77	75	74	72	70	69	67
	—	*18.1*	*16.4*	*14.9*	*14.0*	*13.2*	*12.4*	*11.8*	*11.2*	*10.8*	*10.3*	*9.8*	*9.4*	*9.1*	*8.8*	*8.4*	*8.1*	*7.7*
210	98	96	94	92	90	88	86	85	83	81	79	78	76	75	73	71	70	68
	—	*17.7*	*16.0*	*14.6*	*13.8*	*13.0*	*12.2*	*11.7*	*11.1*	*10.6*	*10.0*	*9.7*	*9.2*	*9.0*	*8.7*	*8.3*	*8.0*	*7.6*

Table 1-6—Relative humidity and equilibrium moisture content at various dry-bulb temperatures and wet-bulb depressions below 212°F—concluded

Dry-bulb temper- ature (°F)	Relative humidity[1] and equilibrium moisture content [2] (%) at various wet-bulb depression temperatures (°F)																		
	19	20	21	22	23	24	25	26	27	28	29	30	32	34	36	38	40	45	50
100	44 *7.8*	41 *7.4*	39 *7.0*	37 *6.7*	35 *6.4*	33 *6.1*	30 *5.7*	28 *5.4*	26 *5.2*	24 *4.9*	22 *4.6*	21 *4.2*	17 *3.6*	13 *3.1*	10 *2.4*	7 *1.6*	4 *0.7*	— —	— —
105	46 *7.9*	44 *7.6*	42 *7.3*	40 *6.9*	37 *6.7*	35 *6.4*	34 *6.1*	31 *5.7*	29 *5.4*	28 *5.2*	26 *4.8*	24 *4.6*	20 *4.2*	17 *3.6*	14 *3.1*	11 *2.4*	8 *1.8*	— —	— —
110	48 *8.1*	46 *7.7*	44 *7.5*	42 *7.2*	40 *6.8*	38 *6.6*	36 *6.3*	34 *6.0*	32 *5.7*	30 *5.4*	28 *5.2*	26 *4.8*	23 *4.5*	20 *4.0*	17 *3.5*	14 *3.0*	11 *2.5*	4 *1.1*	— —
115	50 *8.2*	48 *7.8*	45 *7.6*	43 *7.3*	41 *7.0*	40 *6.7*	38 *6.5*	36 *6.2*	34 *5.9*	32 *5.6*	31 *5.4*	29 *5.2*	26 *4.7*	23 *4.3*	20 *3.9*	17 *3.4*	14 *2.9*	8 *1.7*	2 *0.4*
120	51 *8.3*	49 *7.9*	47 *7.7*	45 *7.4*	43 *7.2*	41 *6.8*	40 *6.6*	38 *6.3*	36 *6.1*	34 *5.8*	33 *5.6*	31 *5.4*	28 *5.0*	25 *4.6*	22 *4.2*	19 *3.7*	17 *3.3*	10 *2.3*	5 *1.1*
125	53 *8.3*	51 *8.0*	48 *7.7*	47 *7.5*	45 *7.2*	43 *7.0*	41 *6.7*	39 *6.5*	38 *6.2*	36 *6.0*	35 *5.8*	33 *5.5*	30 *5.2*	27 *4.8*	24 *4.4*	22 *4.0*	19 *3.6*	13 *2.7*	8 *1.6*
130	54 *8.3*	52 *8.0*	50 *7.8*	48 *7.6*	47 *7.3*	45 *7.0*	43 *6.8*	41 *6.6*	40 *6.4*	38 *6.1*	37 *5.9*	35 *5.6*	32 *5.3*	29 *4.9*	26 *4.6*	24 *4.2*	21 *3.8*	15 *3.0*	10 *2.0*
140	56 *8.4*	54 *8.0*	53 *7.8*	51 *7.6*	49 *7.3*	47 *7.1*	46 *6.9*	44 *6.6*	43 *6.4*	41 *6.2*	40 *6.0*	38 *5.8*	35 *5.4*	32 *5.1*	30 *4.8*	27 *4.4*	25 *4.1*	19 *3.4*	14 *2.6*
150	58 *8.3*	57 *8.0*	55 *7.8*	53 *7.5*	51 *7.3*	49 *7.1*	48 *6.9*	46 *6.7*	45 *6.4*	43 *6.2*	42 *6.0*	41 *5.8*	38 *5.4*	36 *5.2*	33 *4.9*	30 *4.5*	28 *4.2*	23 *3.6*	8 *2.9*
160	60 *8.2*	58 *7.9*	57 *7.7*	55 *7.4*	53 *7.2*	52 *7.0*	50 *6.8*	49 *6.7*	47 *6.4*	46 *6.2*	44 *6.0*	43 *5.8*	41 *5.5*	38 *5.2*	35 *4.9*	33 *4.6*	31 *4.3*	25 *3.7*	21 *3.2*
170	62 *8.0*	60 *7.8*	59 *7.6*	57 *7.3*	55 *7.2*	53 *6.9*	52 *6.7*	51 *6.6*	49 *6.4*	48 *6.2*	47 *6.0*	45 *5.7*	43 *5.5*	40 *5.2*	38 *4.9*	35 *4.6*	33 *4.4*	28 *3.7*	24 *3.2*
180	63 *7.8*	62 *7.6*	60 *7.4*	58 *7.2*	57 *7.0*	55 *6.8*	54 *6.5*	52 *6.4*	51 *6.2*	50 *6.0*	48 *5.8*	47 *5.7*	45 *5.4*	42 *5.2*	40 *4.8*	38 *4.6*	35 *4.4*	30 *3.8*	26 *3.3*
190	65 *7.7*	63 *7.4*	62 *7.2*	60 *7.0*	58 *6.8*	57 *6.6*	56 *6.4*	54 *6.2*	53 *6.0*	51 *5.9*	50 *5.7*	49 *5.5*	46 *5.3*	44 *5.0*	42 *4.8*	39 *4.5*	37 *4.4*	32 *3.8*	28 *3.3*
200	66 *7.5*	64 *7.2*	63 *7.0*	61 *6.9*	60 *6.6*	58 *6.4*	57 *6.2*	55 *6.0*	54 *5.9*	53 *5.7*	52 *5.6*	51 *5.4*	48 *5.2*	46 *4.9*	43 *4.7*	51 *4.5*	39 *4.3*	34 *3.8*	30 *3.3*
210	67 *7.4*	65 *7.1*	64 *6.9*	63 *6.8*	61 *6.5*	60 *6.3*	59 *6.1*	57 *5.9*	56 *5.8*	54 *5.5*	53 *5.4*	52 *5.3*	50 *5.1*	47 *4.8*	45 *4.6*	43 *4.4*	41 *4.2*	36 *3.7*	32 *3.8*

[1] Relative humidity values not italic.

[2] Equilibrium moisture content values italic.

Table 1-7—Relative humidity and equilibrium moisture content at various dry-bulb temperatures and wet-bulb depressions above 212°F.

Dry-bulb temper-ature (°F)	Relative humidity[1] and equilibrium moisture content[2] (%) at various wet-bulb depression temperatures (°F)														
	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
215	92	90	89	87	85	83	82	80	78	77	75	74	72	71	69
	14.4	*13.5*	*12.7*	*12.0*	*11.4*	*10.8*	*10.3*	*9.8*	*9.4*	*9.0*	*8.7*	*8.3*	*8.0*	*7.8*	*7.5*
220	—	—	—	—	—	84	82	81	79	77	76	74	73	71	70
	—	—	—	—	—	*10.8*	*10.3*	*9.8*	*9.4*	*9.0*	*8.6*	*8.3*	*8.0*	*7.7*	*7.4*
225	—	—	—	—	—	—	—	—	—	—	76	75	73	72	70
	—	—	—	—	—	—	—	—	—	—	*8.5*	*8.2*	*7.9*	*7.6*	*7.3*
230	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
235	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
240	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
245	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
250	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
255	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
260	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—
	—	—	—	—	—	—	—	—	—	—	—	—	—	—	—

Table 1-7—Relative humidity and equilibrium moisture content at various dry-bulb temperatures and wet-bulb depressions above 212°F—concluded

Dry-bulb temperature (°F)	Relative humidity[1] and equilibrium moisture content[2] (%) at various wet-bulb depression temperatures (°F)														
	19	**20**	**22**	**24**	**26**	**28**	**30**	**35**	40	**45**	**50**	**55**	**60**	**70**	**80**
215	68	66	63	61	58	56	53	47	42	37	33	29	25	19	14
	7.3	*7.0*	*6.6*	*6.2*	*5.9*	*5.6*	*5.3*	*4.7*	*4.2*	*3.8*	*3.4*	*3.0*	*2.7*	*2.2*	*1.7*
220	68	67	64	62	59	56	54	48	43	38	34	30	26	20	15
	7.2	*7.0*	*6.6*	*6.2*	*5.8*	*5.5*	*5.3*	*4.6*	*4.2*	*3.7*	*3.4*	*3.0*	*2.7*	*2.2*	*1.7*
225	69	68	65	62	60	57	55	49	44	39	35	31	27	21	16
	7.1	*6.9*	*6.4*	*6.1*	*5.7*	*5.4*	*5.2*	*4.6*	*4.1*	*3.7*	*3.3*	*3.0*	*2.7*	*2.2*	*1.7*
230	69	68	65	63	60	58	55	50	45	40	35	31	28	22	16
	7.0	*6.7*	*6.3*	*6.0*	*5.7*	*5.4*	*5.1*	*4.5*	*4.0*	*3.6*	*3.3*	*2.9*	*2.6*	*2.1*	*1.7*
235	—	—	—	63	61	58	56	50	45	41	36	32	29	22	17
	—	—	—	*5.9*	*5.6*	*5.3*	*5.0*	*4.4*	*4.0*	*3.5*	*3.2*	*2.9*	*2.6*	*2.1*	*1.7*
240	—	—	—	—	—	—	57	51	46	41	37	33	29	23	18
	—	—	—	—	—	—	*4.9*	*4.4*	*3.9*	*3.5*	*3.1*	*2.8*	*2.6*	*2.1*	*1.7*
245	—	—	—	—	—	—	—	52	47	42	38	34	30	24	18
	—	—	—	—	—	—	—	*4.3*	*3.8*	*3.4*	*3.1*	*2.8*	*2.6*	*2.1*	*1.7*
250	—	—	—	—	—	—	—	—	47	43	38	35	31	25	19
	—	—	—	—	—	—	—	—	*3.7*	*3.3*	*3.0*	*2.7*	*2.5*	*2.0*	*1.6*
255	—	—	—	—	—	—	—	—	—	43	39	35	32	25	20
	—	—	—	—	—	—	—	—	—	*3.3*	*2.9*	*2.7*	*2.4*	*2.0*	*1.6*
260	—	—	—	—	—	—	—	—	—	—	40	36	32	26	21
	—	—	—	—	—	—	—	—	—	—	*2.9*	*2.6*	*2.3*	*1.9*	*1.6*

[1] Relative humidity values not italic.

[2] Equilibrium moisture content values italic.

Table 1-8—Specific gravity of wood

Species	Average specific gravity
SOFTWOODS	
Baldcypress	0.42
Cedar	
Alaska	0.42
Atlantic white-	0.31
Eastern redcedar	0.44
Incense	0.35
Northern white	0.29
Port-Orford	0.39
Western redcedar	0.31
Douglas-fir	
Coast type	0.45
Interior west	0.46
Interior north	0.45
Interior south	0.43
Fir	
Balsam	0.33
California red	0.36
Grand	0.35
Noble	0.37
Pacific silver	0.40
Subalpine	0.31
White	0.37
Hemlock	
Eastern	0.38
Western	0.42
Larch, western	0.48
Pine	
Eastern white	0.34
Lodgepole	0.38
Ponderosa	0.38
Red	0.41
Southern pine	
Loblolly	0.47
Longleaf	0.54
Shortleaf	0.47
Sugar	0.34
Western white	0.35
Redwood	
Old-growth	0.38
Second-growth	0.34
Spruce	
Black	0.38
Engelmann	0.33
Red	0.37
Sitka	0.37
Tamarack	0.49
HARDWOODS	
Alder, red	0.37
Apple	0.61
Ash	
Black	0.45
Green	0.53
White	0.55
Aspen	
Bigtooth	0.36
Quaking	0.35
Basswood, American	0.32
Beech, American	0.56
HARDWOODS—continued	
Birch	
Paper	0.48
Sweet	0.60
Yellow	0.55
Buckeye, yellow	0.33
Butternut	0.36
Cherry, black	0.47
Chestnut, American	0.40
Cottonwood, black	0.31
Dogwood, flowering	0.64
Elm	
American	0.46
Rock	0.57
Slippery	0.48
Hackberry	0.49
Hickory, pecan	
Bitternut	0.60
Hickory, true	
Mockernut	0.64
Pignut	0.66
Shagbark	0.64
Shellbark	0.62
Holly, American	0.50
Hophornbeam, eastern	0.63
Laurel, California	0.51
Locust, black	0.66
Madrone, Pacific	0.58
Maple	
Soft	
Bigleaf	0.44
Red	0.49
Silver	0.44
Hard	
Black	0.52
Sugar	0.56
Oak, red	
Black	0.56
California black	0.51
Laurel	0.56
Northern red	0.56
Pin	0.58
Scarlet	0.60
Southern red	0.52
Water	0.56
Willow	0.56
Oak, white	
Bur	0.58
Chestnut	0.57
Live	0.80
Overcup	0.57
Post	0.60
Swamp chestnut	0.60
White	0.60
Persimmon, common	0.64
Sweetgum	0.46
Sycamore, American	0.46
Tanoak	0.58
Tupelo	
Black	0.46
Water	0.46
Walnut, black	0.51
Willow, black	0.36
Yellow-poplar	0.40

Table 1-8—Specific gravity of wood-concluded

Species	Average specific gravity[1]
IMPORTED[2]	
Afrormosia	0.61
Albarco	0.48
Andiroba	0.54
Angelique	0.60
Apitong	0.69
Avodire	0.48
Balata (Bulletwood)	0.85
Balsa	0.16
Banak	0.42
Benge	0.65
Bubinga	0.71
Caribbean pine	0.68
Cativo	0.40
Ceiba	0.25
Cocobolo	0.89
Courbaril	0.71
Cuangare	0.31
Degame	0.67
Determa	0.52
Ebony, East Indian	0.70
Ebony, African	0.82
Gmelina	0.41
Goncalo alves	0.84
Greenheart	0.80
Hura	0.38
Ilomba	0.40
Imbuya	0.53
Ipe	0.92
Iroko	0.54
Jarrah	0.67
Jelutong	0.36
Kapur	0.64
Karri	0.82
Kempas	0.71
Keruing	0.69
Lauan	
Red	0.34
White	0.55
IMPORTED[2]—continued	
Lignumvitae	1.05
Limba	0.38
Mahogany, African	0.42
Mahogany, true	0.45
Manni	0.58
Merbau	0.64
Mersawa	0.52
Mora	0.78
Obeche	0.30
Ocote pine	0.55
Okoume	0.33
Opepe	0.63
Parana pine	0.46
Pau Marfim	0.73
Peroba de campos	0.63
Peroba rosa	0.66
Primavera	0.40
Purpleheart	0.67
Ramin	0.52
Roble (Quercus)	0.70
Roble (Tabebuia)	0.52
Rosewood, Indian	0.75
Rosewood, Brazilian	0.80
Rubberwood	0.49
Sande	0.49
Santa Maria	0.52
Sapele	0.55
Sepetir	0.56
Spanish cedar	0.41
Sucupira (Bowdichia)	0.74
Sucupira (Diplotropis)	0.78
Teak	0.55
Wallaba	0.78

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[1] Based on ovendry weight and green volume

[2] Refer to table 1-2 for botanical name.

Table 1-9—Calculated weights of wood per thousand board feet actual measure

	Approximate correction factor per 1,000 board feet for each 1 percent moisture content change		Weight (lb) per 1,000 actual board feet of various moisture content levels					
Species	Below 30 percent moisture content	Above 30 percent moisture content	6%	15%	25%	40%	60%	80%
			SOFTWOODS					
Baldcypress	13.2	21.9	2,527	2,646	2,778	3,063	3,501	3,939
Cedar								
Alaska	14.4	21.9	2,498	2,628	2,772	3,063	3,501	3,939
Atlantic white-	10.9	16.1	1,838	1,936	2,045	2,261	2,583	2,905
Eastern redcedar	16.4	22.9	2,587	2,735	2,899	3,210	3,668	4,126
Incense	13.1	18.2	2,056	2,174	2,305	2,553	2,917	3,281
Northern white	11.1	15.1	1,697	1,797	1,908	2,115	2,417	2,719
Port-Orford	12.6	20.2	2,339	2,452	2,578	2,843	3,247	3,651
Western redcedar	12.2	16.1	1,807	1,917	2,039	2,261	2,583	2,905
Douglas-fir								
Coast type	12.3	23.4	2,753	2,864	2,987	3,283	3,751	4,219
Interior west	13.2	23.9	2,799	2,918	3,050	3,355	3,833	4,311
Interior north	14.0	23.4	2,712	2,838	2,978	3,282	3,750	4,218
Fir								
Balsam	9.9	17.2	1,998	2,087	2,186	2,408	2,752	3,096
California red	10.6	18.7	2,183	2,278	2,384	2,624	2,998	3,372
Grand	10.7	18.2	2,114	2,210	2,317	2,553	2,917	3,281
Noble	10.1	19.2	2,264	2,355	2,456	2,699	3,083	3,467
Pacific silver	10.4	20.8	2,461	2,555	2,659	2,919	3,335	3,751
Subalpine	10.5	16.1	1,848	1,943	2,048	2,262	2,584	2,906
White	12.2	19.2	2,213	2,323	2,445	2,698	3,082	3,466
Hemlock								
Eastern	12.6	19.8	2,271	2,384	2,510	2,771	3,167	3,563
Western	11.5	21.8	2,570	2,674	2,789	3,065	3,501	3,937
Larch, western	11.3	25.0	2,979	3,081	3,194	3,501	4,001	4,501
Pine								
Eastern white	12.3	17.7	2,007	2,118	2,241	2,480	2,834	3,188
Lodgepole	11.5	19.8	2,299	2,402	2,518	2,774	3,170	3,566
Ponderosa	12.6	19.8	2,271	2,384	2,510	2,771	3,167	3,563
Red	12.2	21.3	2,484	2,594	2,716	2,990	3,416	3,842
Southern pine								
Loblolly	12.9	24.4	2,873	2,989	3,118	3,427	3,915	4,403
Longleaf	15.0	28.1	3,298	3,433	3,583	3,939	4,501	5,063
Shortleaf	12.9	24.4	2,873	2,989	3,118	3,427	3,915	4,403
Sugar	12.6	17.7	2,000	2,113	2,239	2,479	2,833	3,187
Western white	10.0	18.2	2,130	2,220	2,320	2,552	2,916	3,280
Redwood								
Old-growth	14.9	19.8	2,215	2,349	2,498	2,771	3,167	3,563
Second-growth	13.2	17.7	1,985	2,104	2,236	2,479	2,833	3,187
Spruce								
Black	11.3	19.8	2,303	2,405	2,518	2,773	3,169	3,565
Engelmann	10.0	17.2	1,994	2,084	2,184	2,406	2,750	3,094
Red	10.6	19.2	2,252	2,347	2,453	2,698	3,082	3,466
Sitka	10.8	19.2	2,246	2,343	2,451	2,697	3,081	3,465
Tamarack	12.0	25.5	3,030	3,138	3,258	3,573	4,083	4,593
			HARDWOODS					
Alder, red	9.9	19.2	2,268	2,357	2,456	2,698	3,082	3,466
Apple	10.9	31.7	3,870	3,968	4,077	4,449	5,083	5,717
Ash								
Black	9.3	23.4	2,824	2,908	3,001	3,282	3,750	4,218
Green	14.3	27.6	3,246	3,375	3,518	3,866	4,418	4,970
White	13.9	28.6	3,392	3,517	3,656	4,012	4,584	5,156

Table 1-9—Calculated weights of wood per thousand board feet actual measure-continued

	Approximate correction factor per 1,000 board feet for each 1 percent moisture content change		Weight (lb) per 1,000 actual board feet of various moisture content levels					
Species	Below 30 percent moisture content	Above 30 percent moisture content.	8%	15%	25%	40%	60%	80%
			HARDWOODS—continued					
Aspen								
Bigtooth	10.3	18.7	2,191	2,284	2,387	2,626	3,000	3,374
Quaking	10.3	18.2	2,125	2,217	2,321	2,555	2,919	3,283
Basswood, American	6.2	16.6	2,019	2,081	2,143	2,340	2,672	3,004
Beech, American	8.9	29.1	3,579	3,659	3,748	4,084	4,666	5,248
Birch								
Paper	8.8	25.0	3,049	3,128	3,216	3,510	4,010	4,510
Sweet	11.9	31.2	3,779	3,886	4,005	4,377	5,001	5,625
Yellow	9.2	28.6	3,502	3,585	3,677	4,009	4,581	5,153
Buckeye, yellow	8.9	17.2	2,021	2,101	2,190	2,407	2,751	3,095
Butternut	11.3	18.7	2,168	2,270	2,383	2,627	3,001	3,375
Cherry, black	13.8	24.4	2,853	2,977	3,115	3,428	3,916	4,404
Chestnut, American	11.6	20.8	2,430	2,534	2,650	2,916	3,332	3,748
Cottonwood, black	8.5	16.1	1,897	1,974	2,059	2,263	2,585	2,907
Dogwood, flowering	6.8	33.3	4,168	4,229	4,297	4,664	5,330	5,996
Elm								
American	10.2	23.9	2,871	2,963	3,065	3,355	3,833	4,311
Rock	12.2	29.6	3,567	3,677	3,799	4,156	4,748	5,340
Slippery	11.5	25.0	2,974	3,078	3,193	3,501	4,001	4,501
Hackberry	11.8	25.5	3,036	3,142	3,260	3,574	4,084	4,594
Hickory, pecan								
Bitternut	14.7	31.2	3,711	3,843	3,990	4,376	5,000	5,624
Hickory, true								
Mockernut	9.1	33.3	4,113	4,195	4,286	4,665	5,331	5,997
Pignut	9.3	34.3	4,246	4,330	4,423	4,805	5,491	6,177
Shagbark	10.9	33.3	4,071	4,169	4,278	4,666	5,332	5,998
Shellbark	6.6	32.2	4,037	4,096	4,162	4,517	5,161	5,805
Holly, American	8.3	26.0	3,187	3,262	3,345	3,647	4,167	4,687
Hophornbeam, eastern	7.9	32.8	4,076	4,147	4,226	4,594	5,250	5,906
Laurel, California	15.1	26.5	3,093	3,229	3,380	3,721	4,251	4,781
Locust, black	21.2	34.3	3,961	4,152	4,364	4,813	5,499	6,185
Madrone, Pacific	7.8	30.2	3,738	3,808	3,886	4,227	4,831	5,435
Maple								
Soft								
Bigleaf	12.8	22.9	2,673	2,788	2,916	3,209	3,667	4,125
Red	13.1	25.5	3,004	3,122	3,253	3,573	4,083	4,593
Silver	12.4	22.9	2,683	2,795	2,919	3,210	3,668	4,126
Hard								
Black	12.3	27.0	3,228	3,338	3,462	3,793	4,333	4,873
Sugar	12.3	29.1	3,498	3,609	3,732	4,084	4,666	5,248
Oak, red								
Black	11.7	29.1	3,511	3,616	3,733	4,083	4,665	5,247
California black	16.4	26.5	3,061	3,209	3,373	3,720	4,250	4,780
Laurel	6.3	29.1	3,640	3,697	3,760	4,082	4,664	5,246
Northern red	13.6	29.1	3,467	3,589	3,725	4,084	4,666	5,248
Pin	13.0	30.2	3,616	3,733	3,863	4,230	4,834	5,438
Scarlet	13.2	31.2	3,748	3,867	3,999	4,377	5,001	5,625
Southern red	9.6	27.0	3,290	3,376	3,472	3,790	4,330	4,870
Water	10.4	29.1	3,543	3,637	3,741	4,084	4,666	5,248
Willow	6.4	29.1	3,636	3,694	3,758	4,081	4,663	5,245
Oak, white								
Bur	15.4	30.2	3,558	3,697	3,851	4,230	4,834	5,438
Chestnut	10.1	29.6	3,616	3,707	3,808	4,154	4,746	5,338
Live	17.5	41.6	4,997	5,155	5,330	5,833	6,665	7,497
Overcup	10.7	29.6	3,603	3,699	3,806	4,156	4,748	5,340
Post	11.0	31.2	3,799	3,898	4,008	4,375	4,999	5,623
Swamp chestnut	10.7	31.2	3,806	3,902	4,009	4,375	4,999	5,623
White	10.8	31.2	3,803	3,900	4,008	4,374	4,998	5,622

Table 1-9—Calculated weights of wood per thousand board feet actual measure—continued

Species	Approximate correction factor per 1,000 board feet for each 1 percent moisture content change		Weight (lb) per 1,000 actual board feet of various moisture content levels					
	Below 30 percent moisture content	Above 30 percent moisture content	6%	15%	25%	40%	60%	80%
			HARDWOODS—continued					
Persimmon, common	7.0	33.3	4,164	4,227	4,297	4,665	5,331	5,997
Sweetgum	8.9	23.9	2,902	2,982	3,071	3,354	3,833	4,311
Sycamore, American	10.7	23.9	2,858	2,954	3,061	3,354	3,832	4,310
Tanoak	9.0	30.2	3,710	3,791	3,881	4,228	4,832	5,436
Tupelo								
Black	10.4	23.9	2,866	2,960	3,064	3,355	3,833	4,311
Water	12.4	23.9	2,817	2,929	3,053	3,354	3,832	4,310
Walnut, black	13.4	26.5	3,132	3,253	3,387	3,719	4,249	4,779
Willow, black	8.6	18.7	2,232	2,309	2,395	2,625	2,999	3,373
Yellow-poplar	10.6	20.8	2,454	2,549	2,655	2,916	3,332	3,748
			IMPORTED					
Afrormosia	18.9	31.7	3,677	3,847	4,036	4,448	5,082	5,716
Albarco	16.7	25.0	2,851	3,001	3,168	3,501	4,002	4,502
Andiroba	17.1	28.1	3,246	3,400	3,571	3,937	4,499	5,061
Angelique	14.2	31.2	3,724	3,852	3,994	4,377	5,001	5,625
Apitong	12.8	35.9	4,365	4,480	4,608	5,031	5,749	6,467
Avodire	13.5	25.0	2,927	3,049	3,184	3,501	4,001	4,501
Balata	14.1	44.2	5,417	5,544	5,685	6,197	7,081	7,965
Balsa	4.9	8.3	965	1,009	1,058	1,166	1,332	1,498
Banak	10.2	21.8	2,600	2,692	2,794	3,063	3,499	3,935
Benge	15.6	33.8	4,027	4,167	4,323	4,739	5,415	6,091
Bubinga	16.4	36.9	4,415	4,563	4,727	5,178	5,917	6,654
Caribbean pine	17.8	35.4	4,179	4,339	4,517	4,960	5,668	6,376
Cativo	14.0	20.8	2,374	2,500	2,640	2,918	3,334	3,750
Ceiba	7.9	13.0	1,503	1,574	1,653	1,823	2,083	2,343
Cocobolo	34.6	46.3	5,196	5,507	5,853	6,489	7,415	8,341
Courbaril	18.9	36.9	4,356	4,526	4,715	5,179	5,917	6,655
Cuangare	8.7	16.1	1,890	1,968	2,055	2,260	2,582	2,904
Degame	17.0	34.8	4,129	4,282	4,452	4,885	5,581	6,277
Determa	16.5	27.0	3,126	3,275	3,440	3,792	4,332	4,872
Ebony, East Indian	16.2	36.4	4,352	4,498	4,660	5,105	5,833	6,561
Ebony, African	7.0	42.6	5,381	5,444	5,514	5,975	6,827	7,679
Gmelina	14.4	21.3	2,431	2,561	2,705	2,990	3,416	3,842
Goncalo alves	27.4	43.7	5,032	5,279	5,553	6,127	7,001	7,875
Greenheart	12.8	41.6	5,108	5,223	5,351	5,831	6,663	7,495
Hura	14.5	19.8	2,224	2,355	2,500	2,770	3,166	3,562
Ilomba	10.5	20.8	2,456	2,551	2,656	2,916	3,332	3,748
Imbuya	18.4	27.6	3,148	3,314	3,498	3,866	4,418	4,970
Ipe	23.4	47.8	5,670	5,881	6,115	6,710	7,666	8,622
Iroko	19.0	28.1	3,202	3,373	3,563	3,939	4,501	5,063
Jarrah	8.0	34.8	4,343	4,415	4,495	4,883	5,579	6,275
Jelutong	13.4	18.7	2,116	2,237	2,371	2,625	2,999	3,373
Kapur	13.9	33.3	4,001	4,126	4,265	4,668	5,334	6,000
Karri	6.6	42.6	5,391	5,450	5,516	5,975	6,827	7,679
Kempas	15.9	36.9	4,427	4,570	4,729	5,178	5,916	6,659
Keruing	12.8	35.9	4,365	4,480	4,608	5,031	5,749	6,467
Lauan, red and white	10.0-16.1	17.7-28.6	2,064-3,339	2,154-3,484	2,254-3,645	2,481-4,011	2,835-4,583	3,189-5,155
Limba	11.7	19.8	2,293	2,398	2,515	2,772	3,167	3,564
Mahogany, African	14.8	21.8	2,490	2,623	2,771	3,063	3,499	3,935
Mahogany, true	16.7	23.4	2,645	2,795	2,962	3,280	3,748	4,216
Manni	11.5	30.2	3,653	3,757	3,872	4,231	4,835	5,439

Table 1-9—Calculated weights of wood per thousand board feet actual measure—concluded

	Approximate correction factor per 1,000 board feet for each 1 percent moisture content change		Weight (lb) per 1,000 actual board feet of various moisture content levels					
Species	Below 30 percent moisture content	Above 30 percent moisture content	6%	15%	25%	40%	60%	80%
			IMPORTED—continued					
Merbau	23.8	33.3	3,762	3,976	4,214	4,666	5,332	5,998
Mersawa	11.5	27.0	3,245	3,349	3,464	3,791	4,331	4,871
Mora	9.1	40.6	5,060	5,142	5,233	5,684	6,496	7,308
Obeche	10.3	15.6	1,785	1,878	1,981	2,188	2,500	2,812
Ocote pine	15.1	28.6	3,362	3,498	3,649	4,010	4,582	5,154
Okoume	*9.8*	*17.2*	*2,000*	*2,088*	*2,186*	*2,407*	*2,751*	*3,095*
Opepe	16.9	32.8	3,862	4,014	4,183	4,596	5,251	5,908
Parana pine	13.4	23.9	2,795	2,916	3,050	3,356	3,834	4,312
Pau Marfim	*18.2*	*38.0*	*4,507*	*4,671*	*4,853*	*5,324*	*6,084*	*6,844*
Peroba de campos	19.8	32.8	3,791	3,969	4,167	4,594	5,250	5,906
Peroba rosa	19.2	34.3	4,010	4,183	4,375	4,814	5,500	6,186
Primavera	*13.8*	*20.8*	*2,378*	*2,502*	*2,640*	*2,917*	*3,333*	*3,749*
Purpleheart	22.0	34.8	4,011	4,209	4,429	4,887	5,583	6,279
Ramin	13.0	27.0	3,210	3,327	3,457	3,792	4,332	4,872
Roble (Quercus)	8.7	36.4	4,528	4,606	4,693	5,102	5,829	6,557
Roble (Tabebuia)	17.5	27.0	3,102	3,260	3,435	3,792	4,332	4,872
Rosewood, Indian	26.8	39.0	4,435	4,676	4,944	5,468	6,248	7,028
Rosewood, Brazilian	28.6	41.6	4,731	4,988	5,274	5,833	6,665	7,497
Rubberwood	18.6	25.5	2,871	3,038	3,224	3,572	4,082	4,592
Sande	14.1	25.5	2,980	3,107	3,248	3,573	4,083	4,593
Santa Maria	12.7	27.0	3,216	3,330	3,457	3,791	4,331	4,871
Sapele	13.0	28.6	3,414	3,531	3,661	4,012	4,584	5,156
Sepetir	17.6	29.1	3,370	3,528	3,704	4,083	4,665	5,247
Spanish cedar	13.1	21.3	2,463	2,581	2,712	2,990	3,416	3,842
Sucupira (Bowdichia)	18.5	38.5	4,568	4,735	4,920	5,397	6,167	6,937
Sucupira (Diplotropis)	22.3	40.6	4,747	4,948	5,171	5,689	6,501	7,314
Teak	21.4	28.6	3,211	3,404	3,618	4,011	4,583	5,155
Wallaba	*25.4*	*40.6*	*4,673*	*4,902*	*5,156*	*5,689*	*6,501*	*7,313*

Table 1-10—Shrinkage values of wood, based on its dimensions when green

	Shrinkage (percent)						
	Dried to 20-percent moisture content[1]		Dried to 6-percent moisture content[2]		Dried to 0-percent moisture content		
Species	Radial	Tangential	Radial	Tangential	Radial	Tangential	Volumetric
			SOFTWOODS				
Baldcypress	1.3	2.1	3.0	5.0	3.8	6.2	10.5
Cedar							
Alaska	0.9	2.0	2.2	4.8	2.8	6.0	9.2
Atlantic white-	1.0	1.8	2.3	4.3	2.9	5.4	8.8
Eastern redcedar	1.0	1.6	2.5	3.8	3.1	4.7	7.8
Incense	1.1	1.7	2.6	4.2	3.3	5.2	7.7
Northern white	0.7	1.6	1.8	3.9	2.2	4.9	7.2
Port-Orford	1.5	2.3	3.7	5.5	4.6	6.9	10.1
Western redcedar	0.8	1.7	1.9	4.0	2.4	5.0	6.8
Douglas-fir							
Coast type	1.6	2.5	3.8	6.1	4.8	7.6	12.4
Interior west	1.6	2.5	3.8	6.0	4.8	7.5	11.8
Interior north	1.3	2.3	3.0	5.5	3.8	6.9	10.7
Fir							
Balsam	1.0	2.3	2.3	5.5	2.9	6.9	11.2
California red	1.5	2.6	3.6	6.3	4.5	7.9	11.4
Grand	1.1	2.5	2.7	6.0	3.4	7.5	11.0
Noble	1.4	2.8	3.4	6.6	4.3	8.3	12.4
Pacific silver	1.5	3.1	3.5	7.4	4.4	9.2	13.0
Subalpine	0.9	2.5	2.1	5.9	2.6	7.4	9.4
White	1.1	2.3	2.6	5.6	3.3	7.0	9.8
Hemlock							
Eastern	1.0	2.3	2.4	5.4	3.0	6.8	9.7
Western	1.4	2.6	3.4	6.2	4.2	7.8	12.4
Larch, western	1.5	3.0	3.6	7.3	4.5	9.1	14.0
Pine							
Eastern white	0.7	2.0	1.7	4.9	2.1	6.1	8.2
Lodgepole	1.4	2.2	3.4	5.4	4.3	6.7	11.1
Ponderosa	1.3	2.1	3.1	5.0	3.9	6.2	9.7
Red	1.3	2.4	3.0	5.8	3.8	7.2	11.3
Southern pine							
Loblolly	1.6	2.5	3.8	5.9	4.8	7.4	12.3
Longleaf	1.7	2.5	4.1	6.0	5.1	7.5	12.2
Shortleaf	1.5	2.6	3.7	6.2	4.6	7.7	12.3
Sugar	1.0	1.9	2.3	4.5	2.9	5.6	7.9
Western white	1.4	2.5	3.3	5.9	4.1	7.4	11.8
Redwood							
Old-growth	0.9	1.5	2.1	3.5	2.6	4.4	6.8
Second-growth	0.7	1.6	1.8	3.9	2.2	4.9	7.0
Spruce							
Black	1.4	2.3	3.3	5.4	4.1	6.8	11.3
Engelmann	1.3	2.4	3.0	5.7	3.8	7.1	11.0
Red	1.3	2.6	3.0	6.2	3.8	7.8	11.8
Sitka	1.4	2.5	3.4	6.0	4.3	7.5	11.5
Tamarack	1.2	2.5	3.0	5.9	3.7	7.4	13.6
			HARDWOODS				
Alder, red	1.5	2.4	3.5	5.8	4.4	7.3	12.6
Apple	2.0	3.5	4.7	8.4	5.9	10.5	16.4
Ash							
Black	1.7	2.6	4.0	6.2	5.0	7.8	15.2
Green	1.5	2.4	3.7	5.7	4.6	7.1	12.5
White	1.6	2.6	3.9	6.2	4.9	7.8	13.3
Aspen							
Bigtooth	1.1	2.6	2.6	6.3	3.3	7.9	11.8
Quaking	1.2	2.2	2.8	5.4	3.5	6.7	11.5
Basswood, American	2.2	3.1	5.3	7.4	6.6	9.3	15.8
Beech, American	1.8	4.0	4.4	9.5	5.5	11.9	17.2
Birch							
Paper	2.1	2.9	5.0	6.9	6.3	8.6	16.2
Sweet	2.2	3.0	5.2	7.2	6.5	9.0	15.6
Yellow	2.4	3.2	5.8	7.6	7.3	9.5	16.8

Table 1-10—Shrinkage values of wood, based on its dimensions when green—continued

	Shrinkage (percent)						
	Dried to 20-percent moisture content[1]		Dried to 6-percent moisture content[2]		Dried to 0-percent moisture content		
Species	Radial	Tangential	Radial	Tangential	Radial	Tangential	Volumetric
			HARDWOODS—continued				
Buckeye, yellow	1.2	2.7	2.9	6.5	3.6	8.1	12.5
Butternut	1.1	2.1	2.7	5.1	3.4	6.4	10.6
Cherry, black	1.2	2.4	3.0	5.7	3.7	7.1	11.5
Chestnut, American	1.1	2.2	2.7	5.4	3.4	6.7	11.6
Cottonwood, black	1.2	2.9	2.9	6.9	3.6	8.6	12.4
Dogwood, flowering	2.5	3.9	5.9	9.4	7.4	11.8	19.2
Elm							
American	1.4	3.2	3.4	7.6	4.2	9.5	14.6
Rock	1.6	2.7	3.8	6.5	4.8	8.1	14.9
Slippery	1.6	3.0	3.9	7.1	4.9	8.9	13.8
Hackberry	1.6	3.0	3.8	7.1	4.8	8.9	13.8
Hickory, pecan							
Bitternut	1.6	3.0	3.9	7.1	4.9	8.9	13.6
Hickory, true							
Mockernut	2.6	3.7	6.2	8.8	7.7	11.0	17.8
Pignut	2.4	3.8	5.8	9.2	7.2	11.5	17.9
Shagbark	2.3	3.5	5.6	8.4	7.0	10.5	16.7
Shellbark	2.5	4.2	6.1	10.1	7.6	12.6	19.2
Holly, American	1.6	3.3	3.8	7.9	4.8	9.9	16.9
Hophornbeam, eastern	2.8	3.3	6.8	8.0	8.5	10.0	18.5
Laurel, California	1.0	2.8	2.3	6.8	2.9	8.5	11.4
Locust, black	1.5	2.4	3.7	5.8	4.6	7.2	10.2
Madrone, Pacific	1.9	4.1	4.5	9.9	5.6	12.4	18.1
Maple							
Soft							
Bigleaf	1.2	2.4	3.0	5.7	3.7	7.1	11.6
Red	1.3	2.7	3.2	6.6	4.0	8.2	12.6
Silver	1.0	2.4	2.4	5.8	3.0	7.2	12.0
Hard							
Black	1.6	3.1	3.8	7.4	4.8	9.3	14.0
Sugar	1.6	3.3	3.8	7.9	4.8	9.9	14.7
Oak, red							
Black	1.5	3.7	3.5	8.9	4.4	11.1	15.1
California black	1.2	2.2	2.9	5.3	3.6	6.6	10.2
Laurel	1.3	3.3	3.2	7.9	4.0	9.9	19.0
Northern red	1.3	2.9	3.2	6.9	4.0	8.6	13.7
Pin	1.4	3.2	3.4	7.6	4.3	9.5	14.5
Scarlet	1.5	3.6	3.5	8.6	4.4	10.8	14.7
Southern red	1.6	3.8	3.8	9.0	4.7	11.3	16.1
Water	1.5	3.3	3.5	7.8	4.4	9.8	16.1
Willow	1.7	3.2	4.0	7.7	5.0	9.6	18.9
Oak, white							
Bur	1.5	2.9	3.5	7.0	4.4	8.8	12.7
Chestnut	1.8	3.6	4.2	8.6	5.3	10.8	16.4
Live	2.2	3.2	5.3	7.6	6.6	9.5	14.7
Overcup	1.8	4.2	4.2	10.2	5.3	12.7	16.0
Post	1.8	3.3	4.3	7.8	5.4	9.8	16.2
Swamp chestnut	1.7	3.6	4.2	8.6	5.2	10.8	16.4
White	1.9	3.5	4.5	8.4	5.6	10.5	16.3
Persimmon, common	2.6	3.7	6.3	9.0	7.9	11.2	19.1
Sweetgum	1.8	3.4	4.2	8.2	5.3	10.2	15.8
Sycamore, American	1.7	2.8	4.0	6.7	5.0	8.4	14.1
Tanoak	1.6	3.9	3.9	9.4	4.9	11.7	17.3
Tupelo							
Black	1.7	2.9	4.1	7.0	5.1	8.7	14.4
Water	1.4	2.5	3.4	6.1	4.2	7.6	12.5
Walnut, black	1.8	2.6	4.4	6.2	5.5	7.8	12.8
Willow, black	1.1	2.9	2.6	7.0	3.3	8.7	13.9
Yellow-poplar	1.5	2.7	3.7	6.6	4.6	8.2	12.7

Table 1-10—Shrinkage values of wood, based on its dimensions when green—continued

	Shrinkage (percent)						
	Dried to 20-percent moisture content[1]		Dried to 6-percent moisture content[2]		Dried to 0-percent moisture content		
Species	Radial	Tangential	Radial	Tangential	Radial	Tangential	Volumetric
			IMPORTED[3]				
Afrormosia	1.0	2.1	2.4	5.1	3.0	6.4	10.7
Albarco	0.9	1.8	2.2	4.3	2.8	5.4	9.0
Andiroba	1.0	2.5	2.5	6.1	3.1	7.6	10.4
Angelique	1.7	2.9	4.2	7.0	5.2	8.8	14.0
Apitong	1.7	3.6	4.2	8.7	5.2	10.9	16.1
Avodire	1.5	2.2	3.7	5.4	4.6	6.7	12.0
Balata (Bulletwood)	2.1	3.1	5.0	7.5	6.3	9.4	16.9
Balsa	1.0	2.5	2.4	6.1	3.0	7.6	10.8
Banak	1.5	2.9	3.7	7.0	4.6	8.8	13.7
Benge	1.7	2.9	4.2	6.9	5.2	8.6	13.8
Bubinga	1.9	2.8	4.6	6.7	5.8	8.4	14.2
Caribbean pine	2.1	2.6	5.0	6.2	6.3	7.8	12.9
Cativo	0.8	1.8	1.9	4.2	2.4	5.3	8.9
Ceiba	0.7	1.4	1.7	3.3	2.1	4.1	10.4
Cocobolo	0.9	1.4	2.2	3.4	2.7	4.3	7.0
Courbaril	1.5	2.8	3.6	6.8	4.5	8.5	12.7
Cuangare	1.4	3.1	3.4	7.5	4.2	9.4	12.0
Degame	1.6	2.9	3.8	6.9	4.8	8.6	13.2
Determa	1.2	2.5	3.0	6.1	3.7	7.6	10.4
Ebony, East Indian	1.8	2.9	4.3	7.0	5.4	8.8	14.2
Ebony, African	3.1	3.6	7.4	8.6	9.2	10.8	20.0
Gmelina	0.8	1.6	1.9	3.9	2.4	4.9	8.8
Goncalo alves	1.3	2.5	3.2	6.1	4.0	7.6	10.0
Greenheart	2.9	3.2	7.0	7.7	8.8	9.6	17.1
Hura	0.9	1.5	2.2	3.6	2.7	4.5	7.3
Ilomba	1.5	2.8	3.7	6.7	4.6	8.4	12.8
Imbuya	0.9	2.0	2.2	4.8	2.7	6.0	9.0
Ipe	2.2	2.7	5.3	6.4	6.6	8.0	13.2
Iroko	0.9	1.3	2.2	3.0	2.8	3.8	8.8
Jarrah	2.6	3.7	6.2	8.8	7.7	11.0	18.7
Jelutong	0.8	1.8	1.8	4.4	2.3	5.5	7.8
Kapur	1.5	3.4	3.7	8.2	4.6	10.2	14.8
Karri	2.6	4.1	6.2	9.9	7.8	12.4	20.2
Kempas	2.0	2.5	4.8	5.9	6.0	7.4	14.5
Keruing	1.7	3.6	4.2	8.7	5.2	10.9	16.1
Lauan, red and white	1.3	2.6	3.0	6.2	3.8	7.7	11.5
Limba	1.5	2.1	3.6	5.0	4.5	6.2	10.8
Mahogany, African	0.8	1.5	2.0	3.6	2.5	4.5	8.8
Mahogany, true	1.0	1.4	2.4	3.3	3.0	4.1	7.8
Manni	1.9	3.2	4.6	7.8	5.7	9.7	15.6
Merbau	0.9	1.5	2.2	3.7	2.7	4.6	7.8
Mersawa	1.3	3.0	3.2	7.2	4.0	9.0	14.6
Mora -	2.3	3.3	5.5	7.8	6.9	9.8	18.8
Obeche	1.0	1.8	2.4	4.3	3.0	5.4	9.2
Ocote pine	1.5	2.5	3.7	6.0	4.6	7.5	12.3
Okoume	1.4	2.0	3.3	4.9	4.1	6.1	11.3
Opepe	1.5	2.8	3.6	6.7	4.5	8.4	12.6
Parana pine	1.3	2.6	3.2	6.3	4.0	7.9	11.6
Pau Marfim	1.5	2.9	3.7	7.0	4.6	8.8	13.4
Peroba de campos	1.3	2.2	3.0	5.3	3.8	6.6	10.5
Peroba rosa	1.3	2.1	3.0	5.1	3.8	6.4	11.6
Primavera	1.0	1.7	2.5	4.1	3.1	5.1	9.1
Purpleheart	1.1	2.0	2.6	4.9	3.2	6.1	9.9
Ramin	1.4	2.9	3.4	7.0	4.3	8.7	13.4
Roble (Quercus)	2.1	3.9	5.1	9.4	6.4	11.7	18.5
Roble (Tabebuia)	1.2	2.0	2.9	4.9	3.6	6.1	9.5
Rosewood, Indian	0.9	1.9	2.2	4.6	2.7	5.8	8.5
Rosewood, Brazilian	1.0	1.5	2.3	3.7	2.9	4.6	8.5
Rubberwood	0.8	1.7	1.8	4.1	2.3	5.1	7.4
Sande	1.3	2.6	3.1	6.2	3.9	7.8	11.7

Table 1-10—Shrinkage values of wood, based on its dimensions when green-concluded

Species	Shrinkage (percent)						
	Dried to 20-percent moisture content[1]		Dried to 6-percent moisture content[2]		Dried to O-percent moisture content		
	Radial	Tangential	Radial	Tangential	Radial	Tangential	Volumetric
	IMPORTED—continued						
Santa Maria	1.5	2.7	3.7	6.4	4.6	8.0	13.6
Sapele	1.5	2.5	3.7	5.9	4.6	7.4	14.0
Sepetir	1.2	2.3	3.0	5.6	3.7	7.0	10.5
Spanish cedar	1.4	2.1	3.4	5.0	4.2	6.3	10.3
Sucupira (Bowdichia)	1.7	2.6	4.0	6.2	5.0	7.8	13.4
Sucupira (Diplotropis)	1.5	2.3	3.7	5.6	4.6	7.0	11.8
Teak	0.8	1.9	2.0	4.6	2.5	5.8	7.0
Wallaba	1.2	2.3	2.9	5.5	3.6	6.9	10.0

[1] These shrinkage values have been taken as 1/3 of the shrinkage to the ovendry condition as given in columns 5 and 6 of this table.

[2] These shrinkage values have been taken as 4/5 of the shrinkage to the ovendry condition as given in columns 5 and 6 of this table.

[3] Refer to table 1-1 for botanical name.

Table 1-11—Average electrical resistance along the grain, for selected species, as measured at 80°F between two pairs of needle electrodes 1-1/4 inches apart and driven to a depth of 5/16 inch

Species	Electrical resistance (megohms) at different levels of moisture content (percent)																		
	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25
Softwoods																			
Cypress, southern	12,600	3,980	1,410	630	265	120	60	33	18.6	11.2	7.1	4.6	3.09	1.78	1.26	0.91	0.66	0.51	0.42
Douglas-fir (coast type)	22,400	4,780	1,660	630	265	120	60	33	18.6	11.2	7.1	4.6	3.09	2.14	1.51	1.10	0.79	0.60	0.46
Fir, California red	31,600	6,760	2,000	725	315	150	83	48	28.8	18.2	11.8	7.6	5.01	3.31	2.29	1.58	1.15	0.83	0.63
Fir, white	57,600	15,850	3,980	1,120	415	180	83	46	26.9	16.6	11.0	6.6	4.47	3.02	2.14	1.55	1.12	0.86	0.62
Hemlock, western	*22,900*	*5,620*	*2,040*	*850*	*400*	*185*	*98*	*51*	*28.2*	*16.2*	*10.0*	*6.0*	*3.89*	*2.52*	*1.58*	*1.05*	*0.72*	*0.51*	*0.37*
Larch, western	39,800	11,200	3,980	1,445	560	250	120	63	33.9	19.9	12.3	7.6	5.02	3.39	2.29	1.62	1.20	0.87	0.66
Pine, eastern white	20,900	5,620	2,090	850	405	200	102	58	33.1	19.9	12.3	7.9	5.01	3.31	2.19	1.51	1.05	0.74	0.52
Pine, longleaf	25,000	8,700	3,160	1,320	575	270	135	74	41.7	24.0	14.4	8.9	5.76	3.72	2.46	1.66	1.15	0.79	0.60
Pine, ponderosa	39,800	8,910	3,310	1,410	645	300	150	81	44.7	25.1	14.8	9.1	5.62	3.55	2.34	1.62	1.15	0.87	0.69
Pine, shortleaf	43,600	11,750	3,720	1,350	560	255	130	69	38.9	22.4	13.8	8.7	5.76	3.80	2.63	1.82	1.29	0.93	0.66
Pine, sugar	22,900	5,250	1,660	645	280	140	76	44	25.7	15.9	10.0	6.6	4.36	3.02	2.09	1.48	1.05	0.75	0.56
Redwood	22,400	4,680	1,550	615	250	100	45	22	12.6	7.2	4.7	3.2	2.29	1.74	1.32	1.05	0.85	0.71	0.60
Spruce, Sitka	22,400	5,890	2,140	830	365	165	83	44	25.1	15.5	9.8	6.3	4.27	3.02	2.14	1.58	1.17	0.91	0.71
Hardwoods																			
Ash, commercial white	12,000	2,190	690	250	105	55	28	14	8.3	5.0	3.2	2.0	1.32	0.89	0.63	0.50	0.44	0.40	0.40
Basswood	36,300	1,740	470	180	85	45	27	16	9.6	6.2	4.1	2.8	1.86	1.32	0.93	0.69	0.51	0.39	0.31
Birch	87,000	19,950	4,470	1,290	470	200	96	53	30.2	18.2	11.5	7.6	5.13	3.55	2.51	1.78	1.32	0.95	0.70
Elm, American	18,200	2,000	350	110	45	20	12	7	3.9	2.3	1.5	1.0	0.66	0.48	0.42	0.40	0.40	0.40	0.40
Hickory, true	—	31,600	2,190	340	115	50	21	11	6.3	3.7	2.3	1.5	1.00	0.71	0.52	0.44	0.40	0.40	0.40
Kahya[1]	44,600	16,200	6,310	2,750	1,260	630	340	180	105.0	60.2	35.5	21.9	14.10	9.33	6.16	4.17	2.82	1.99	1.44
Magnolia	43,700	12,600	5,010	2,040	910	435	205	105	56.2	29.5	16.2	9.1	5.25	3.09	1.86	1.17	0.74	0.50	0.32
Mahogany, American	20,900	6,760	2,290	870	380	180	85	43	22.4	12.3	7.2	4.4	2.69	1.66	1.07	0.72	0.49	0.35	0.26
Maple, sugar	72,400	13,800	3,160	690	250	105	53	29	16.6	10.2	6.8	4.5	3.16	2.24	1.62	1.23	0.98	0.75	0.60
Oak, commercial red[2]	14,400	4,790	1,590	630	265	125	63	32	18.2	11.3	7.3	4.6	3.02	2.09	1.45	0.95	0.80	0.63	0.50
Oak, commercial white	17,400	3,550	1,100	415	170	80	42	22	12.6	7.2	4.3	2.7	1.70	1.15	0.79	0.60	0.49	0.44	0.41
Shorea[3]	*2,890*	*690*	*220*	*80*	*35*	*15*	*9*	*5*	*2.8*	*1.7*	*1.1*	*0.7*	*0.45*	*0.30*	*0.21*	*0.16*	*0.12*	*0.09*	*0.07*
Sweetgum	38,000	6,460	2,090	815	345	160	81	45	25.7	15.1	9.3	6.0	3.98	2.63	1.78	1.26	0.87	0.63	0.46
Tupelo, black[2]	31,700	12,600	5,020	1,820	725	275	120	58	27.6	13.0	6.9	3.7	2.19	1.38	0.95	0.63	0.46	0.33	0.25
Walnut, black	51,300	9,770	2,630	890	355	155	78	41	22.4	12.9	7.8	4.9	3.16	2.14	1.48	1.02	0.72	0.51	0.38
Yellow-poplar[2]	24,000	8,320	3,170	1,260	525	250	140	76	43.7	25.2	14.5	8.7	5.76	3.81	2.64	1.91	1.39	1.10	0.85

[1] Known in the trade as "African mahogany."

[2] The values for this species were calculated from measurements on veneer.

[3] A Philippine hardwood, identified as tanguile or some similar species.

Appendix—Equations for Relating Temperature, Humidity, and Moisture Content

In this appendix, we present a series of equations that relate wet- and dry-bulb temperatures to specific and relative humidities, and equations that relate EMC to relative humidity (RH) and temperature. A psychrometric chart and an example of how to calculate specific and relative humidities are included.

Wet-bulb Temperature and Relative Humidity

When unsaturated air is brought in contact with water, the air is humidified and cooled. If the system is operated so that no heat is gained or lost to the surroundings, the process is adiabatic. Thus, if the water remains at constant temperature, the latent heat of evaporation must equal the sensible heat released by the air in cooling. If the temperature reached by the air when it becomes saturated is the same as the water temperature, this temperature is called adiabatic saturation temperature or the thermodynamic wet-bulb temperature.

When unsaturated air is passed over a wetted thermometer bulb, so that water evaporates from the wetted surface and causes the thermometer bulb to cool, an equilibrium temperature (called the true wet-bulb temperature) is reached. At this point, the rate of heat transfer from the wetted surface is equal to the rate at which the wetted surface loses heat in the form of latent heat of evaporation. The thermodynamic wet-bulb and true wet-bulb temperatures are not necessarily equal, but in the range of 215°F to 300°F the difference between these temperatures is negligible. Thus, the RH values based on the difference between the dry-bulb temperature and the thermodynamic wet-bulb temperature do not differ significantly from RH values based on the difference between the dry-bulb temperature and the true wet-bulb temperature. The maximum difference is 0.54 percent RH; on the average, the difference is +0.25 percent RH.

Relative humidity can be calculated from the adiabatic saturation temperature by the following procedure (Hawkins 1978). By writing energy and mass balances for the process of adiabatic saturation

$$Y = Y_s - \frac{(0.24 + 0.44Y_s)(T_{db} - T_s)}{1094 + 0.44T_{db} - T_s} \qquad (1)$$

where

Y is specific humidity (lb water/lb dry air),

Y_s specific humidity for saturation at T_s (lb water/lb dry air),

T_{db} dry-bulb temperature (°F),

T_s adiabatic saturation temperature (°F),

and

$$Y_s = \frac{\rho_s}{1.61(\rho_t - \rho_s)} \qquad (2)$$

where

ρ_S is vapor pressure at T_s (inHg) and

ρ_t total pressure (inHg).

To calculate relative vapor pressure at T_{db}, it is necessary to calculate partial pressure ρ at T_{db} as follows:

$$\rho = \frac{1.61Y\rho_t}{1 + 1.61Y} \qquad (3)$$

and relative vapor pressure h is

$$h = \frac{\rho}{\rho^*} \qquad (4)$$

where ρ^* is saturated vapor pressure at T_{db} (inHg).

The RH is then defined as

$$\mathrm{RH} = h \times 100 \qquad (5)$$

Example: Given T_{db} = 140°F, T_s = 120°F, and ρ_t = 29.92 inHg, calculate the specific and relative humidities.

Step 1: Find the specific humidity at Y_s from equation (2). To do this we need to know the ρ_s of water at T_s. From table 1-A-1, ρ_s at 120°F is 3.446 inHg.

Thus, from equation (2)

$$Y_s = \frac{3.446}{1.61(29.92 - 3.446)} = 0.0808 \ \text{lb/lb}$$

Step 2: Calculate Y at T_{db} = 140°F. From equation (1)

$$Y = 0.0808 - \frac{(0.24 + 0.44(0.0808))(140^\circ - 120^\circ}{1,094 + 0.44(140^\circ - 120^\circ)}$$
$$= 0.0755 \ \text{lb/lb}$$

Step 3: Calculate ρ at the dry-bulb temperature from equation (3).

$$\rho = \frac{(1.61)(0.0755)(29.92)}{1 + 1.61(0.0755)} = 3.242 \ \text{inHg}$$

Step 4: To calculate relative vapor pressure *h* at the dry-bulb temperature, we need to know the saturated vapor pressure ρ* at T_{db}. From table 1-A-1, ρ* at T_{db} = 140°F is 5.881 inHg. From equation (4)

$$h = \frac{3.242}{5.881} = 0.551$$

or

$$\text{RH} = h \times 100 = 55.1 \ \text{percent}$$

Relative Humidity and Equilibrium Moisture Content

The EMC and RH temperature relationships of tables 1-6 and 1-7 can be expressed in equation form, which is sometimes more convenient than table form. Useful equations can be derived from theories for the adsorption of water on hygroscopic materials. One such equation that works particularly well is

$$M = \frac{1800}{W}\left[\frac{kh}{1 - kh} + \frac{k_1kh + 2k_1k_2k^2h^2}{1 + k_1kh + k_1k_2k^2h^2}\right] \qquad (6)$$

where

M is moisture content (percent),

h relative vapor pressure, and

$$W = 330 + 0.452T_{db} + 0.00415T^2_{db} \qquad (7)$$
$$k = 0.791 + 0.000463T_{db} - 0.000000844T^2_{db} \qquad (8)$$
$$k_1 = 6.34 + 0.000775T_{db} - 0.0000935T^2_{db} \qquad (9)$$
$$k_2 = 1.09 + 0.0284T_{db} - 0.0000904T^2_{db} \qquad (10)$$

Equations (6) to (10) represent least squares regression fits of the data in tables 1-6 and 1-7. As such, they give estimates close to but not exactly the same as those in the tables. For example, the EMC at T_{db} = 140°F and T_s = 120°F from table 1-6 is 8.0 percent. From equations (6) to (10), the EMC is 8.4 percent at 55.1 percent RH.

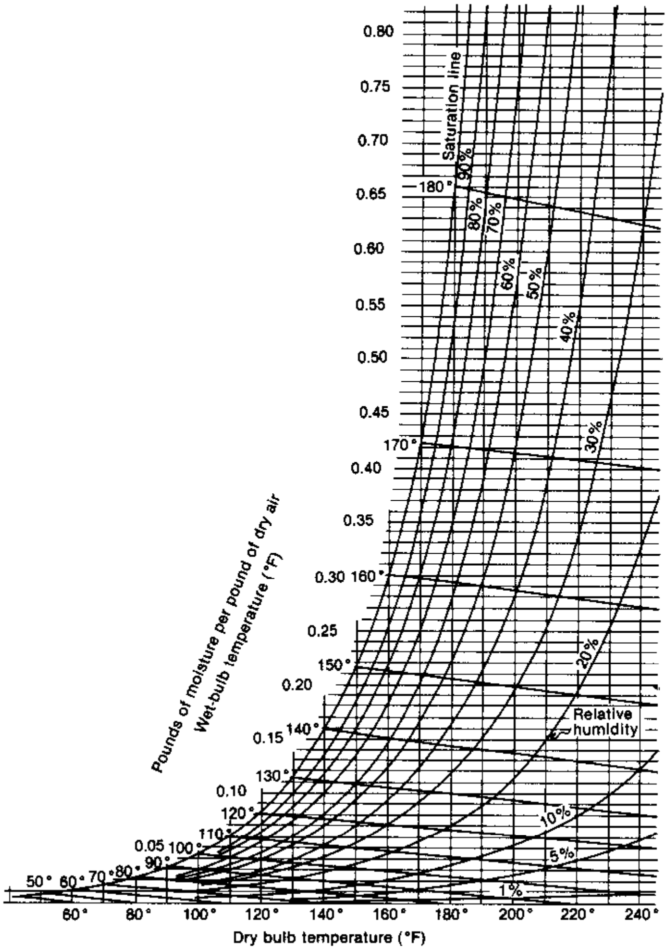

Figure 1-A-1—Psychrometric chart. (ML88 5580)

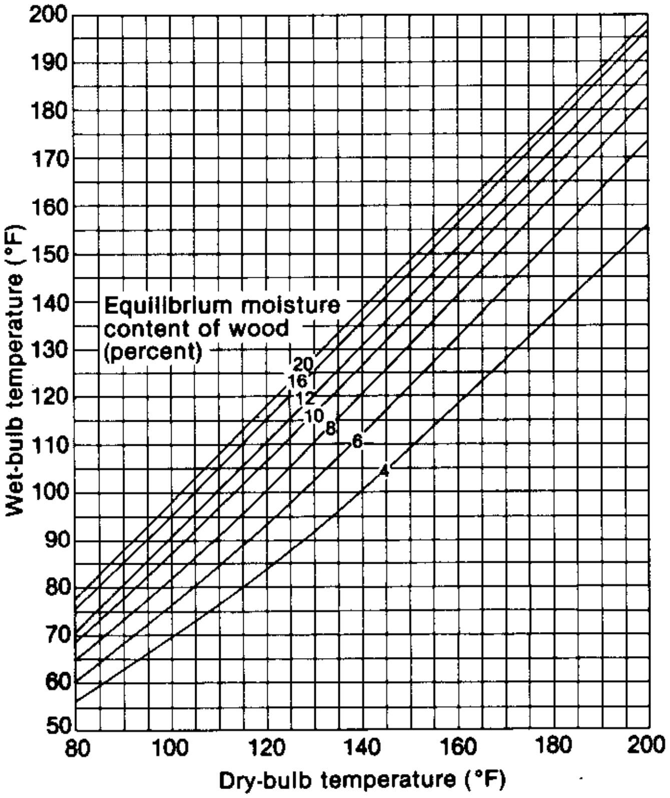

Figure 1-A-2—Lines of constant equilibrium moisture content. (ML88 5577)

Psychrometric Charts

Psychrometric charts are another useful way to represent wet- and dry-bulb temperatures and absolute and relative humidities. Figure 1-A-1 is a typical psychrometric chart showing the relationship between these four variables. Using the example T_{db} = 140°F and T_s = 120°F, the specific humidity at the intersection of these two temperature lines is approximately 0.075 lb/lb and the RH, 55 percent. Figure 1-A-2 shows the relationship between wet- and dry-bulb temperatures and EMC. At the intersection of 140°F dry-bulb temperature and 120°F wet-bulb temperature, the EMC is 8 percent.

Chapter 2
Kiln Types and Features

A lumber dry kiln consists of one or more chambers designed to provide and control the environmental conditions of heat, humidity, and air circulation necessary for the proper drying of wood. As the development of the modern dry kiln has progressed, a number of design modifications have been explored in relation to the mechanism of heat supply, arrangement and type of fans, control of relative humidity or wet-bulb temperature, and use of various materials for construction of the chamber.

The design of a kiln has an important bearing on its operation and drying efficiency. A properly designed and operated kiln will dry most species of lumber or other wood products to any specified moisture content between 3 and 19 percent in a reasonably short time without appreciable losses caused by drying defects.

Classification Systems

Dry kilns can be classified in a number of different ways. In this manual, we have chosen a system that classifies by (1) operational techniques, (2) temperatures of operation, and (3) type of heating and energy source. Other possible classifications might include fan arrangement and method of loading the kiln.

Operational Techniques

Classification by operational techniques distinguishes between the more common compartment-type kiln and the less common progressive-type kiln.

Compartment Kilns

Compartment-type kilns (figs. 2-1 to 2-8) are designed for a batch process in which the kiln is completely loaded or charged with lumber in one operation, and the lumber remains stationary during the entire drying cycle. Temperature and relative humidity are kept as uniform as possible throughout the kiln, and they can be closely controlled over a wide range of temperature and humidity. Temperature and relative humidity

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Chapter 2 was revised by R. Sidney Boone, Research Forest Products Technologist, and William T. Simpson, Supervisory Research Forest Products Technologist.

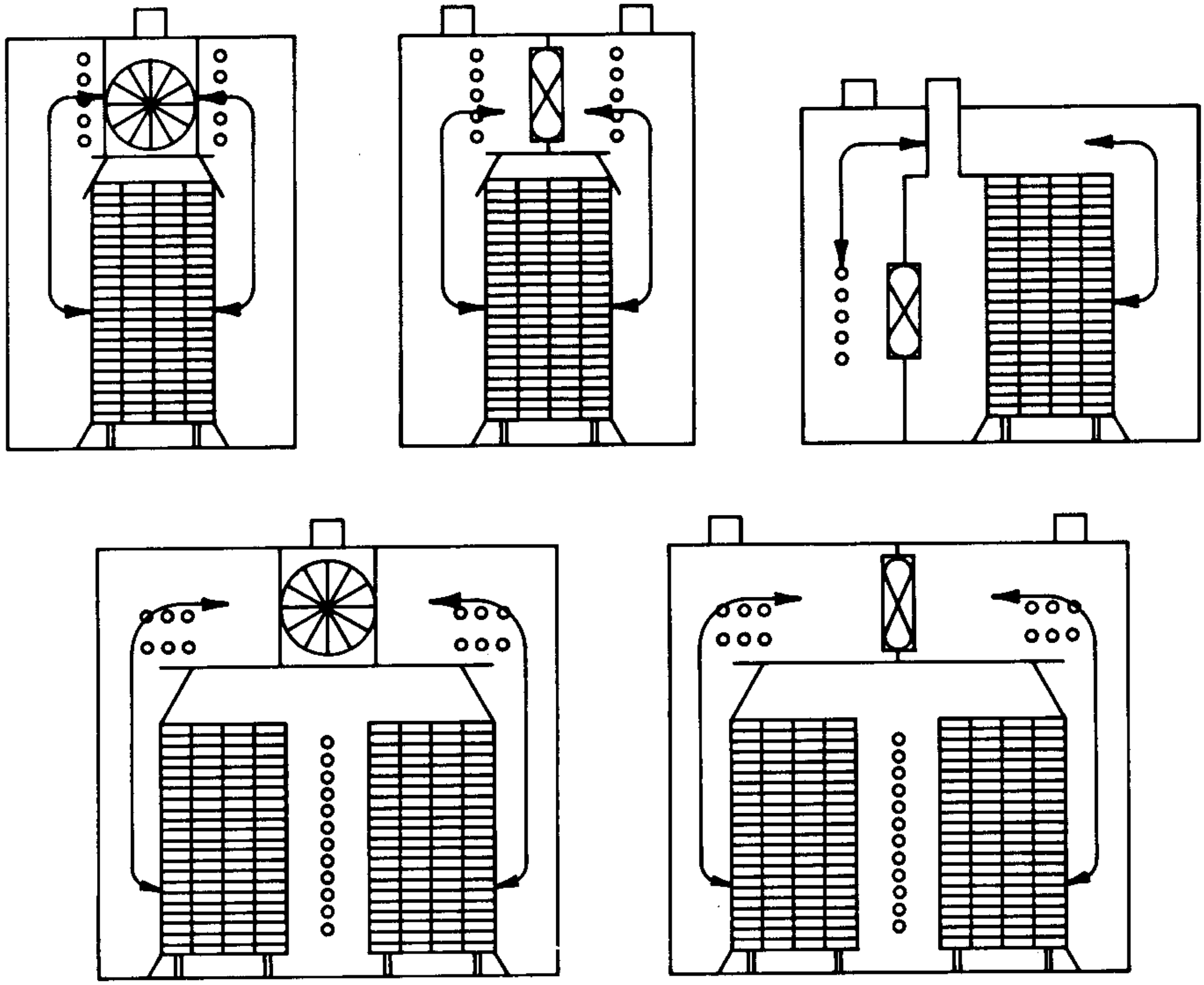


Figure 2-1—Some plans for location of fans and baffles in dry kilns. (ML88 5604)

are changed as the wood dries based on a schedule that takes into account the moisture content and/or the drying rate of the stock being dried. Drying schedules vary by species, thickness, grade, and end use of material as discussed in detail in chapter 7. All modern dry kilns use some type of forced-air circulation system, with air moving through the load perpendicular to the length of the lumber and parallel to the stickers. Although some cross-circulation kilns (airflow parallel to the length of the lumber and perpendicular to the stickers) can still be found, kilns have not been built using this technique for several decades. The natural draft circulation system, which took advantage of the principle that heated air rises, is now considered inefficient and is of historic interest only (Rasmussen 1961). A more detailed discussion of the different types of air circulation systems can be found later in this chapter under the heading General Construction Features.

Compartment kilns can be classified by the method of loading. Perhaps the largest number of kilns are of the track-loaded type. The lumber is stacked on kiln trucks that are rolled into and out of the kiln on tracks. The majority of the softwood lumber in the United States is dried in track-loaded kilns. The other method of loading involves moving stacks or packages of lumber directly into and out of the kiln with a lift truck. These are generally called package-loaded kilns, although they are frequently called side-loaded kilns in the western softwood region. The majority of the hardwood lumber in the United States is dried in package-loaded kilns.

Track-loaded kilns commonly have one or two sets of tracks and occasionally three sets, and are known as single-, double-, or triple-track kilns, respectively (figs. 2-2 to 2-5). The width of the stack of lumber per track is typically 6 to 9 feet. In kilns more than one track wide, some provision for reheating the air is made before it passses through the next stack of lumber. The length of a track kiln is usually some multiple of the lengths of the lumber being dried correlated with the amount of lumber production required. Kiln lengths vary from about 40 to 120 ft; those used for hardwood drying are typically 40 to 66 ft long and those used for

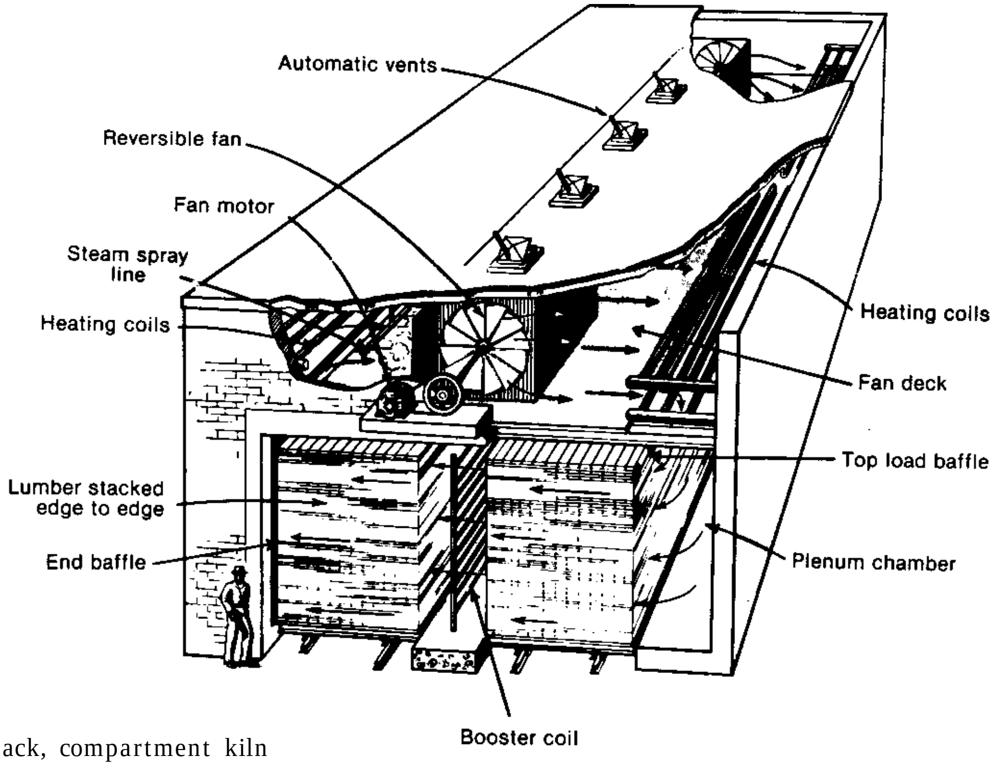


Figure 2.2—Lineshaft, double-track, compartment kiln with alternately opposing fans. Vents are over fan shaft between fans. Vent on high-pressure side of fans becomes fresh air inlet when direction of circulation is reversed. (ML88 5595)

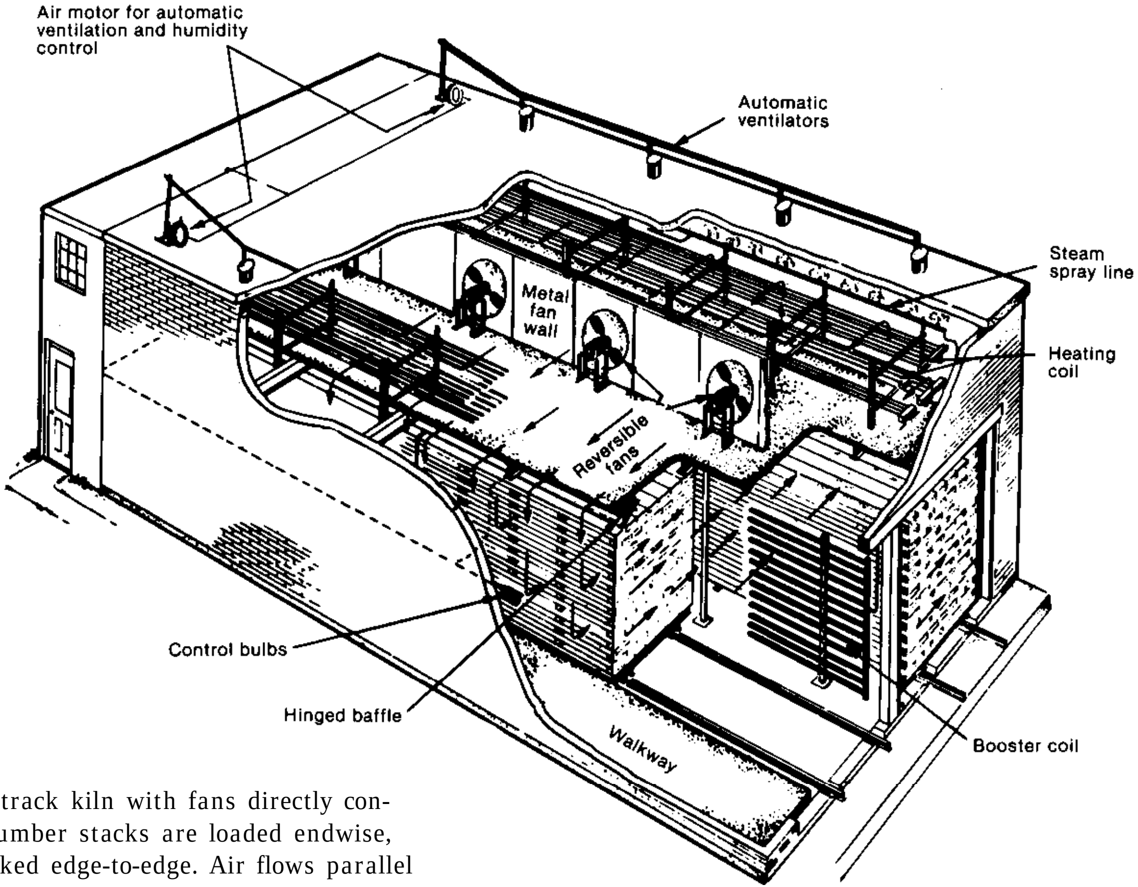


Figure 2-3—Double-track kiln with fans directly connetted to motors. Lumber stacks are loaded endwise, and boards are stacked edge-to-edge. Air flows parallel to stickers. (ML88 5594)

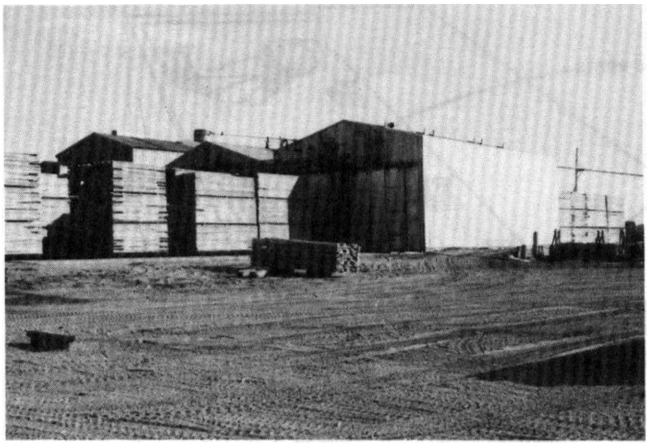


Figure 2-4—Double-tray-loaded aluminum prefabricated kiln with doors at both ends of kiln. (MC88 9017)

softwood, typically 66 to 120 ft long. Lumber-holding capacity can vary from around 25,000 fbm (4/4 basis) to 220,000 fbm (8/4 basis).

Track kilns may have doors at one end or, more commonly, at both ends so that unloading and loading the kiln require a minimum amount of time. Kiln trucks loaded with green lumber are pushed into the kiln immediately after the dried lumber is removed from the kiln. A covered shed is frequently built over the "dry" end of the kiln to protect the dried lumber from inclement weather while it is cooling and awaiting further processing. A cover over the "green" end of the kiln will protect the top courses of freshly sawn lumber from degrading in the sun as a result of uncontrolled drying and from rain or snow. Figure 2-8 shows a kiln with protective cover at both the dry and green ends. Frequently cited advantages of track kilns include short downtime for loading and unloading and more uniform drying primarily because of narrower load widths. Disadvantages include greater building cost, because track kilns require more land area than package kilns especially if kiln has tracks at both ends, and the added expense of track and kiln trucks.

Package-loaded kilns are generally smaller than track-loaded kilns and have a different configuration for loading the lumber (figs. 2-6, 2-7). Large doors permit the stickered and stacked lumber to be loaded into the kiln with a lift truck. Most package kilns are designed to hold 24 ft of lumber from front to back of

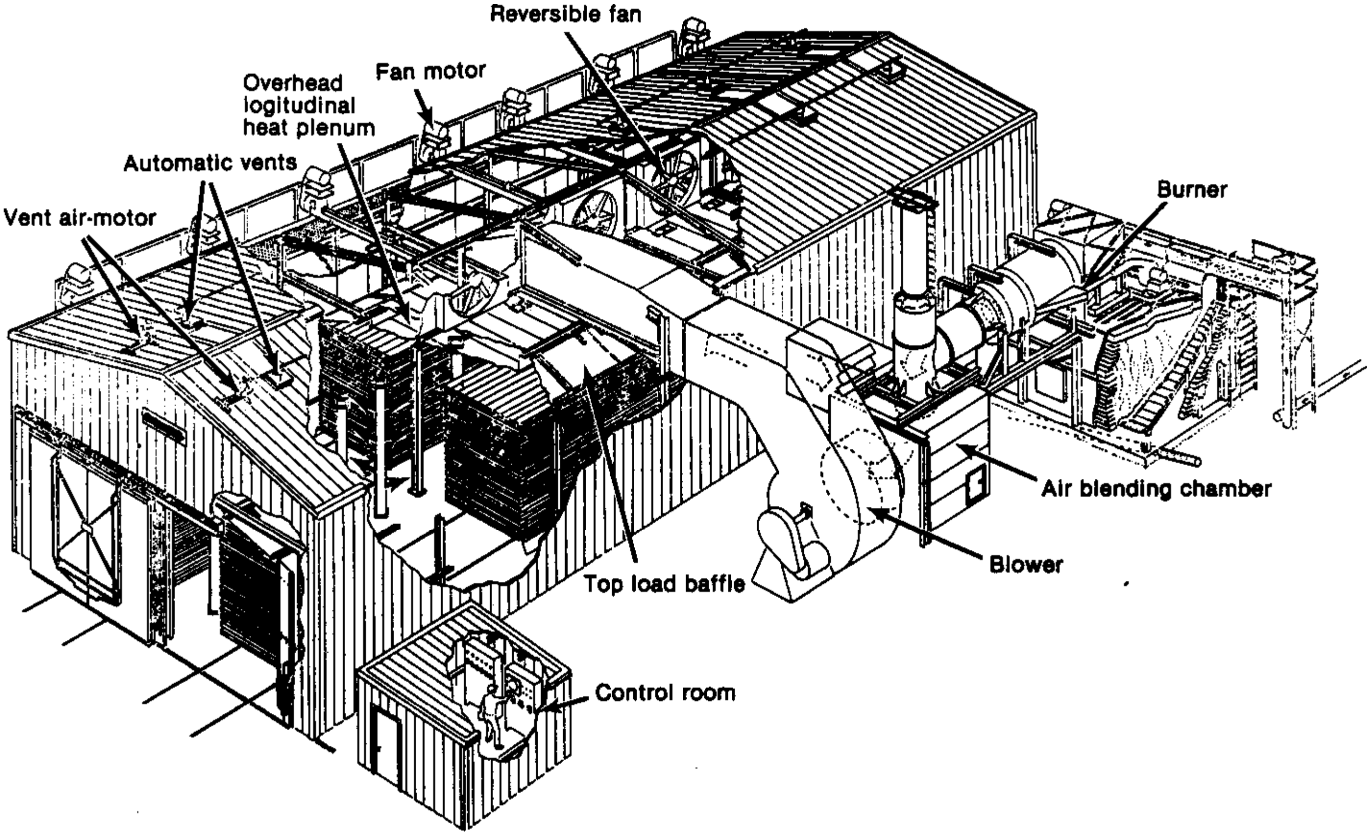


Figure 2-5—Direct-fired, double-track-loaded high temperature kiln in which hot products of combustion are discharged directly into the airstream circulating within the kiln. (ML88 5605)

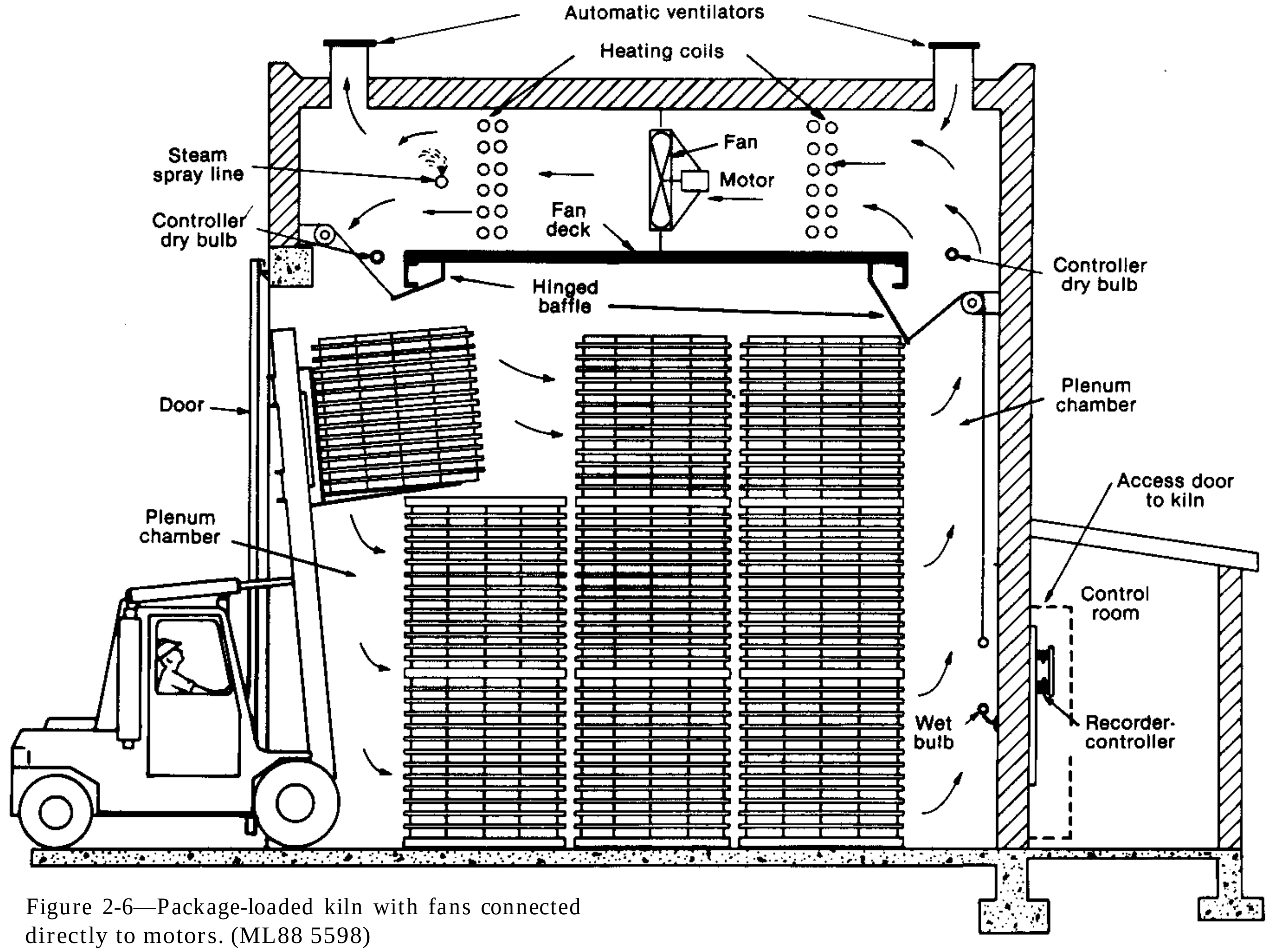


Figure 2-6—Package-loaded kiln with fans connected directly to motors. (ML88 5598)

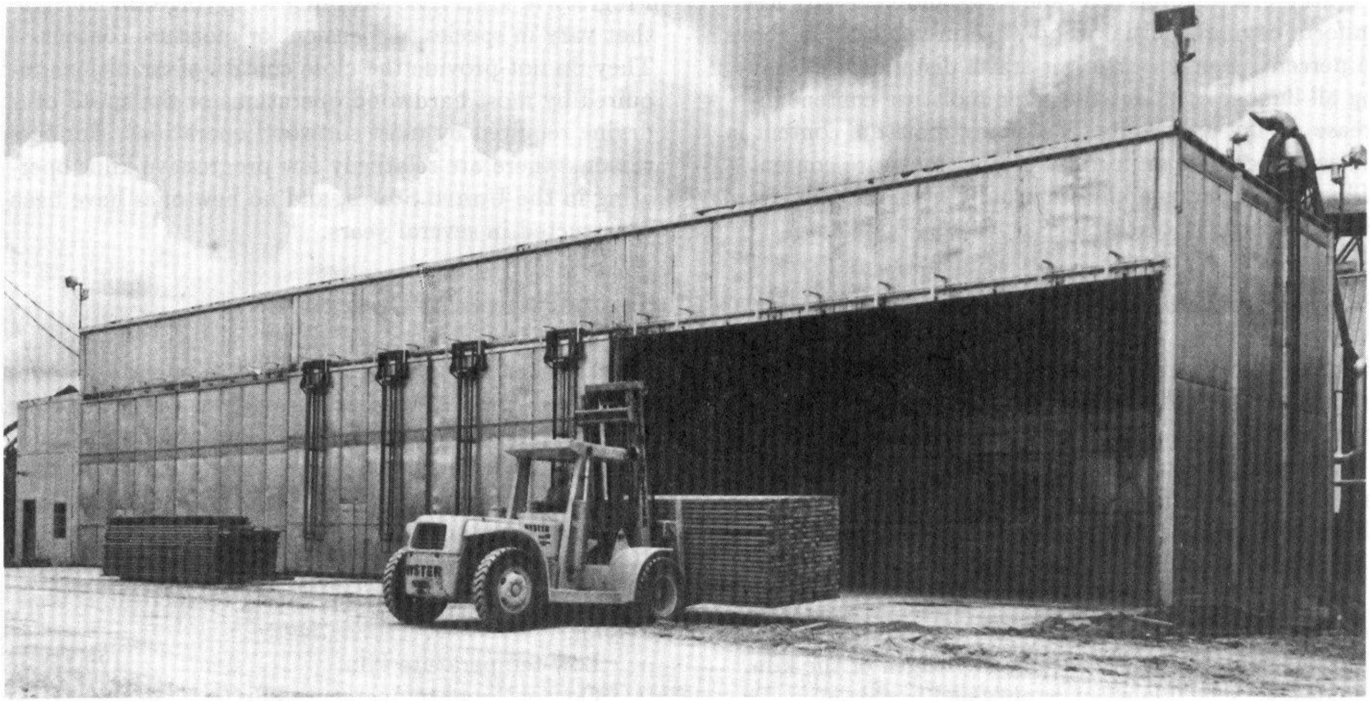


Figure 2-7—Lift truck delivering package of stickered lumber to package-loaded kiln.
(MC88 9024)

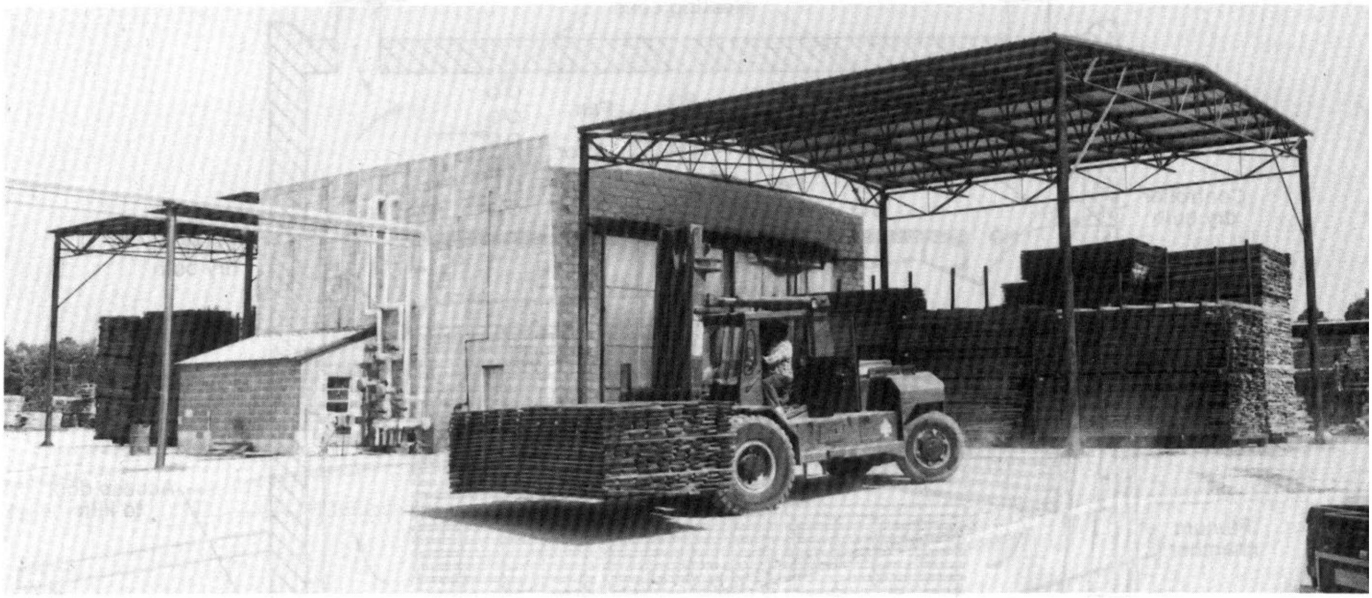


Figure 2-8—Track-loaded, concrete block kiln with doors and protective cover at both ends of kiln. (MC88 9023)

kiln, although some are designed for a depth of 16 ft of lumber. Since airflow in package kilns is from front to back, or vice versa, the length of air travel through the load is also 24 ft. No provision is generally made for reheating the air as it passes through the load. Lumber-holding capacity of package kilns varies from around 25,000 to 90,000 fbm (4/4 basis). Some frequently cited advantages of package kilns include lower building cost and use of less land area. Disadvantages include long downtime for loading and unloading and generally less uniform drying if initial wood moisture content is above 25 percent. Using shorter air-travel distances and having all lumber at about the same moisture content increase drying uniformity. If starting moisture content is below 25 percent, uniformity of final moisture content of lumber in package kilns is usually little different from that of lumber in track kilns.

Progressive Kilns

Progressive-type kilns are designed for a continuous process in which the loads of stacked lumber enter the green end of the kiln and are moved forward, usually on a daily basis, through progressively more severe drying conditions until exiting the dry end of the kiln. Each move forward is accompanied by the removal of a completed load from the dry end and the addition of a fresh green load at the green end. The temperature increases and the humidity decreases as charges move from one zone to the next along the length of the kiln. The desired schedule effect is obtained in this way. To achieve the necessary range of drying conditions, progressive kilns vary in length depending on the species and the initial and final moisture content of lumber being dried. Because of the relatively continuous movement required in this approach, progressive kilns are usually of the track-loading type. As with compartment kilns, the early models relied on natural draft circulation, but forced circulation using either internal fans or external blowers soon became the preferred method of air circulation.

Progressive kilns lack flexibility in drying kiln charges that vary in species, dimension, or moisture content. They do not provide the close control of conditions required by most hardwood operations or the speed of drying required by most softwood operations. For these reasons, there are relatively few progressive kilns operating in the United States, and no new ones have been constructed in several years.

Temperatures of Operation

Most lumber dry kilns are designed to operate within a specified range of temperatures. This range depends largely on the species to be dried and quality and end use of final products. Also considered are amount of production expected, source of energy, and limitations of certain components of the system, such as compressors and electric motors. A common classification of kilns based on maximum operating temperatures is as follows:

Low-temperature kiln	120 °F
Conventional-temperature kiln . . .	180 °F
Elevated-temperature kiln	211 °F
High-temperature kiln	above 212 °F

Regardless of the temperatures used, the basic requirements of controlled heat, humidity, and air circulation apply. Therefore, kilns of different temperature classification differ primarily in terms of the source of heat energy and the type of materials and equipment used in the kiln structure.

Low-Temperature Kilns

Low-temperature kilns typically operate in the range of 70 to 120 °F, though some may not exceed 110 °F. This classification typically includes fan dryers, predryers, shed dryers, and some types of vacuum, dehumidification, and steam-heated kilns.

Conventional-Temperature Kilns

Conventional-temperature kilns typically operate in the range of 110 to 180 °F. The majority of hardwood lumber and sizeable amounts of softwood lumber are dried to final moisture content in kilns operating in this temperature range. These include steam-heated kilns and those designs of dehumidification kilns that operate up to 160 °F. The bulk of the kiln schedules available for the various species and thicknesses are for kilns operating at “conventional temperature.”

Elevated-Temperature Kilns

Elevated-temperature kilns typically operate in the range of 110 to 211 °F. The final dry-bulb temperature in a schedule for use in an elevated-temperature kiln is commonly 190 or 200 °F and occasionally as high as 210 °F. Many western softwood operations and some southern pine operations have kilns operating in this range. A few easy-to-dry hardwood species may use elevated temperatures in the final step of the schedule.

High-Temperature *Kilns*

High-temperature kilns typically operate for most of the drying schedule at temperatures above 212 °F, usually in the range of 230 to 280 °F. Perhaps the majority of southern pine lumber and increasing amounts of western softwood lumber are dried in high-temperature kilns. These kilns are more often used for drying construction-grade lumber where some surface checking and end splitting are acceptable in the grade, rather than upper-grade lumber where these defects are less acceptable. A very small amount of hardwood lumber is dried at high temperatures.

Type of Heating and Energy Source

The type of heating of lumber dry kilns and the energy source for that heat can be divided into the following categories: steam, direct fire (hot air), electricity, hot water and hot oil, and solar. Heat is required in a dry kiln for four purposes: (1) to warm the wood and the water in the wood; (2) to evaporate moisture from the wood; (3) to replace the heat lost from the kiln structure by conduction or radiation; and (4) in kilns with vents, to warm the fresh air entering the kiln.

Steam

Steam has long been the most widely used heating medium for kiln drying of lumber. Steam is moved from the boiler into the kiln by pipes, and the heat is then transferred to the circulating air in the kiln. Historically, many lumber processing operations required steam for a variety of applications, and it was therefore natural to include sufficient boiler capacity for kiln-drying operations. With the increasing popularity of electrically powered sawmills, the dry kilns are frequently the principal user of steam at an installation. In the early days of dry kilns, burning of wood waste in the boiler was the standard procedure. As oil and natural gas became more available and less expensive, most operations switched to these energy sources for their boilers. Since the “oil scare” and rising prices of the 1970’s, there has been a return to burning of wood waste to generate steam. A more detailed discussion of boilers, including such items as sizing and horsepower, can be found in chapter 11. For a more complete discussion of heat transfer surfaces and how temperatures are achieved and controlled in a kiln, see Heating Systems section later in this chapter.

Direct Fire

Direct-fired heating systems differ from steam heating systems in that the heated air for the kiln originates directly from the burning of oil, natural gas, or wood waste. The heated air produced from the burning of the fuel is passed through a mixing or blending chamber to control the temperature and volume of air going into the kiln (fig. 2-5). Direct-fired systems have been used extensively for high-temperature drying of softwoods, especially southern pine. The required temperatures are easily achieved and controlled, and any discoloration of the wood caused by combustion gases is of little consequence in most softwood operations. Direct-fired systems are seldom used for drying hardwoods, primarily because these systems do not provide the close control of relative humidities generally required for proper hardwood drying.

Electricity

The use of electric power to heat a dry kiln is currently most often thought of as related to dehumidification drying systems or the type of vacuum drying systems using electric energy (radiofrequency, microwave, or electric resistance blankets). I" dehumidification systems, electricity is used to power the compressor or heat pump and the strip heaters that are frequently used to bring the kiln up to a minimum temperature for efficient operation of the compressors. For small kilns drying 500 to 1,000 fbm, designs using electric strip heaters have been suggested (Rice 1977).

Hot Water and Hot Oil

Some kilns are heated by hot water rather than steam. These systems have much lower drying efficiency and are not commonly found in typical commercial operations. However, hot water heating systems are sometimes found in smaller homemade or do-it-yourself installations where steam generation is regarded as either impractical or too expensive.

Few lumber dry kilns in the United States use the hot oil system, although interest in using this system has increased since the mid-1980's, particularly in plants that have both particleboard presses and dry kilns.

Solar

In the United States and Canada, use of solar energy to heat a lumber dry kiln is limited to small operations or hobbyists where drying large quantities of lumber on a tight production schedule is not required. Interest in totally solar-heated kilns or solar-assisted kilns is much higher in tropical countries, especially those where more traditional forms of energy are very expensive or are not readily available.

General Construction Features

Construction Materials

Dry kilns are constructed of a number of materials, including aluminum prefabricated panels, concrete block, poured concrete, brick, wood, and plywood. Various kinds of vapor barriers are used to restrict movement of water vapor from inside the kiln into the strutural members and panels and thus prevent deterioration of the structure. To have acceptable efficiency, kilns must be reasonably well insulated against loss of heat through the structure. In addition, doors and other openings must fit tightly to minimize loss of heat and humidity. The choice of building materials is frequently governed by such things as operational temperatures required for the species and thicknesses to be dried, life expectancy of the kiln, capital investment, insurance, source of energy, and type of heating system.

Aluminum

Many kilns constructed in the last decade use prefabricated aluminum panels with fiberglass or some form of rigid foam insulation. The panels are joined together and bolted to structural load-bearing members of either steel or aluminum (figs. 2-4 to 2-7). fill-length wall and roof panels are manufactured (prefabricated) in standard dimensions for rapid installation on site and to give flexibility in kiln size. All connecting joints should be designed to minimize heat losses and to allow for expansion and contraction of the metal with changing temperature. This ability to withstand expansion and contraction without damaging the structure makes aluminum the preferred construction material for kilns expected to be operated at high temperatures (above 212 °F).

Kiln doors are of similar lightweight, insulated, aluminum panel construction, mounted in a steel or aluminum frame, with additional bracing for strength and rigidity. Most doors are moved by hangers, which are connected to rollers operating on a rail over the door opening. Some type of flexible gasket is generally used around the opening to minimize air infiltration and leakage.

Because aluminum is extremely resistant to corrosion, no special vapor sealants or moisture barriers are required. However, regular inspections are needed to ensure that no leaks develop in the joints, and any punctures or tears in the skin of the panel need to be repaired to prevent moisture from the kiln atmosphere passing through to the insulation and reducing its effectiveness. If a steel supporting structure is used, usual precautions of applying a good paint or sealer must be observed to protect the steel from the corrosive atmosphere found in most kiln environments. Particular attention should be paid to locations where the steel support structure comes into contact with sources of cold temperature (where condensation will occur on the steel), such as around doors and the first 12 to 18 inches above floor level of the vertical support columns.

Concrete Block, Poured Concrete, and Brick

Concrete block, poured concrete, and brick, which are sometimes known collectively as masonry, have historically been used for construction of low-temperature, conventional-temperature, and elevated-temperature dry kilns (figs. 2-2, 2-3, 2-8). Concrete block filled with some type of insulation material, such as vermiculite or rigid foam, is currently the most common type of masonry kiln. Kilns with poured concrete walls are occasionally seen, but the use of brick has largely fallen from use. Masonry kilns may have either load-bearing or nonload-bearing walls. Where walls are nonload bearing, the block or brick is laid between structural steel members that support the roof beams or trusses. Masonry materials should be of high quality, taking into consideration such factors as durability, insulating properties, and resistance to moisture, humidity, and temperature fluctuations. A high quality mortar must also be used. To protect the masonry against humidity and condensation and to reduce heat and vapor transmissions, the interior walls and ceiling must be given one or two coats of a specially formulated heat- and vapor-resistant kiln paint or coating. Some designs suggest an inside coating of lightweight concrete to improve insulation and to retard moisture movement into the concrete block. Such designs also require a vapor-resistant coating. Expansion and contraction of these masonry materials during routine kiln operation can cause cracks, which should be sealed promptly to prevent further deterioration of the wall and roof. Largely because of this expansion and contraction, masonry materials are not usually chosen when constructing high-temperature kilns.

Roofing materials for masonry kilns are frequently prefabricated aluminum panels or a “built-up” roof consisting of a layered composite of roofers’ felt, vapor barrier, and insulation on top of wood, reinforced concrete slabs, or metal decking.

Kiln doors on newer masonry kilns are frequently the same type of aluminum prefabricated panel doors as those used on aluminum prefabricated kilns. Some older kilns may have doors constructed of insulated wood panels; however, these doors are heavy and deteriorate with time.

Wood and Plywood

The use of wood for kiln construction is usually limited to low-temperature applications where inexpensive, short-term installations are planned, and where small, possibly homemade facilities are considered adequate. Plywood interiors in metal or wooden buildings are fairly common in dehumidification kilns. Construction for dehumidification kilns requires insulation values of R-20 or more for walls and roof; higher values are needed in colder climates. Vapor barriers must be extremely tight for efficient operation, and great care must be given when installing to ensure proper joints.

Foundations and Floors

Kilns must be built on a firm foundation to prevent shifting and settlement. The structural misalignment and cracks caused by settling of the foundation are ‘more serious in kilns than in many other types of construction. Misalignment of kilns throws the track system out of line in track-loaded kilns, which creates serious problems when moving kiln trucks. Misalignment of kilns with lineshaft fan systems can also cause wear and maintenance problems in the fan system. Settling of the structure can cause cracks, which cause heat loss and problems in humidity control.

Foundation footings and walls are almost invariably made of concrete. Their width or bearing area is determined by the character of the soil and by the loads to be imposed upon them.

Most kiln floors are made of poured concrete, usually 6 in thick. Placing some form of insulation under the concrete floor is an increasingly common practice. This reduces heat loss and helps to prevent condensation of water on the kiln floor in the early part of the kiln run when the relative humidity of the air is high and the floor may be cold.

In some cases, a thick layer of crushed stone may be used. In package-loaded kilns, which use lift trucks to load and unload lumber, floors made of crushed stone are difficult to maintain. Uneven floors can cause lumber stacks to lean, resulting in poor drying, or to fall, damaging the structure or injuring workers. Another disadvantage of crushed stone is that heat is more readily lost to the soil or, alternatively, moisture from the soil enters the kiln when kiln humidity is low. However, crushed stone does permit rapid drainage when condensation and water from melting snow or ice accumulate in the kiln during warmup.

Heating Systems

The drying of lumber requires the removal of large quantities of water from the wood. For example, drying southern pine dimension stock green from the saw to 15 percent moisture content requires the removal of 1.92 lb (0.23 gal) of water per board foot (24.9 lb/ft^3). Drying l-in-thick red oak lumber green from the saw to 7 percent moisture content requires the removal of 1.83 lb (0.22 gal) of water per board foot (22 lb/ft^3). Since the heat of evaporation of water is approximately 1,000 Btu/lb, great quantities of heat energy must be generated and transferred to the circulating air and to the wood in the drying process. This section discusses the mechanism of heat energy transfer from the generating source into the kiln and types of heat transfer surfaces.

The principal methods of conducting heat into the kiln are (1) indirect, where a hot fluid (commonly steam) flows into the kiln through pipes and radiates heat to the kiln atmosphere through a suitable radiating surface, and (2) direct, where hot gases are discharged directly into the kiln atmosphere.

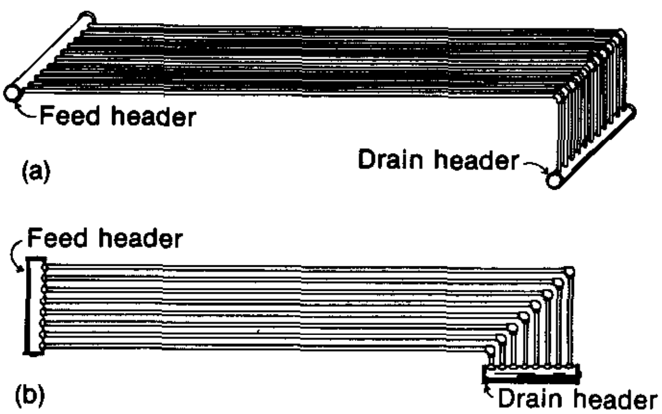


Figure 2-9—Headers with heating coils. (ML88 5599)

Indirect Heating

Perhaps the best examples of hot fluids used in indirect heating systems are steam, hot water, and hot oil. Steam systems are by far the most common in lumber drying, though systems using hot water or hot oil are occasionally found.

Steam.-Steam is used at various pressures. Since the temperature of steam varies with different levels of pressure, more radiating surface is required to maintain a given heat transfer rate or operating temperature with low-pressure steam than with high-pressure steam (see ch. 11 for a more detailed discussion of energy).

Steam is transported from the boiler to one or more kilns through large insulated pipes, often called the main feedline. At the kiln, steam enters one or more distribution header pipes, from which each bank of heating pipes originates (fig. 2-9). A condensate header is located at the opposite end of the bank of pipes. Plain iron pipes were the standard material for radiating surfaces for many years, but now finned pipe heating coils are used almost exclusively (figs. 2-10, 2-11). Depending on diameter and other factors, finned pipes are considered to have from four to eight times the radiating capacity of conventional black iron pipes. Finned pipes are made of iron, aluminum, or copper piping, which are wound with thin metal strips or attached to discs by welding or pressing to increase the heat transfer surface. Fins are made of various materials. Heavy gauge steel is the most rigid and serviceable but is subject to corrosion, and aluminum is an excellent heat conductor but much more subject to damage. The heat transfer rate of aluminum fins is twice as great as that of steel fins. Copper is an excellent conductor but is generally considered too expensive for extensive use in lumber dry kilns and is easily damaged because of its softness.

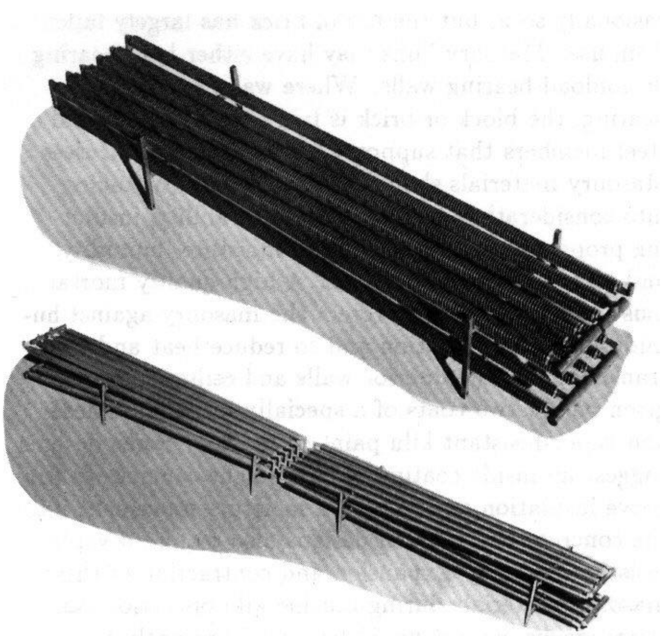


Figure 2-10—Return-bend heating coil made with fin pipe. (M 106142)

The return-bend heating system has historically been the most common arrangement of steam pipes within a kiln (fig. 2-10). In this system, the banks of pipes leave the distributing header, extend the length of shorter kilns, and return to a discharge (condensate) header. In longer kilns (over 66 ft), a return-bend header is at each end of the kiln, such that returns meet in the middle of the kiln (fig. 2-10, bottom).

It is now considered better practice to divide the heating coils into banks of shorter length, single-pass coils (fig. 2-11) rather than return-bend coils. These short banks can be separately valved and thus produce more uniform temperatures along their length than do long coils.

As heat is transferred from steam through the coils to the kiln atmosphere, the temperature of the steam drops. It cools to the point of condensation, and water (condensate) begins to gather along the length of the coil, providing the opportunity for uneven heating in the kiln. Thus, all horizontal coils should be installed with a downward pitch varying from 1/8 to 1/4 in per foot of coil length to allow for drainage of condensate.

In multiple-track kilns where the circulating air passes through more than one truckload of lumber, it is good practice to install booster or reheat coils between the tracks (figs. 2-1 to 2-3, 2-12). The coils may be arranged either vertically or horizontally and serve to maintain a more uniform temperature within the kiln.

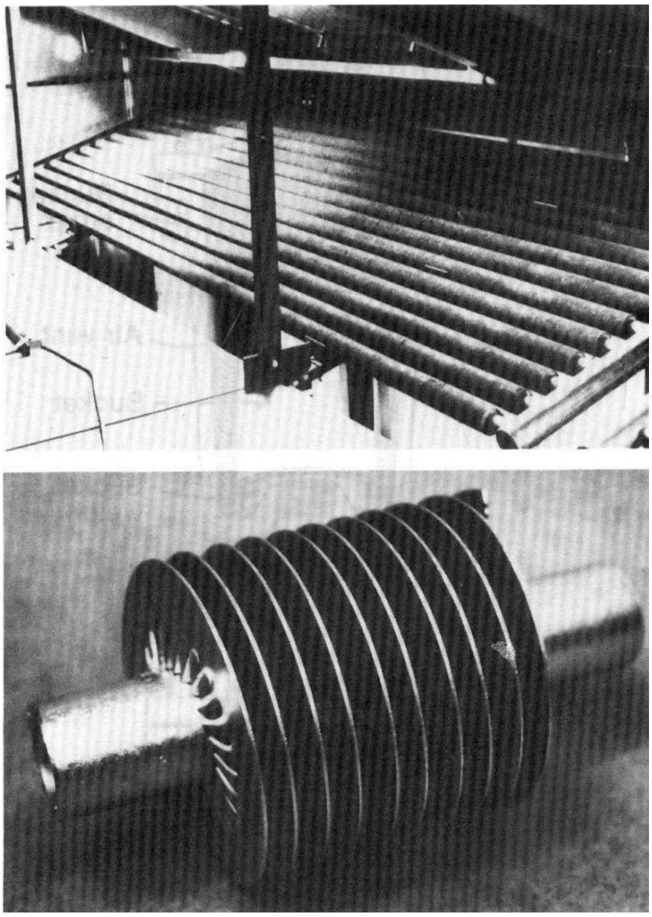


Figure 2-11—Horizontal single-pass header coils and enlarged view of coils. (MC88 9027)

Hot water and hot oil—In hot water and hot oil systems, the liquid is circulated by pumps through heating coils similar to those used in a steam kiln. The lower amount of heat available from hot water (where no latent heat is present) in comparison with steam requires a greater radiating surface. Maximum temperature attainable in the kiln is about 180 °F, which is adequate for many operations. However, few of these systems are currently in use in the United States. Hot oil systems work on the principle of pumping heated oil through the heating coils in the kiln, though temperatures considerably higher than hot water can be attained.

Direct Heating

In direct-heated kilns, the hot gases produced by burning gas, oil, or wood waste are discharged directly into the kiln. These hot gases frequently pass through a mixing or blending chamber to control temperature and volume of air entering the kiln.

Burners commonly have electrically or pneumatically modulated fuel valves, which operate in connection with the recorder-controller. The fuel and air supply for combustion is regulated to maintain the desired kiln temperature. Some designs use several burner nozzles, which can be operated individually or the series modulated over a wide turndown range. Many burners are designed to utilize wood waste and oil or gas interchangeably.

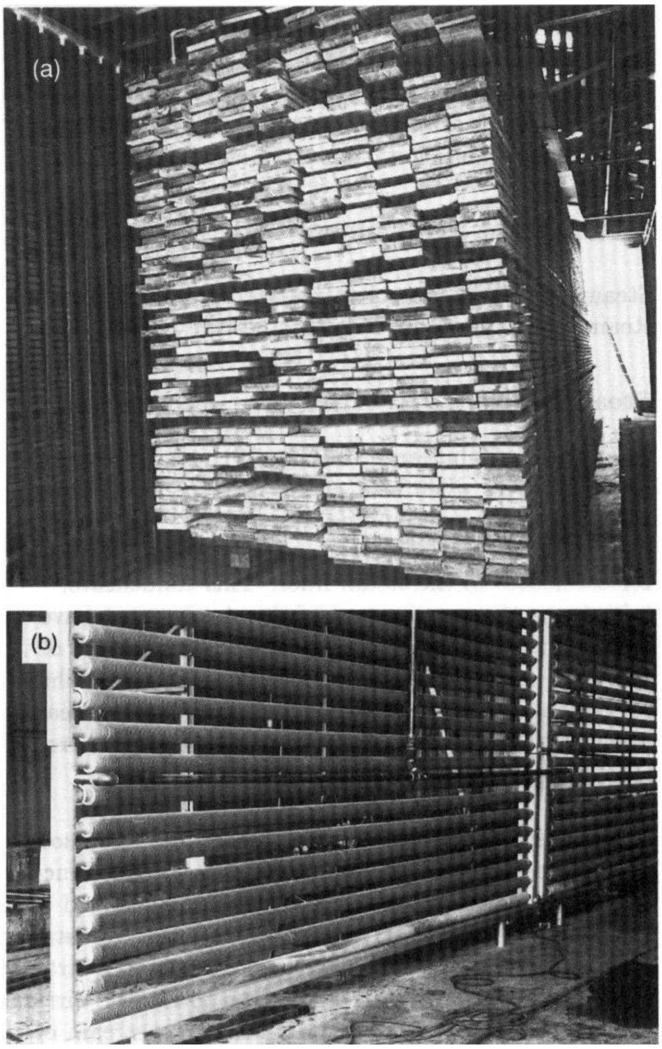


Figure 2-12—Booster coils. (a) Vertical booster or reheat coils between loads in track-loaded kiln. (b) Booster coils in horizontal position. (MC88 9032, MC88 9033)

In the blending chamber the hot products of combustion are mixed with the circulating air, raising its temperature to the point where subsequent mixing in the kiln will produce the required temperature as governed by the dry-bulb control mechanism. Temperature-limit switches on the inlet and discharge ends of the combustion chamber shut down burners if they overheat. The discharge air is usually limited to a maximum of 425 to 450 °F. A centrifugal blower forces the heated air from the burner through ducts to a plenum chamber, which distributes the air to the circulation fans (fig. 2-5). Most kiln air makes repeated circuits through the lumber piles, and only a portion is returned to the heating chamber, usually by means of a collecting plenum running the full length of the kiln. As mentioned earlier, in some designs the heat energy is transmitted from the burner through a heat exchanger to the circulating air to prevent combustion gases from entering the kiln.

Steam Traps and Control Valves

Steam traps and control valves are used to conserve steam and regulate its flow through the heating coils.

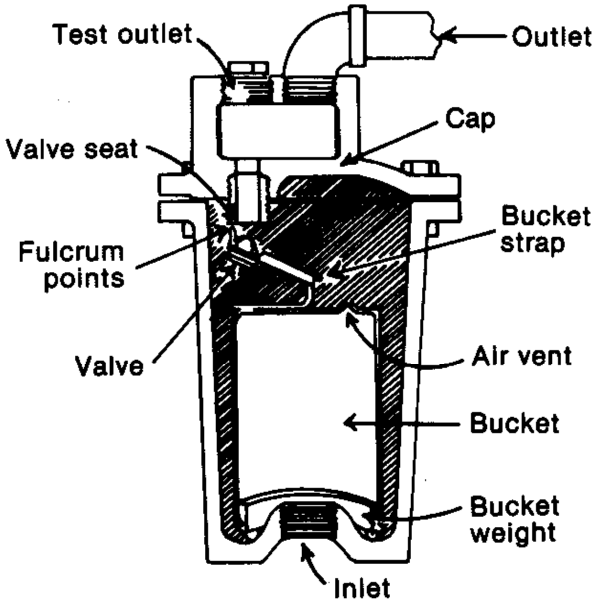
Steam Traps

In any steam kiln, large volumes of condensate form as steam cools when heat energy is transferred from the coils to the surrounding atmosphere. For every 1,000 Btu of heat delivered, approximately 1 lb of water condenses in the steam lines. This condensate, initially at the temperature of the steam, must have a controlled discharge, otherwise the temperature of the coils would drop as they fill with condensate thus preventing the entry of the higher temperature steam. Steam traps operate like automatic valves to control the flow and discharge of steam.

Steam traps are installed in the drain lines to remove condensate without the loss of steam. Another function of steam traps is to release trapped air mixed with the steam. Steam traps should be installed downstream from and below the coils. For best operation, a strainer must be placed upstream of the trap to remove dirt and oil, and a check valve must be placed downstream of the trap to prevent back pressure or reverse condensate flow. A blowdown valve should be provided to periodically clean out scale and debris from the line. All heating coils should be individually trapped to prevent the condensate from short circuiting from one coil to another. The return line to the boiler must be large enough to handle peak loads of condensate.

Proper sizing of steam traps for dry kilns is extremely important and is more difficult in a dry kiln operation than in many other applications of steam traps. It is just as harmful to oversize a trap as it is to undersize. Undersizing a trap retards the discharge of condensate, which results in a slow and waterlogged heating system. Oversizing a trap causes a discharge of some steam with each discharge of condensate, which interferes with efficient operation of the heating system and wastes energy.

Steam traps generally used on dry kilns are of three types: mechanical or gravity, thermostatic, and thermodynamic.



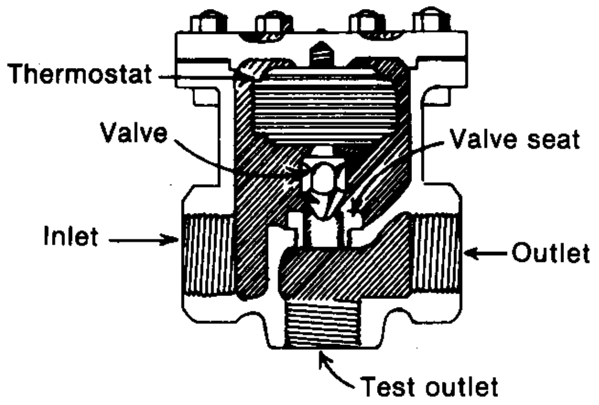


Figure 2-14—Thermostatically controlled steam trap. (ML88 5596)

The mechanical or gravity-type traps often used on dry kiln heating systems are of the inverted bucket or open-bucket design. The inverted bucket design (fig. 2-13) has generally superseded the open-bucket type and is the most commonly used mechanical trap. As steam condenses in the heating system, the condensate flows into the trap. When the trap is filled, the condensate discharges through the outlet pipe. As soon as the system is free of condensate, steam enters the inverted bucket. The pressure of steam causes the bucket to rise against the valve arm until the valve closes the discharge port. Air trapped in the bucket escapes through a vent in the top of the trap. Condensate again begins to flow into the trap, displacing the steam in the bucket. This reduces the buoyancy of the bucket until it again rests on the bottom of the trap. The discharge valve then opens and allows the condensate to be discharged. Since the air in the top of the trap es capes before the condensate does, air binding is kept to

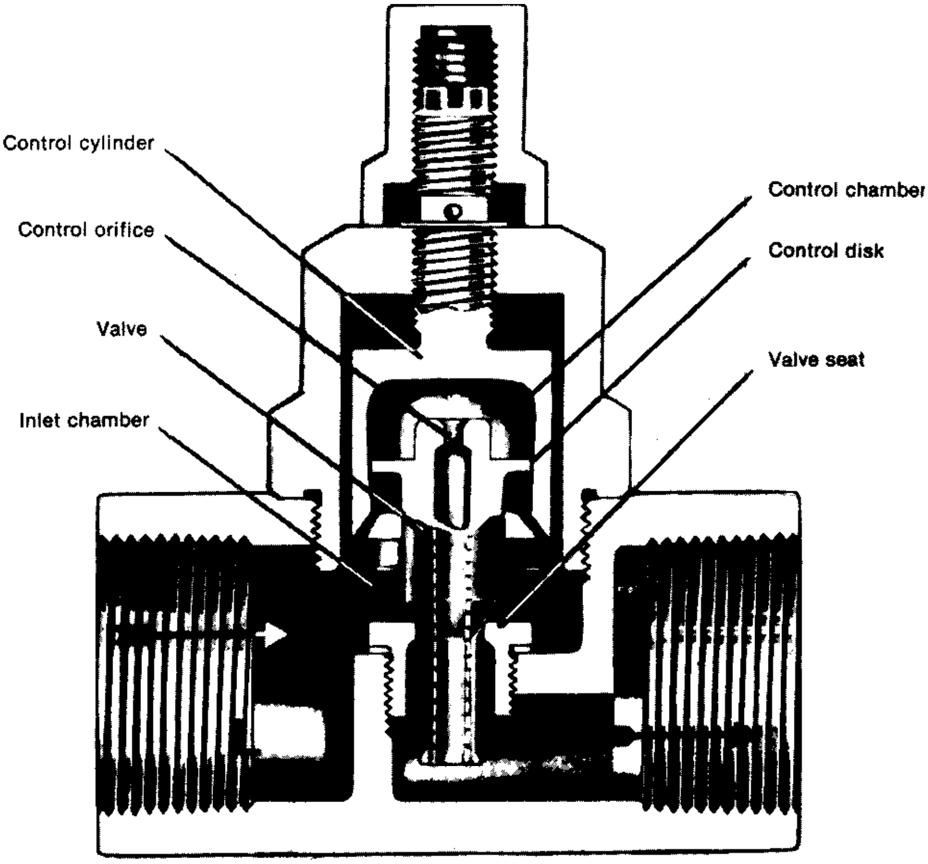


Figure 2-15—Impulse steam trap. (MC88 9038)

a minimum. Because bucket-type traps contain liquid condensate or water, it is important to provide adequate insulation in colder climates to prevent freezing of the water and damage to the trap.

In a typical thermostatic trap (fig. 2-14), a bellows that expands or contracts with changes in temperature is attached to a valve stem and valve. As the bellows expands or contracts, it closes or opens the valve. When the heating system is first turned on, the coils and trap are cold and contain air and water. At this point, the bellows are contracted and the valve is open. As steam enters the heating system, it displaces the water and air and forces them through the open valve. When all the air and water have been discharged, the trap is filled with live steam. By then the trap temperature has increased enough to cause the bellows to expand, closing the valve and preventing loss of steam through the trap outlet. After the valve is closed, condensate again begins to accumulate and cool the bellows. This contracts the bellows enough to open the discharge valve, and the cycle is repeated.

The third type of trap is the thermodynamic or impulse design (fig. 2-15). The flow of condensate through this trap is controlled by differences in pressure between the inlet chamber and the control chamber. When the steam is off and the trap is filled with air, the pressure is the same in the inlet as in the control chamber, and the control valve rests firmly against the valve seat. When condensate enters the trap, the pressure in the inlet chamber becomes greater than that in the control chamber. The pressure on the underside of the control disk lifts the control valve free of the valve seat, and air and condensate pass through the valve opening into the discharge line.

The control cylinder has a reverse taper that adjusts the flow of condensate around the control disk and into the control chamber, until the pressures above and below the disk are balanced. The temperature of the condensate then increases because of the hot steam behind it. The hot condensate entering the lower pressure control chamber flashes into steam, which increases in volume and retards the flow of condensate through the control-valve orifice. When the downward pressure on the upper surface of the valve and valve disk exceeds the upward pressure on the rim of the valve disk, the valve is forced downward, shutting off the flow of condensate through the main orifice. The temperature in the control chamber then drops, and the cycle is repeated.

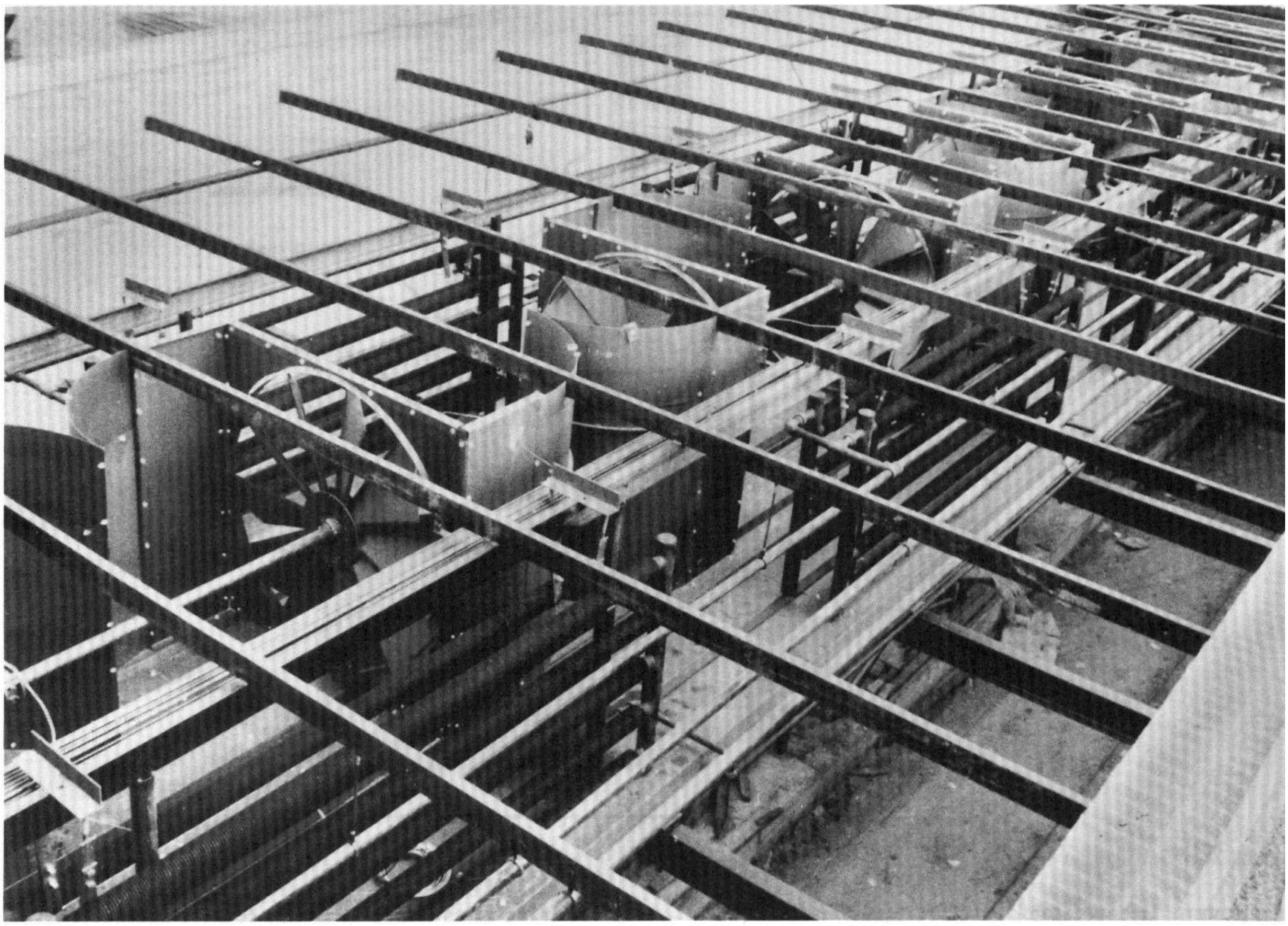


Figure 2-16—Fans in lineshaft arrangement showing disc fans and zig-zag baffle-shroud system, which directs the air through the lumber in either direction depending on fan and motor rotation. (MC88 9022)

Control Valves

Both manually and automatically operated valves are used to control the flow of steam into the coils. Pressure regulators and reducing valves are also used to control the pressure of the steam.

Steam flow is regulated by automatically controlled air-operated or electrically operated control valves coupled to the recorder-controller (see section on Equipment to Control Drying Conditions). Hand-operated gate valves are usually installed upstream of the control valves for "on-off" control of the steam supply. Hand valves are also advantageous on the feed and drain lines of individual heating-coil banks, especially in hardwood drying operations. These hand valves enable operators to close certain banks for better control at lower temperatures, thereby reducing excessive fluctuations in temperature due to overshoot of the dry bulb when all banks are open. The ability to isolate banks of coils also permits damaged or leaking ones to be removed and repaired without disturbing the remainder of the heating system.

Air-Circulation Systems

To dry lumber, air of controlled temperature and humidity must be passed uniformly over its surface. This circulating air is the "workhorse" of the dry kiln. As such, the air performs two functions: it carries heat to the wood to effect evaporation, and it removes the evaporated water vapor. Effective and uniform circulation of air involves several factors: the size, location, and speed of the fans to drive the air; provision for reversal of air circulation; installation and use of baffles to direct the air through the load; and placement of stickers within the load to facilitate the movement of air across each piece of lumber.

Kiln Fans

In modern kilns, fans can be classified in two broad categories: internal fan kilns, that is, fans located inside the kiln itself; and external blower kilns, a system where the fan or blower is located outside the kiln and the air is conducted into the kiln through ducts.

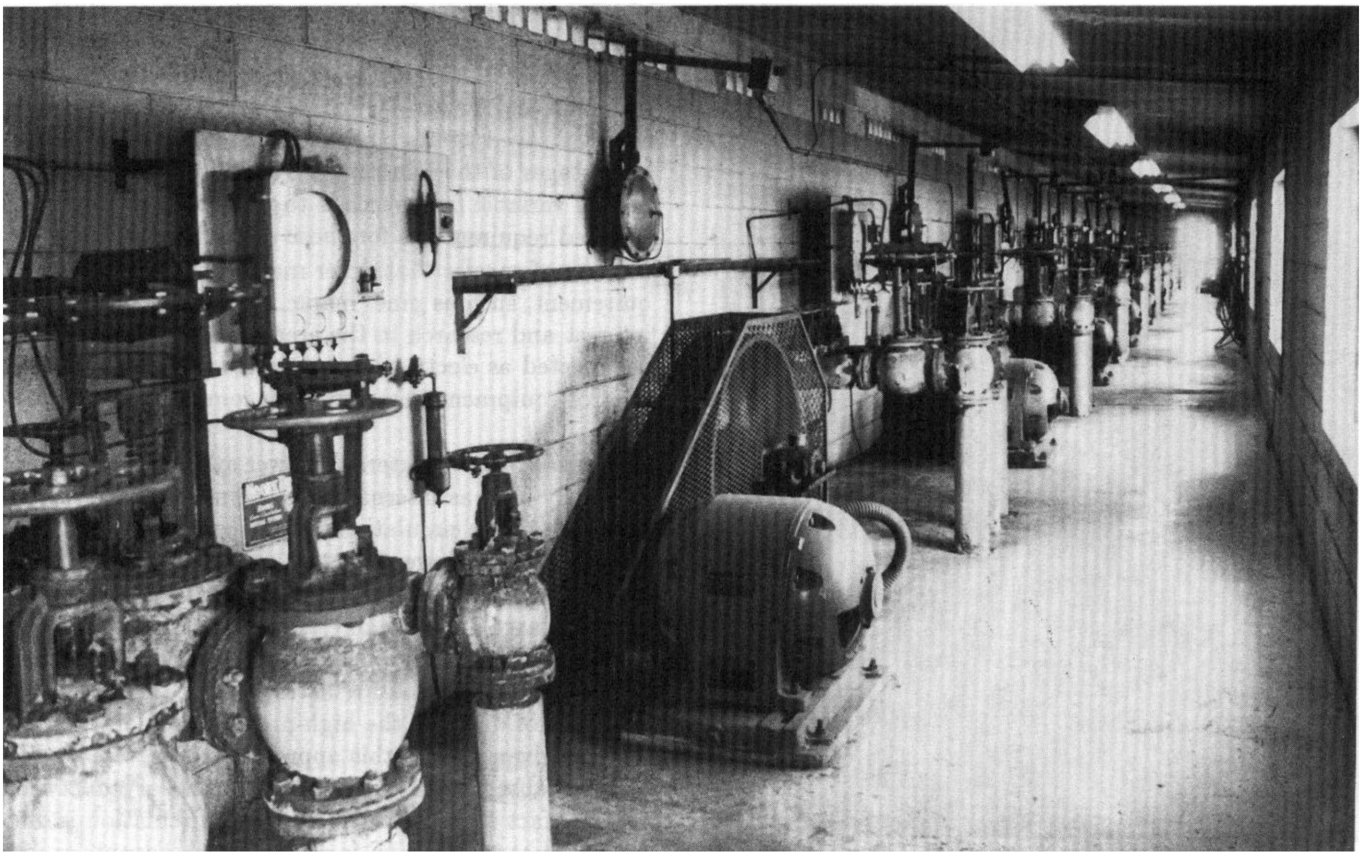


Figure 2-17—Control room for battery of lineshaft kilns, showing motor and pulley on lineshaft, recorder-controller, air-operated control valves to headers, hand-operated valves, and air-motor controlling vents. (MC88 9021)

Before discussing different types of fans in these two categories, it may be helpful to review the following laws regarding fans: (1) the volume of air moved varies directly with the fan speed in revolutions per minute (rpm), (2) the static pressure varies with the square of the fan speed, and (3) the horsepower varies as the cube of the fan speed and directly as the air density. For more detailed discussion of fan engineering and power consumption, see chapter 11.

Internal fans.-For internal fan kilns, there are two principal arrangements of the fans: lineshaft and cross-shaft. In both of these arrangements, the fans are typically placed overhead, with a false ceiling or deck between the fans and the load of lumber but not extending beyond the edge of the lumber (figs. 2-1 to 2-3, 2-5, 2-6).

In the traditional lineshaft arrangement, a series of multibladed disc fans (up to 84 in. in diameter in some large softwood kilns) is mounted on a single shaft running the full length of the kiln. The fans are alternately a left- and right-hand design. They are housed in a zigzag baffle-shroud system that directs the air across the kiln (figs. 2-2, 2-16). So that air circulation may be reversed efficiently, the fans are designed to operate in either direction. The motor, usually 50 to 75 horsepower, is generally located in the operating room or control room at the end of the kiln (fig. 2-17). This type of lineshaft arrangement provides for moving large volumes of air at low speeds (up to 400 ft/min through the load) with a minimum of power, and it is particularly suited to drying lumber with low initial moisture content or a species that needs to be dried slowly.

In a more recent adaptation to the lineshaft arrangement, propeller-type fans are mounted on the lineshaft (fig. 2-18). This modification can deliver upwards of 800 ft/min through the load, and the propeller-type fans are considerably more efficient per motor horsepower than disc fans. When changing from disc to propeller-type fans in retrofit operations, it may be necessary to change the type of bearings used for the shaft.

In the cross-shaft arrangement, fans are mounted on individual shafts aligned across the width of the kiln (figs. 2-3, 2-5). Each fan is driven by an individual motor (usually about 7.5 hp) either belt driven or direct connected. The motor may be mounted inside or outside the kiln. Motors mounted inside the kiln must be of special construction to withstand high temperatures, especially in kilns operating above 200 °F. With externally mounted motors, consideration should be given to offering some protection from the weather, particu-

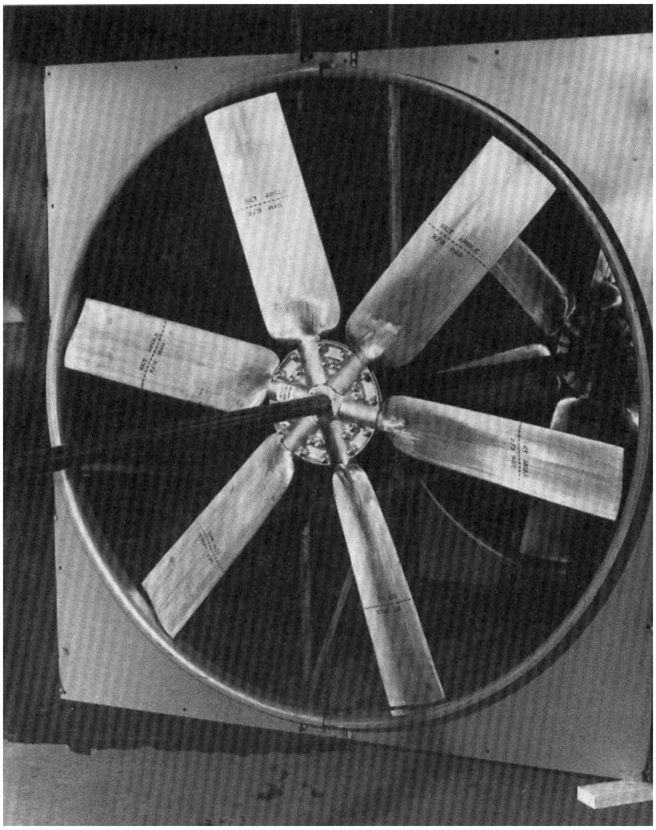


Figure 2-18—Propeller-type fans mounted on lineshaft. (MC88 9020)

larly in colder climates where freezing of condensed water vapor on the motor or shaft may present problems. Either multiblade-disc or propeller-type fans are commonly used for cross-shaft kilns. They can deliver large volumes of air at speeds considerably higher than the fans found in the traditional lineshaft kilns. With the modern trend to higher air velocities, especially desirable in the high-temperature kilns, propeller-type fans are becoming increasingly popular. These fans have two to six blades, some of which have adjustable pitch; are made of cast aluminum; operate at high revolutions per minute; and are capable of producing air velocities of 1,500 ft/min or more (fig. 2-19).

Traditionally, kilns have been designed such that fan speeds and thus the velocity of air through the load of lumber do not change during the time of the kiln run. However, for the most efficient drying, higher airspeeds are needed during the early stages of drying when the wood is wet and large quantities of water need to be evaporated. Later in the drying schedule, lower airspeeds are adequate as the wood becomes drier and less moisture needs to be evaporated. As electrical energy costs have increased over the last decade, there has been increasing interest in installing control equipment on fan motors so that fan speeds can be adjusted during the run, thus saving on energy costs. The amount of savings appears to be higher in softwood drying, which generally starts with relatively high moisture content woods that can be dried rapidly with minimal drying degrade. In hardwood drying, which uses milder schedules and slower drying, less energy costs are apparently saved through reduction in fan speeds in the later stages of the kiln run. Perhaps the greater advantage of variable fan speeds is to provide flexibility in airspeed requirements for those operations that dry a number of species that differ markedly in airspeed requirement, such as pine, maple, and oak. Continuing interest and research in the area of variable speed fans is expected as electrical energy costs rise and cost of control equipment becomes more competitive.

External fans.—External blower systems, though not as widely used as internal fan systems, offer another approach to air circulation. These commonly use only one motor and blower to move air into the kiln. In this system, air is drawn from the discharge side of the load through large ducts to an external centrifugal blower, from which the air is passed over the heater, humidified to the proper level, and redistributed in the kiln by another set of ducts to the high-pressure side of the load. The disadvantages of this approach are the low air velocities caused by the length of the necessary ductwork and the fact that the direction of air circulation is difficult, if not impossible, to reverse. The advantage of this approach is that the air circulation system (the major moving parts of a kiln) is concentrated in an easily accessible place and can be readily serviced.

Baffles

To achieve uniform and, where desired, rapid drying, the properly heated and humidified air must be uniformly directed to and through the lumber. To do this effectively, all alternate flow paths must be blocked so that airflow over, under, and around the load is prevented. The best practical way to do this is by using hinged baffles. The lack of effective use of baffling is one of the major causes of uneven or too slow drying. Airflow under the load in a track-loaded kiln may be prevented by having baffles hinged to the floor that can be turned up against the kiln trucks to prevent air bypassing under the load. An alternative is to construct the floor of the kiln with a trough just wide enough to accommodate the rails and trucks and high enough so that the lowest course of lumber just clears the level of the floor (fig. 2-2). The use of ceiling-hinged baffles arranged so their lower free edge rests on the top of the load is an effective way of preventing airflow over the top of the load. As the load shrinks during drying, the baffles must have the ability to move down to keep contact with the load (fig. 2-6). Airflow around the ends of the load can be prevented by mounting bifold-hinged baffles in or near kiln corners, ensuring contact with the ends or corners of the load. A real effort should be made to construct all kiln loads so that no holes or

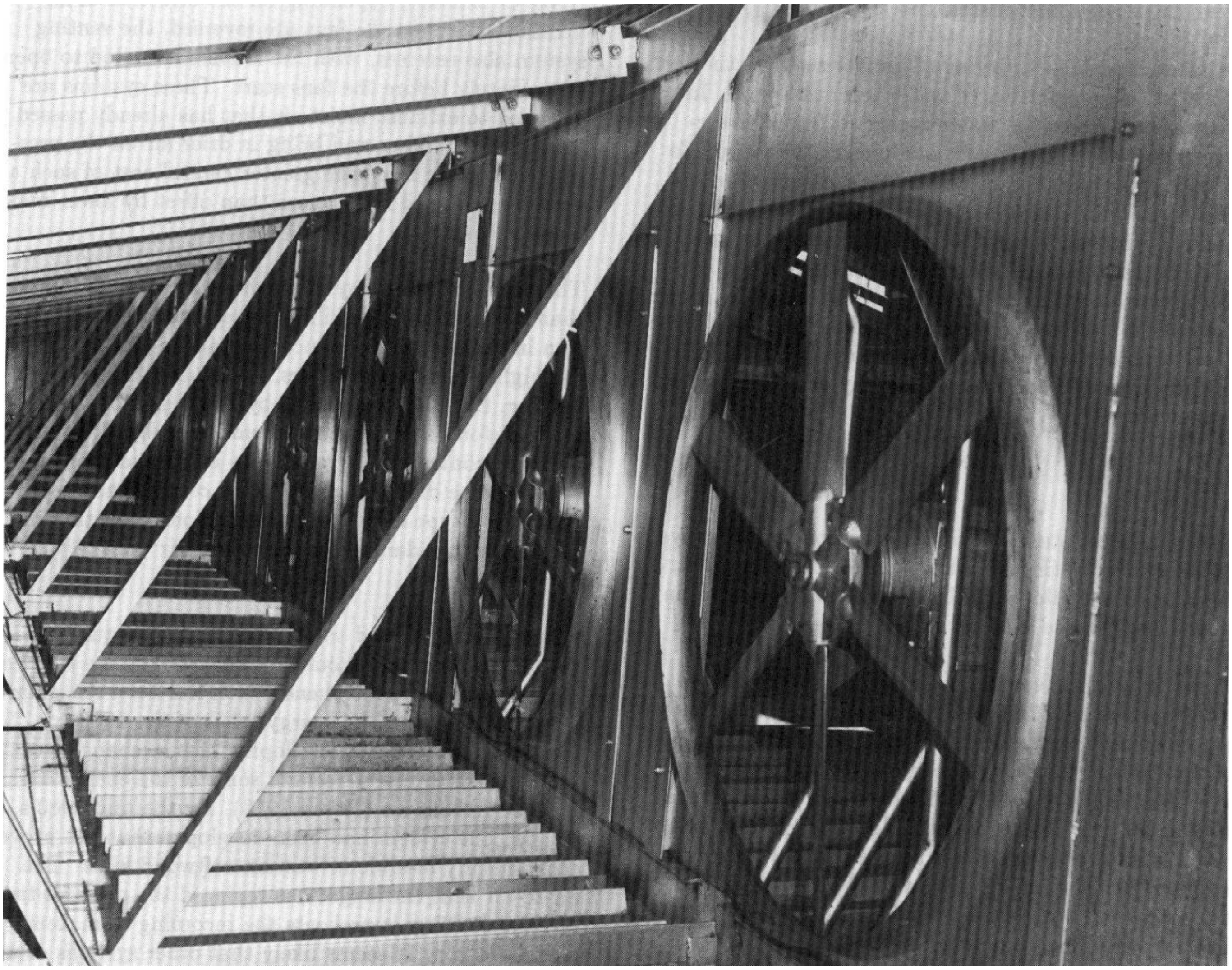


Figure 2-19—Propeller-type fans of cast aluminum in cross-shaft arrangement. (MC88 9019)

gaps occur between stacks because of mixed lumber lengths or stacks of uneven height.

Considerable care must be taken by personnel unloading the kiln to make sure all hinged baffles (floor, ceiling, and end) have been moved away from load before starting to move the load out of the kiln. Failure to do so results in baffles being ripped off or damaged. If baffles are damaged, they should be replaced immediately so that uniform air circulation can be maintained.

Plenum Chamber

The proper design and use of the plenum chamber or plenum space are necessary for adequate and uniform air circulation in a kiln. The plenum chamber is the space between the lumber and the wall on either side of a track-loaded kiln or between the lumber and the door or wall in a package-loaded kiln (figs. 2-2, 2-6). This area provides space for the fans to build up slight air pressure before passing through the courses of lumber, thereby improving the uniformity of air distribution through the load. When the fans reverse direction, the positive pressure reverses sides; the other side is always under slightly negative pressure. The plenum chambers should be wide enough so that the static pressure built up in them is sufficient to ensure uniform air flow across the loads from bottom to top. A frequently heard rule-of-thumb for estimating plenum width is that the width of the plenum should be equal to the sum of the sticker openings. Thus, if the sum of the sticker openings from top to bottom on one side of the load is 60 in, the plenum on that side should be about 60 in wide. A properly designed and loaded kiln will have adequate plenum space.

It would be a mistake in loading package kilns to put an extra row of packages in what should be the plenum space on the door side. This results in improper and nonuniform air circulation, and it is a practice to be strongly discouraged.

Venting and Humidification Systems

As mentioned before, drying of lumber requires the removal of large quantities of water from the wood. In conventional kilns, the water is carried from the surface of the wood by the air passing over the wood. To achieve proper drying of lumber, the amount of moisture in the kiln atmosphere (humidity) must be precisely controlled. When the humidity inside the kiln is higher than desired, the excess moisture is vented to the outside atmosphere and replaced with air from the outside. When the humidity inside the kiln is lower than desired, additional moisture is added to the kiln atmosphere by a steam spray or water spray-atomization.

Venting

Excess kiln moisture can be vented in one of two ways: (1) by static venting with the fans required for air circulation in the kiln or (2) by pressure venting with an additional fan and ductwork.

In static venting, vents are placed in the roof on the intake and exhaust sides of the fans. When the vents are opened, fresh air is drawn in on the suction side of the fan and moist air forced out on the pressure side (figs. 2-1 to 2-3, 2-5). When the direction of rotation of the fans is reversed, the flow of air through the vents is also reversed. The size and number of vents required depend on the species to be dried, that is, the amount of water to be removed from the wood. Species with large quantities of water, such as most pines and poplars, require more ventilation than species with lower initial moisture content, such as oak or hard maple or woods that have been air dried or partially dried in a predryer. Kilns may have one or two lines of vents running the length of the kiln depending on the fan arrangement (lineshaft (fig. 2-2) or cross-shaft (figs. 2-3, 2-5, 2-6)). Each line is automatically opened and closed by pneumatically or electrically powered motors activated by the recorder-controller system. In some cases, an additional row or two of manually operated vents are located on the roof. Opening these vents can provide additional venting when drying species that require large venting capacities (such as sugar pine or white pine). Static venting is the most common method of venting currently used in dry kilns.

In the pressure or powered venting systems, roof openings are replaced with two identical metal ducts placed inside the kiln, running the full length in the zone above the fan deck. These ducts vent to the atmosphere through louvered openings. Adjustable openings along the length of each duct regulate the volume of air discharged into or withdrawn from the kiln; thus air is distributed uniformly throughout the kiln. A fan unit at the end of each duct acts interchangeably as intake or exhaust, depending on the direction of air circulation. When the fans are reversed, the venting system also reverses, with the louvers actuated to open immediately before the fans start. These systems are designed to exhaust moist air that has already passed through the lumber and bring in drier air on the pressure side of the fan. The greater capital cost of such a system is claimed to be more than offset by lower maintenance costs.

The vent system in any kiln exhausts more air volume than it draws into the kiln to accommodate the expansion in volume of cooler incoming air as it is heated to the higher kiln temperatures. In the case of powered venting, this is accomplished by the design of the fan blade airfoil. The venting system is regulated by the recorder-controller mechanism as in normal roof venting. In some direct-fired kilns, the centrifugal blower produces a type of powered ventilation by venting moisture through a damper in the return-air duct to the blower.

When venting is used to control excess moisture in the air, substantial amounts of heat energy are thrown away or wasted. This phenomenon has been recognized for some time, but the energy crisis of the 1970's increased the interest in developing heat exchangers or economizers to use or reclaim some of the energy exhausted in vent air (Rosen 1979). By the mid-1980's, at least one system had been developed that has proven economically feasible in western softwood kilns. The air-to-air heat exchanger has replaced the need for traditional venting; it preheats the incoming or makeup air to the kiln. It seems likely that other systems or improvements to this system will be forthcoming, and the effectiveness and savings in energy costs to heat kilns will increase over the next decade.

Humidification

Control of the wet-bulb temperature or humidity in the kiln is important during the drying, equalizing, and conditioning stages of the drying operation. Close control of wet-bulb temperatures is especially important in the early stages of drying hardwood species that are prone to surface checks, such as oak and beech, and to minimize surface and end checking in the upper grades of softwood species. Close control of wet-bulb temperatures is also important during the conditioning phase at the conclusion of the kiln run of any species requiring this stress-relief treatment.

As mentioned earlier, when the humidity or the wet-bulb temperature of the kiln atmosphere is lower than desired, additional moisture is added. In steam-heated kilns, humidity is usually supplied as steam spray from the same source that supplies the heating coils. Steam is ejected through special nozzles on a steam spray line located in the airstream adjacent to the circulation fans, so the spray is mixed with the circulating air before it reaches the lumber (figs. 2-2, 2-6). As with the heating system, steam spray is regulated by the recorder-controller.

If high-pressure steam is used for heating the kiln and is available for humidification, it should not be used directly to humidify the kiln. Use of high-pressure steam adds a considerable amount of heat to the kiln in addition to increasing the humidity. This may cause fluctuation or overshoot of the dry-bulb temperature such that it is difficult or impossible to maintain the wet-bulb depression desired. This may be especially troublesome during conditioning when controlling wet-bulb depression is critical and adding large quantities of steam is necessary to increase the wet-bulb temperature. Steam pressure for the steam spray line should, therefore, be reduced to about 15 lb/in^2-gauge by a pressure regulator some distance before the line enters the kiln. If permitted by safety regulations, the portion of the line between the regulator and the kiln should be left uninsulated so that the superheat in the steam can dissipate, and the steam for humidification will be cooled to near saturation (250-260 °F). Another alternative is to install a desuperheater in the spray line. This device injects water as a fine spray or mist into the steam spray line, thereby removing the superheat and reducing the temperature of the steam to near saturation.

In some installations that do not have a source of steam for humidification, water sprays are sometimes used. The water should be injected into the kiln in the form of a fine mist. It is highly desirable to heat the spray water since cold water has an appreciable cooling effect in the kiln and can cause fluctuation of the dry-bulb temperature and poor control of drying conditions. In some kilns, water sprays are used in conjunction with steam sprays, but extra care must be taken to prevent water droplets from falling on the lumber and creating stains.

For close control of wet-bulb temperatures in direct-fired kilns where no steam is available from the central boiler, a small boiler may need to be installed to generate the large volumes of low-pressure steam required for proper conditioning of the lumber.

Equipment to Control Drying Conditions

While drying conditions in most commercial dry kilns are controlled by automatic or semiautomatic controllers, manual control is sometimes used in smaller installations or home-designed equipment.

Automatic Control Equipment

Automatic systems can be further divided into semiautomatic and fully automatic. Semiautomatic systems record and control on set points that are changed from time to time during the kiln run by an operator. In fully automatic systems, process control information is entered at the start of the kiln run, and any needed changes are made automatically by the equipment during the kiln run.

Several process control techniques, some using specialized equipment, are available for use with either the semiautomatic or the fully automatic control equipment. They include zone control (see Zone Control section), variable frequency speed control for fans (see Kiln Fans section), and in-kiln moisture meters. In-kiln moisture meters are generally of two types: (1) the resistance meter, in which electrodes (pins) are driven or screwed into boards in the charge of lumber, and (2) the capacitive admittance meter, in which the electrode (a strip of metal) lies flat on the surface of the lumber. The electrode is slipped into the load parallel to the stickers. Electric signals on both systems are converted to moisture content values and read on a meter. Both types of meters are subject to temperature corrections and are not considered very reliable at moisture contents above 30 percent. In-kiln resistance meters are frequently used to monitor moisture content of drying lumber below 30 percent and may be used to control kiln schedules. Capacitive admittance meters are most commonly used in softwood kilns to monitor moisture content of drying lumber below 30 percent and are frequently used to determine when a charge is finished. Some capacitive admittance meters are connected to the controller to shut the kiln down when a predetermined moisture content is achieved.

Semiautomatic Control Systems

Semiautomatic dry kiln control systems are typically characterized by having a recorder-controller. This instrument continuously measures and records on a chart the conditions prevailing in the kiln and controls the heat and humidity to conform to the conditions preset by the kiln operator. As drying progresses, the operator changes the instrument set-points to the desired conditions in the kiln. This may be done based on time elapsed since the start of the run or on the current moisture content of the wood as measured by a sampling technique such as weighing sample boards. The first is more typical of a softwood drying operation, and the latter is more commonly used in drying hardwoods. Once a dry-bulb and a wet-bulb temperature have been set, the instrument automatically controls the conditions until they are reset.

Signals indicating the current conditions in the kiln are received at the recorder-controller from sensors located in the kiln. There is typically only one wet-bulb temperature sensor in a kiln but multiple dry-bulb temperature sensors. This is because the wet-bulb temperature is essentially the same throughout the kiln, but the dry-bulb temperature may vary considerably over the length and height of the kiln. The instrument compares these kiln conditions to the instrument set-point conditions, Changes in the kiln conditions are made through signals to air-operated valves that open or close heating systems, valves that open or close vents electrically, and humidification systems as necessary to bring the kiln to set-point conditions.

For many years, the recorder-controller and its companion valve systems worked in an on-off mode; that is, the controller told the valve to be completely open or completely closed. This method often wastes energy and does not offer as close control of kiln conditions as may be desired. More recently the use of proportional valves and controllers has become the accepted practice in most kiln operations. In this approach valves are open to varying degrees depending on how far the kiln environment deviates from set-point conditions, thus offering more precise control and saving energy.

Sensors currently used in lumber dry kilns are of three types. The traditional sensor used for over 50 years is the gas-filled or liquid-vapor system. A more recent introduction is an electric system using a resistance temperature detector (RTD). A third type of sensor is used to measure equilibrium moisture content (EMC) of the kiln atmosphere. This sensor measures EMC directly by electric resistance measurements across electrodes clamped to a small wood specimen or cellulose pad (EMC wafer) mounted in the kiln.

Liquid-vapor or gas-filled systems consist of four main parts: (1) the temperature-sensing bulbs inside the kiln, (2) the armor-protected capillary tubes connecting the bulbs with the recorder-controller, (3) the helical movement (Bourdon tubes) inside the recorder-controller that provides the mechanical force to move the pens on the recorder chart and the air relay portion of the controller, and (4) the clock movement that turns the recording chart.

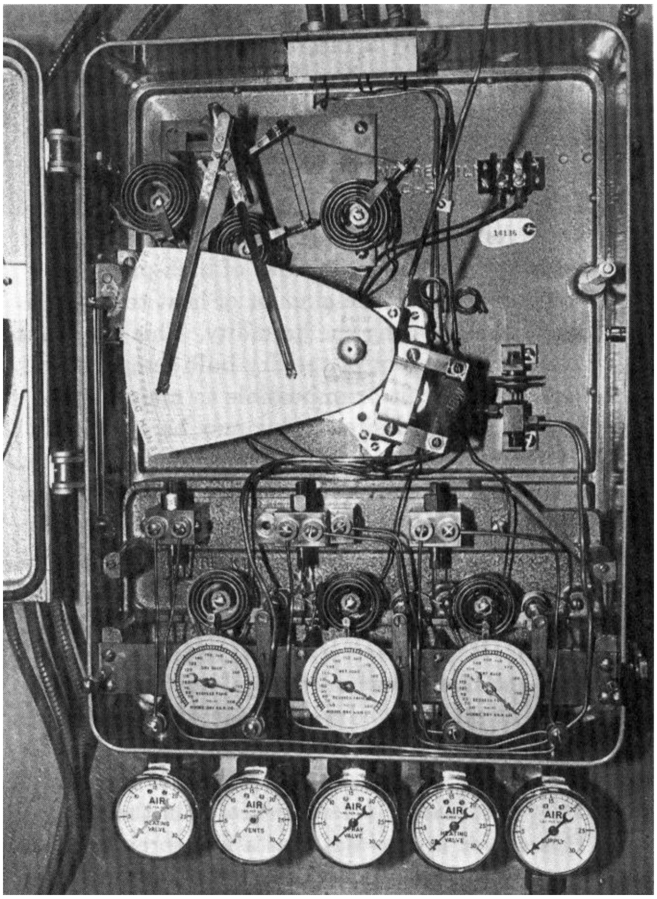


Figure 2-20—Internal view of three-pen, gas-filled recorder-controller (Moore type) showing Bourdon tubes, air relays, clock, gauges, and dials. (MC88 9018)

The dry-bulb and wet-bulb temperature-sensing units are connected individually by long capillary tubes to the Bourdon tubes inside the recorder-controller (fig. 2-20), which is normally located in the kiln control room. The bulbs and capillary and Bourdon tubes are sealed with a volatile liquid (butane) and its vapor. Increasing kiln temperature causes an increase of pressure in the liquid-vapor system; the capillary tube transmits the pressure change into the helical or Bourdon tube, causing it to expand. This movement is transmitted to the pen arm, which moves radially outward on the recording chart to indicate the increase in temperature. When the temperature in the dry kiln decreases, the reverse process takes place.

A typical dry kiln is usually equipped with one wet bulb and two or more pairs of dry bulbs. The wet bulb measures the wet-bulb temperature in the kiln resulting from the cooling effect of evaporation on the moist wick and controls the humidity in the kiln through the instrument. The paired or dual dry-bulb system (two bulbs connected to a common capillary tube) measures and controls the temperature of the kiln environment on the entering-air side of the lumber load in the kiln. The entering-air side of the load will always be the hotter side. When the air circulation reverses, the opposite side becomes hotter, and the bulb on the opposite side of the load becomes the controlling bulb. Larger kilns have two or more pairs of dual-control bulbs to better control the temperature in different zones of the kiln.

The controlling function of the liquid-vapor instrument is a pneumatic system of operating valves that control the amount of steam entering the dry kiln. Inside the recorder-controller case of a Moore instrument, the capillary tube from each bulb system is divided, with one lead going to the recording function and the other to a second Bourdon tube. Foxboro and Honeywell liquid-vapor instruments do not split this capillary but achieve the same results using mechanical linkages. As pressure changes within the system, needle-type air valves are brought into play, thereby accurately controlling heat input into the kiln and also controlling venting and spray or humidification.

Although the gas-filled or liquid-vapor control system has been time proven to be very dependable and adequately accurate, it does have some disadvantages when compared to the newer electronic recorder-controllers.

Electronic recorder-controllers use platinum RTD-type bulbs for sensors of both dry-bulb and wet-bulb temperatures and are connected to the instrument by 16-gauge, three-conductor lead wire. The recording function of the RTD control system contains an electronic servo module that measures resistance changes of a RTD and positions the pen accordingly on the chart. The instrument contains a separate servo module for each measuring system (fig. 2-21). For example, a three-pen RTD electronic control system will have three servo module units, one for the wet bulb and two for the dry bulbs.

The principal element of the controlling system is either a modulating or an off-on pneumatic control unit, which tracks the measured variable through movement of the pen linkage. When the measured variable crosses the set point, the control unit actuates a pneumatic or electrical relay, which in turn sends an air signal to the control valves, activating them as required.

The heart of the RTD electronic system is the servo module assembly, which contains an electronic bridge circuit, balancing amplifier, slide wire, and direct-current balance motor. One of the elements of the electronic bridge circuit is a resistance bulb that senses the dry-bulb or wet-bulb temperature. An external relay switches in the appropriate resistance bulb when fans reverse, thus assuring measurement of entering air temperature.

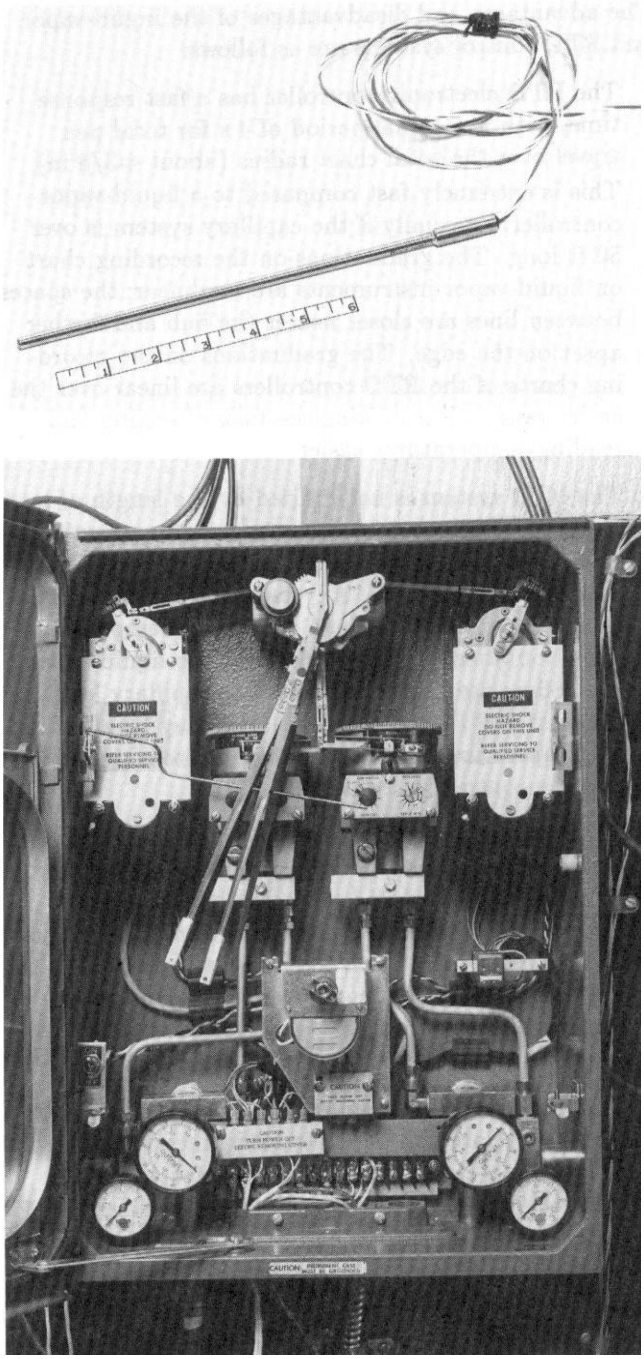


Figure 2-21—RTD sensor and instrument. (M87 0167, M88 132-4)

The advantages and disadvantages of the liquid-vapor and RTD control systems are as follows:

1. The RTD electronic controller has a fast response time, with a nominal period of 4 s for total pen travel over the total chart radius (about 4-3/8 in). This is extremely fast compared to a liquid-vapor controller, especially if the capillary system is over 50 ft long. The graduations on the recording chart on liquid-vapor instruments are nonlinear; the spaces between lines are closer nearer the hub and farther apart on the edge. The graduations on the recording charts of the RTD controllers are linear over the entire range, thus making the task of setting and reading temperatures easier.
2. The RTD system is not limited by the length of lead required. The control instrument can be mounted at distances of up to 2,000 ft with no loss of accuracy or response time. Any temperature changes caused by variation in lead length are compensated for automatically. By comparison, the liquid-vapor controllers are generally limited to capillary lengths of about 100 ft, and the capillaries may be affected by temperature changes between the sensing bulbs and the control instrument.
3. Temperature ranges can be easily changed on the RTD electronic controller by simply removing the existing range card and replacing it with a new range card. The liquid-vapor system requires removing the instrument from the kiln and returning it to the manufacturer or repair facility, where the system has to be refilled and recalibrated with special equipment.
4. The liquid-vapor instruments are sensitive to bulb locations related to the instrument mounting (higher or lower). If these distances change for any reason, calibration is affected. The RTD system is not affected by bulb location, and sensing bulbs can be moved at any time without affecting the calibration of the instrument.
5. If any damage occurs to the sensing system of the RTD controller, it can be repaired at the site. Sensing bulbs can be replaced in a matter of minutes, and damage to lead wires can be repaired without any change in calibration or accuracy of the instrument. Liquid-vapor systems require removing the instrument from the kiln with all capillary lines and bulbs intact and returning the instrument to the manufacturer or repair facility.
6. Perhaps the biggest advantage of the RTD electronic controller is the ease of calibration. Unlike the time-consuming two-person operation of using buckets of hot water or hot oil and an etched stem thermometer required for calibrating the liquid-vapor system (see ch. 4), the calibration of the RTD controller is a very simple one-man operation using a decade box. A given amount of electrical resistance can be applied to the instrument for various temperature ranges, and a direct readout on the chart indicates either proper or improper calibration. Adjustments are done very easily at the front of the instrument by simply adjusting the appropriate linkage. Note that this technique calibrates only the instrument, not the RTD sensor. The sensor is generally assumed to be accurate. Proper resistance in the RTD sensor can be checked against an electronic bridge. To check the total system, sensors and instrument, it is suggested that the sensor(s) be placed in an ice-water slurry (32 °F) and then boiling water (212 °F) and the respective values read on the instrument chart.

Fully Automatic Control Systems

In this manual, fully automatic control means the process control information or other drying schedule information is entered at the start of the kiln run. Any changes in temperature or humidity are made automatically by the controller during the kiln run. These changes may also include determination of final target moisture content and shutdown of the kiln. Override changes are possible with these systems, but seldom used. This procedure differs from semiautomatic control in which the recorder-controller effectively maintains preset conditions but does not change set points, which must be changed by the operator. Fully automatic systems range from cam-operated controllers, used in some regions for several decades, to controllers based on load cells that weigh the load or part of it, to the rather recently introduced computerized controllers that measure or infer changing lumber moisture content in the kiln.

Cam controllers represent the earliest attempt at fully automatic control. They are a form of time-based schedule and depend on the assumption that for a given species, thickness, and grade of lumber, the load moisture content and hence the conditions in the kiln will depend on the length of time drying has been in progress. Two specially cut cams are required, one to control the dry-bulb temperature, the other to control the wet-bulb temperature. Different cams have to be cut for different species and thicknesses.

The advantages of cam controllers include the following: (1) schedules are predetermined and monitoring is minimal; (2) schedules can be ramped or moved smoothly from one set of conditions to the next rather than arranged in steps, which cause abrupt changes in conditions and which may waste energy or put extra loads on the boiler; and (3) cams can be cut to give very predictable, reproducible results, based on experience in drying a given thickness(es) of given species starting at similar initial moisture contents.

The disadvantages of cam controllers include the following: (1) there is no direct link between the controller and the moisture content of the lumber at any given time during the kiln run—a load drying more slowly than usual could easily be shut down while at a moisture content higher than desired; conversely, a load drying more rapidly than usual could easily be overdried; (2) a recorder-controller rigged for following cams is not readily converted to other forms of set-point determination; (3) care and experience are necessary to cut accurate cams; and (4) failure to monitor at frequent intervals may result in not implementing necessary changes in response to unforeseen factors such as boiler shutdown, steam leak, or loss of water to the wet bulb.

Load-cell systems are available that weigh the load or a portion of it and make changes in the schedule as the lumber dries. Selected boards are sampled to determine initial or “green” weight in the usual way by cutting, weighing, ovendrying, and reweighing moisture sections (ch. 6); these values are averaged or weighted. This information together with details of the schedule to be followed are preprogrammed into the controller at the start of the run, and the system takes complete control of the drying operation. The main disadvantages of this approach are the problems of sampling and determining reliable initial moisture content values, drying on the average moisture content of the load or portion sampled, and lacking an indication of board-to-board variation in moisture content in the load during drying. A preferred approach would be to use very small load cells to follow the weight loss of individual sample boards and to make these data available to the control system by board or in groups of boards.

Since about the middle 1980’s, computerized controllers have been introduced in both softwood and hardwood operations. The introduction of desk-top-sized personal computers has provided a big boost to computerized control systems. Computerized control systems can range from those that are little more than electric cam time-based systems to those that measure the moisture content of the wood in certain ranges and infer the moisture content of the wood in other moisture content ranges. Since there is currently no reliably accurate method of measuring wood moisture content above the fiber saturation point (about 30 percent) except by weighing, values above 30 percent are inferred from controlled temperature and relative humidity conditions in the kiln. Moisture values below fiber saturation point are determined by measuring the electrical resistance between metal pins or electrodes driven into the board. Pins may be of different lengths so that moisture contents in the core and near the surface may be monitored and some idea of gradient may be determined. Some systems not only closely monitor and control temperature and humidity conditions in the kiln but also make changes in fan speeds and monitor or control energy consumption. One computer may control from 1 to as many as 8 to 10 dry kilns.

Computerized kiln controllers will likely find wider acceptance in the lumber industry in the future. Many current installations have shown that computerization can make the operation of dry kilns easier and can reduce the cost of producing high-quality lumber. The technology is advancing rapidly, and as we learn to sense more variables such as shrinkage, stress, wood temperature, and moisture content, we will add to the precision with which computer controllers can dry lumber.

Zone Control

Zone control is a process control technique for equalizing dry-bulb temperatures throughout the kiln and can be used with either semiautomatic or fully automatic control systems. Cool spots in the kiln have long been noted for uneven drying, producing lumber that is higher in moisture content than desired. Hot spots tend to produce lumber that is drier than desired. In zone control, the kiln is divided into several zones, with temperature sensors coupled to control valves or dampers in the heating system. Zones typically run along the length of the kiln; some designs have vertical zones as well. The number of independently controlled zones can vary from 2 up to 24. Historically, zone control with gas-filled recorder-controllers meant that long (66 ft or longer) kilns were divided into two zones: one zone for each end, or one zone control for operating the reheat coils in a double-track kiln and another zone control for operating the overhead heating coils. Computerized control with electronic RTD sensors has made it possible to control a much larger number of zones. With computerized control, paired sensors measure the, temperature drop across the load (TDAL or ΔT) and seek, through their circuits with control equipment, to keep the drying rate at the same level in all zones. This technique is successful and rather widespread in newer high-temperature softwood kilns in both the southern and western United States. It is expected to become more common in older remodeled or retrofitted softwood kilns and some hardwood operations. However, in conventional-temperature hardwood kilns, the TDAL is usually so small that trying to control using this variable is not very promising.

Manual Control Equipment

Some form of automatic kiln control is commonly used on commercial kilns in the United States and Canada. However, manual control is possible and is generally of interest to very small operations, often using home designed equipment, and to operations in which a person monitors the kiln on nearly a full-time basis. For successful manual control of drying conditions, the dry- and wet-bulb temperatures must be known. If these temperatures differ from those desired, the valves that regulate the flow of steam (heat) and spray (humidity) into the kiln must be adjusted until the desired temperature readings are obtained. The appropriate amount of venting must also be watched and adjusted. To keep the temperature or temperatures reasonably close to those desired requires considerable operator time for monitoring and making minor adjustments to valves.

Temperature-Measuring Devices

The temperature-measuring devices commonly used for manual control are of two classes, indicating and recording. Glass-stemmed indicating thermometers are frequently used. The most satisfactory glass-stemmed thermometers have the graduations etched on the stem. Thermometers with separate scales stamped on an attached metal strip are not very satisfactory, since any shifting of the strip with relation to the thermometer tube will result in incorrect readings. Indicating digital thermometers have largely replaced the pressure-spring type mentioned in the earlier edition of this manual. The sensor for these digital thermometers may be either a thermocouple or a RTD. Type–T (copper-constantan) thermocouple wire is suggested for most dry kiln use.

Glass-stemmed indicating thermometers of the maximum type are also used to obtain dry-bulb temperatures. Maximum thermometers show the highest temperature to which they have been exposed. After each reading, they must be shaken down like clinical thermometers. Care should be taken in using maximum thermometers to allow enough time for the mercury to reach a peak temperature.

Digital thermometers with the capability to be coupled to a printer are also available when written records of the temperature are desired over a period of time. As with indicating-type thermometers, the sensor of recording thermometers can be either a thermocouple or an RTD.

Humidity-Measuring Devices

To follow standardized kiln schedules with manual control requires a knowledge of the wet-bulb temperature or the relative humidity of the air circulating in the kiln. This can be done by using an instrument that reads relative humidity directly or with wet-bulb thermometry, which reads the wet-bulb temperature. The difference between the dry-bulb temperature and the wet-bulb temperature is the wet-bulb depression. By knowing these values and by using a psychrometric chart, relative humidity can be calculated (see appendix to ch. 1). As discussed in some detail in the appendix to chapter 1, wet-bulb sensors must be continuously wetted and located in a position in the kiln where sufficient airflow over the sock or wick will provide adequate evaporation of the water and thereby cooling so that accurate wet-bulb temperatures can be determined. The wet-bulb wick should be changed after every kiln charge or more frequently if it becomes hard or crusty and is not wicking properly. If kiln conditions are to be controlled by monitoring relative humidity and dry-bulb temperatures, then a high-quality relative humidity sensor should be obtained. Inexpensive sensors or meters of the type commonly found in hardware stores are not recommended as they do not stay in calibration well and can rather quickly give misleading or erroneous readings. Wet- and dry-bulb hygrometers are sometimes used for manual control. These provide wet- and dry-bulb temperatures from the same instrument and are illustrated in chapter 3 under Equipment for Determining Temperatures.

Specialized Drying Approaches and Kiln Types

Dehumidification Kilns

Dehumidification kilns have been mentioned in several places in this chapter. In many respects, these kilns are similar to steam-heated or direct-fired kilns, but they differ enough to warrant a separate description. Dehumidification kilns have several advantages: a boiler may not be required (except as required for stress relief or desired for warmup); they are more energy efficient, offering good control in drying refractory species that require a low initial dry-bulb temperature as well as high relative humidity; and a low-cost kiln structure is adequate for some applications. Disadvantages are that dehumidification kilns operate primarily on electrical energy, which in some regions may be more expensive than gas, oil, or wood residue (even though these kilns are more energy efficient than other types of kilns); maximum temperatures are limited to about 160 °F and in some units to about 120 °F; and, in some cases, there may be concern over chemicals in the condensate.

Air-circulation systems are essentially the same as those used in steam or direct-fired kilns. The entire dehumidification unit may be located outside the kiln in an equipment room and blowers used to circulate air between the dehumidifier and the kiln. Another common arrangement is a split system with the compres-

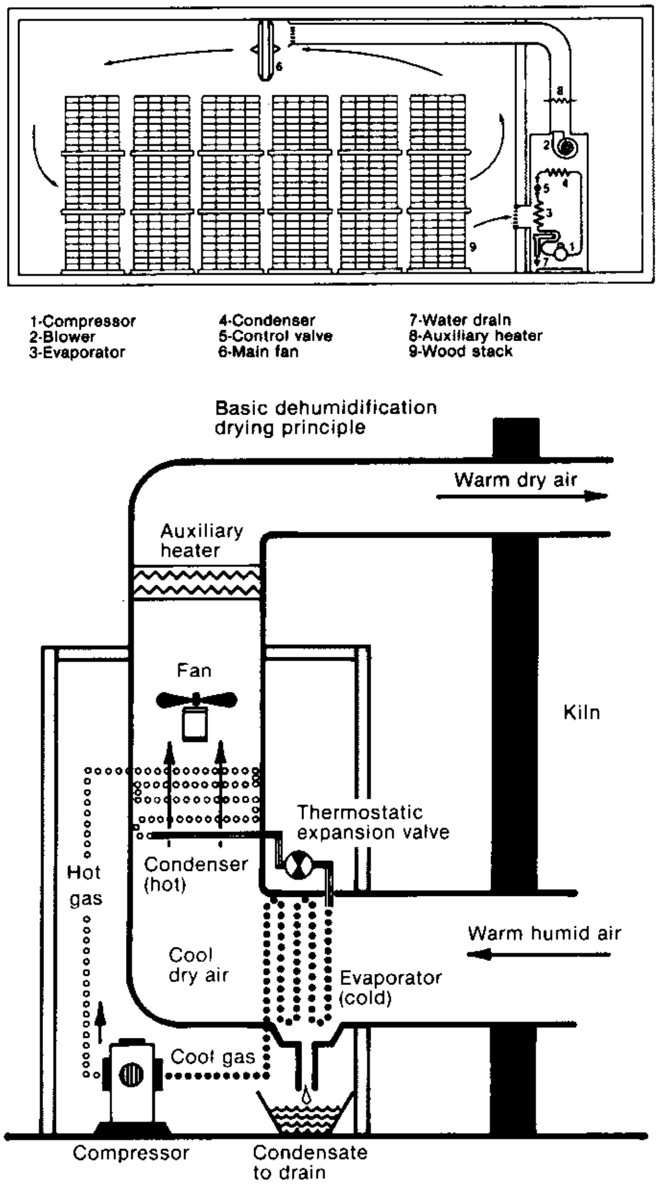


Figure 2-22—View of a typical dehumidification kiln and schematic of typical dehumidification drying system. (ML88 5625)

sor and control panel in a separate equipment room and the blower and coil cabinet inside the kiln. In some smaller systems (less than 10,000 fbm), the entire dehumidification unit may be inside the kiln. Air circulation within the drying compartment is provided as in the other types of kilns. While earlier designs typically had air velocities in the lower range, the industry has gradually increased the air velocity to a level comparable to that used in a conventional-temperature hardwood kiln. A typical dehumidification kiln is shown in figure 2-22.

The major difference between dehumidification kilns and other types of kilns is the method by which water is removed from the kiln air. The majority of the water is condensed on the coils of the dehumidifier and removed as liquid, rather than being vented to the outside atmosphere. Many larger dehumidification systems have provisions for periodically venting excess heat, and some moisture is vented in the process of venting heat, but only a small part of the total moisture in the air is vented. These two characteristics account for the greater energy efficiency of dehumidification kilns. First, since little moist air is vented to the outside of the kiln, the energy contained in the warm, moist air is not lost. Second, when the moisture in the air condenses on the cold coils of the dehumidifier, the heat of vaporization is recovered. Most dehumidification kilns are built so that this recovered energy is used in drying the lumber. The same approximately 1,000 Btu of energy per pound of water required to evaporate the water from the lumber in the first place is recovered in this condensation.

Kiln control systems on dehumidification kilns of about 5,000 fbm and larger are similar to those of other kilns. They typically use RTD dry- and wet-bulb sensors and recorder-controllers. Controllers for smaller systems may use a timer to control the percentage of time the compressor operates or a humidistat to activate the compressor. Most large systems (over 10,000 fbm) used for drying hardwood lumber are installed with a boiler for warmup and conditioning or stress relief. Smaller systems often have electrical resistance heating elements that are used to bring the kiln up to operating temperature to the point where the compressor can supply enough energy to maintain the desired drying conditions. These heating elements can also be used to attain the higher temperatures often called for near the end of the drying schedule.

Materials of construction vary from wood to masonry to prefabricated aluminum panels. The main criteria are that the drying compartment be well insulated so that maximum benefit can be derived from the energy efficiency and that the compartment be both airtight and moisture resistant. For medium to large kilns, insulation values of R-20 for walls and R-30 for roofs are recommended. Slightly lower values may be acceptable in warmer climates. For smaller kilns (10,000 fbm capacity or less) with less compression-generated heat, higher R values are required. Very serviceable and low-cost kilns can be built with simple wood-frame construction, in both large and small sizes.

In general, one can expect that drying stresses will be present after dehumidification kiln drying, as they are after drying in other type kilns. When drying lumber for uses where drying stress must be relieved, special provisions must be made if the system is not equipped with a boiler. A small-capacity electric or gas-fired boiler can be incorporated in the kiln for this purpose.

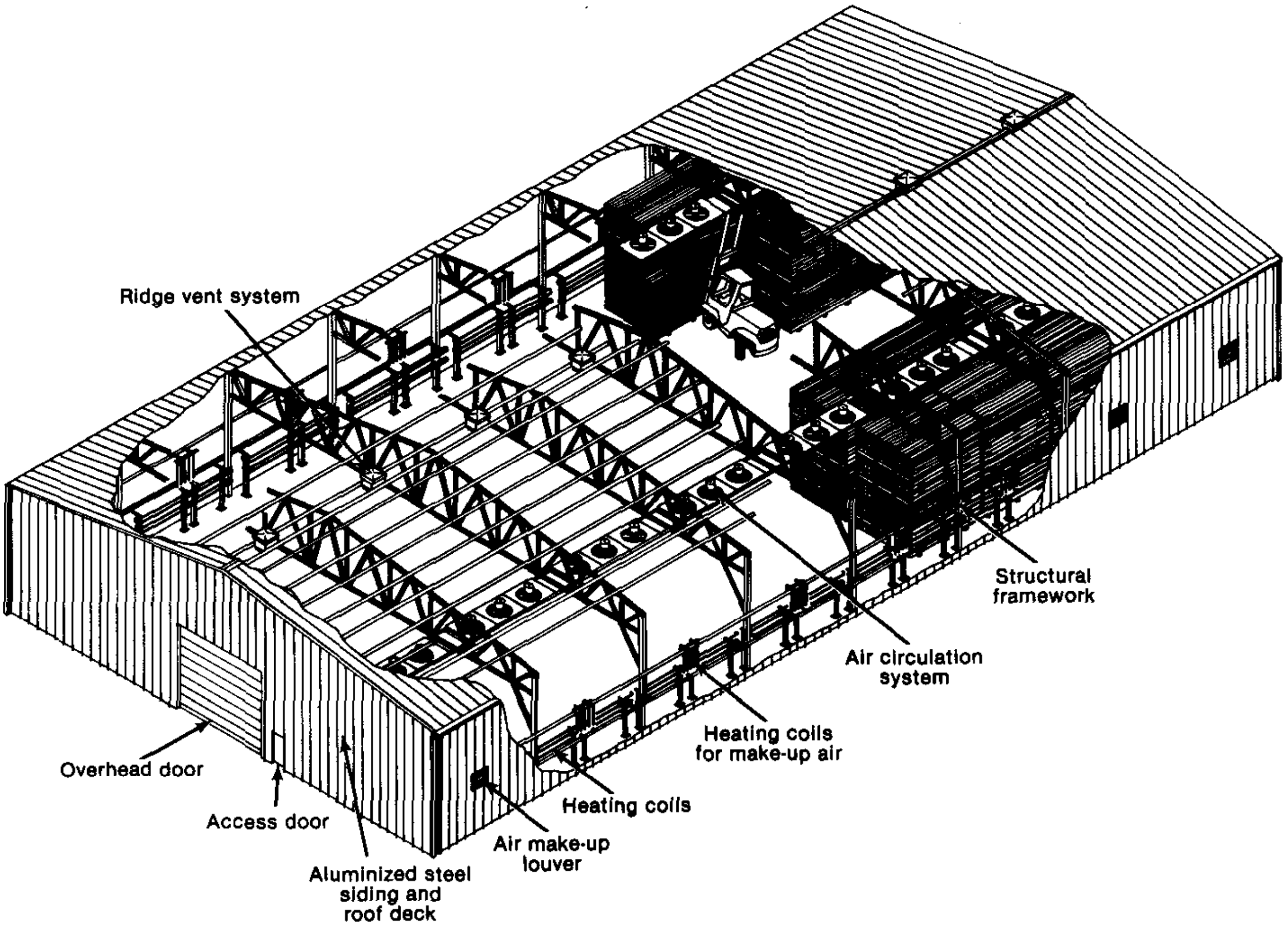


Figure 2-23—Typical predryer. (ML88 5600)

It is very important to properly size the compressor for the thickness and species to be dried in the dehumidifier. If the compressor is too small, there is a risk of stain, increased warp, and checking. If the compressor is too large, humidities in the kiln can cycle excessively, possibly resulting in a lack of heat.

Predryers

Predryers are large low-temperature dryers used to dry green lumber to a moisture content of around 25 percent prior to drying to a lower final moisture content in a kiln. Also called warehouse dryers, these large free span buildings range in lumber-holding capacity from 50,000 to over 1,000,000 fbm and are typically sized at four times kiln capacity (fig. 2-23). Generally, predryers are forklift loaded, although track loading may be preferred in some cases. Most predryers are preengineered buildings of structural steel with 1 to 2 in of rigid foam insulation between painted steel or aluminum sheathing. They commonly have concrete floors. Temperature and relative humidity are controlled with temperature set-points typically ranging from 75 to 100 °F and with relative humidity maintained between 60 and 90 percent.

Predryers for controlling air-drying conditions have been used successfully for over 25 years by some companies in the northern latitudes of the United States where natural air-drying conditions are unfavorable for many months, from both the standpoint of defect development and length of air-drying time. However, in recent years high lumber prices and high interest rates have produced financial incentives strong enough to interest lumber producers in other areas, especially hardwood producers who had typically air dried their lumber 60 to 90 days or longer before final drying in the kiln.

The advantages of predrying over air drying in the yard are brighter lumber, more uniform moisture content of dried lumber, and reduction of drying defects, all in about one-third less time. Inventory can be reduced by one-third to one-half, freeing capital and yard space. Several species and thicknesses can be mixed in these dryers. Thus, lumber of different moisture contents, species, and thicknesses may be in the predryer at the same time; drier lumber can be moved frequently out to the kilns and newly acquired green lumber can be moved in. The lumber is usually arranged by blocks in a zone to group similar species, thicknesses, and levels of moisture content. Disadvantages of predrying over air drying are largely associated with costs of building, energy, and maintenance.

Predryers are typically heated with steam and finned coils. Humidity is controlled by external venting when humidities are too high and by using moisture released from the lumber to maintain humidities as high as required. Larger predryers are divided into two and sometimes three zones; conditions are controlled separately in each zone by a recorder-controller similar to those described earlier in this chapter. In some installations, temperature and humidity conditions are maintained with dehumidification units.

Temperatures are usually sensed by electronic RTDs, and humidity is sensed by wet-bulb thermometry or with relative humidity sensors using the cellulose pad or similar sensor. Placement of the sensors above the load in the rafters is often criticized because the sampled air is not as representative of the air entering the stacks as one would like. However, the free-span construction of the structure does not provide much choice in where to place the sensors.

Air circulation is usually provided by overhead fans arranged in a row horizontally over the plenum between the two rows of lumber (fig. 2-22). The air is directed down into the plenum by belt-driven or directly driven fans, and then it is passed through the stacks of lumber. One criticism of predryers has been uneven air distribution, resulting in uneven drying from top to bottom of the stacks. Various forms of baffle systems have been suggested to improve distribution and uniformity of airflow. Exhaust ventilation should be designed so that it does not direct the humid exhaust air down onto the roof; this has been reported to cause localized deterioration of the roof. Rather, exhaust ventilation should consist of “upblast” units that direct vented air straight up and way from the building. The makeup air enters through louvers in the walls and can be preheated if needed.

The concept of using predryers rather than air drying has gained wide acceptance in the hardwood industry, though it may not be a technique that works well and is profitable for all operations and installations. The techniques are still evolving, and many changes are likely to be seen in the next few years.

Solar Dry Kilns

Interest in solar dry kilns was low until the energy concerns of the mid-1970's. The advantage of solar kilns is the free and often abundant energy available, but the disadvantage is that there is a cost to collecting free energy. Free energy is also low-intensity energy, which often limits the operating temperature of a kiln to approximately 130 °F unless prohibitively expensive special solar collectors are used. Despite the cost of collecting the energy, another advantage of solar kilns is that relatively small, simple, and inexpensive kilns are possible, and this level of technology is often well suited for small operations.

The average annual solar energy available on a horizontal surface in the United States ranges from 1,000 to 2,000 Btu per day per square foot of collector area. Average amounts for several locations are given in table 2-1. Tilting the collector surface perpendicular to the sun maximizes the intensity of the direct solar radiation and minimize losses caused by the reflection of the direct radiation. The general rule for maximizing solar radiation on a year-round basis is to tilt the collector at an angle to the ground equal to the latitude. If solar radiation is to be maximized in the summer months in locations where latitude and ambient temperature make winter drying impractical, direct radiation can be maximized by reducing the tilt angle to about 15° less than the latitude. In the northern hemisphere, the collector should face directly south.

Solar kilns can operate by direct solar collection (greenhouse type) or by indirect solar collection where the collector is isolated in some way from the drying compartment. They can also operate with solar energy alone or with supplemental energy. The four types of solar kilns are as follows:

1. Direct collection (greenhouse)
   a. Solar only, which is characterized by wide diurnal and day-to-day changes in temperature and relative humidity
   b. Solar with supplemental energy, which is characterized by the ability to follow a drying schedule and has large nighttime heat losses because of the low insulating ability of the transparent cover
2. Indirect collection (isolated drying compartment)
   a. Solar only, where the diurnal change in temperature and relative humidity can be reduced by energy storage and reduced heat losses at night
   b. Solar with supplemental energy, where scheduled drying is possible and nighttime losses are minimized

Generalized solar kiln designs are shown in figure 2-24. Possible collector surfaces are south-facing walls, east and west walls, and a roof. Solar collection is either direct (fig. 2-24a,c) or indirect (fig. 2-24b,d). The collector surface is either uninsulated (fig. 2-24a,b) or insulated at night (fig. 2-24c,d).

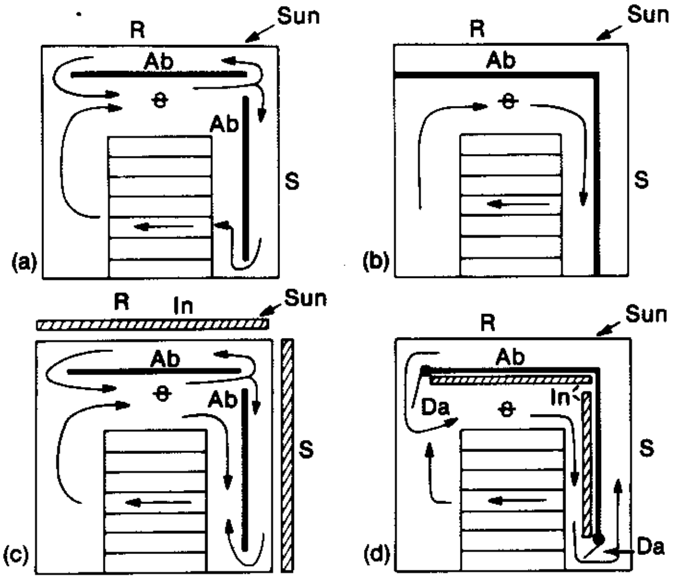


Figure 2-24—Generalized solar kiln design types. (a) Uninsulated dryer and collector are one unit. Airflow mixes on both sides of absorber panel (Ab). (b) Uninsulated, improved design. Airflow mixes within chamber. (c) Insulated (ln) externally. Airflow mixes on both sides of Ab, day and night. (d) Insulated (ln) internally. Air flows over the front of the absorber panel (Ab) when damper (Da) is open. (ML88 5603)

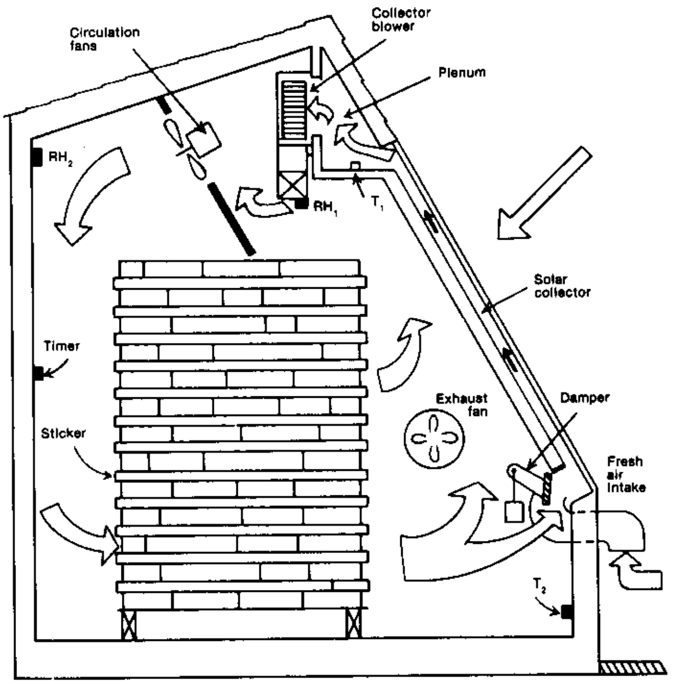


Figure 2-25—Solar kiln design for northern latitudes, showing inexpensive control system. (ML88 5602)

In the simplest uninsulated form (fig. 2-24a), air flows on both sides of the absorber surfaces (Ab). The drying chamber and collector surfaces are one unit as in a true greenhouse structure. A somewhat improved design (fig. 2-24h) isolates the collector surfaces (R and S) and the outer absorber surface (Ab) from the drying chamber. The energy absorbed on the absorber surface flows through the absorber to its inner surface where it is transferred to the circulating kiln air. Both of these systems suffer large nighttime heat losses.

For the insulated designs, two variations are possible. In the simpler of these designs (fig. 2-24c), airflow is similar to that in figure 2-24a except that diurnal insulation (ln) is accomplished by external means such as shutters or blankets. Collector and absorber surfaces are also isolated in the design shown in figure 2-24d, with the drying air acting as the medium for heat transfer. When the dampers (Da) are open, the air flows over the black absorber surface (Ab) and back into the dryer chamber. When the dampers are closed, nighttime airflow is interrupted, thereby reducing nighttime (and cloudy day) heat losses because the absorber has an insulated back (ln). A more detailed schematic of this type of solar kiln is shown in figure 2-25. In another common variation of this insulated-type solar kiln, the solar collector is detached from the drying compartment, and blowers transfer the heated air from the collector to the drying compartment (fig. 2-26).

At present, solar drying is not widely used in the United States. The main uses are hobbyists or small woodworking shops that do not require large drying capacity and that do not wish to make large capital investments in drying equipment.

Vacuum Drying

Vacuum drying of lumber is not a new idea, and, in fact, it has been considered since the turn of the century. However, vacuum drying did not come into use until the 1970's because it was considered uneconomical. The principal attraction of vacuum drying is that the lowered boiling temperature of water in a partial vacuum allows free water to be vaporized and removed at temperatures below 212 °F almost as fast as it can at high-temperature drying at above 212 °F at atmospheric pressure. Drying rate is therefore increased without the dangers of defects that would surely develop in some species during drying above 212 °F. Vacuum drying is essentially high-temperature drying at low temperatures. During the early 1970's, the economic outlook for vacuum drying became more favorable, largely because of the increased costs of holding large inventories of lumber during long drying processes. This is particularly true in the drying of thick, refractory, high-

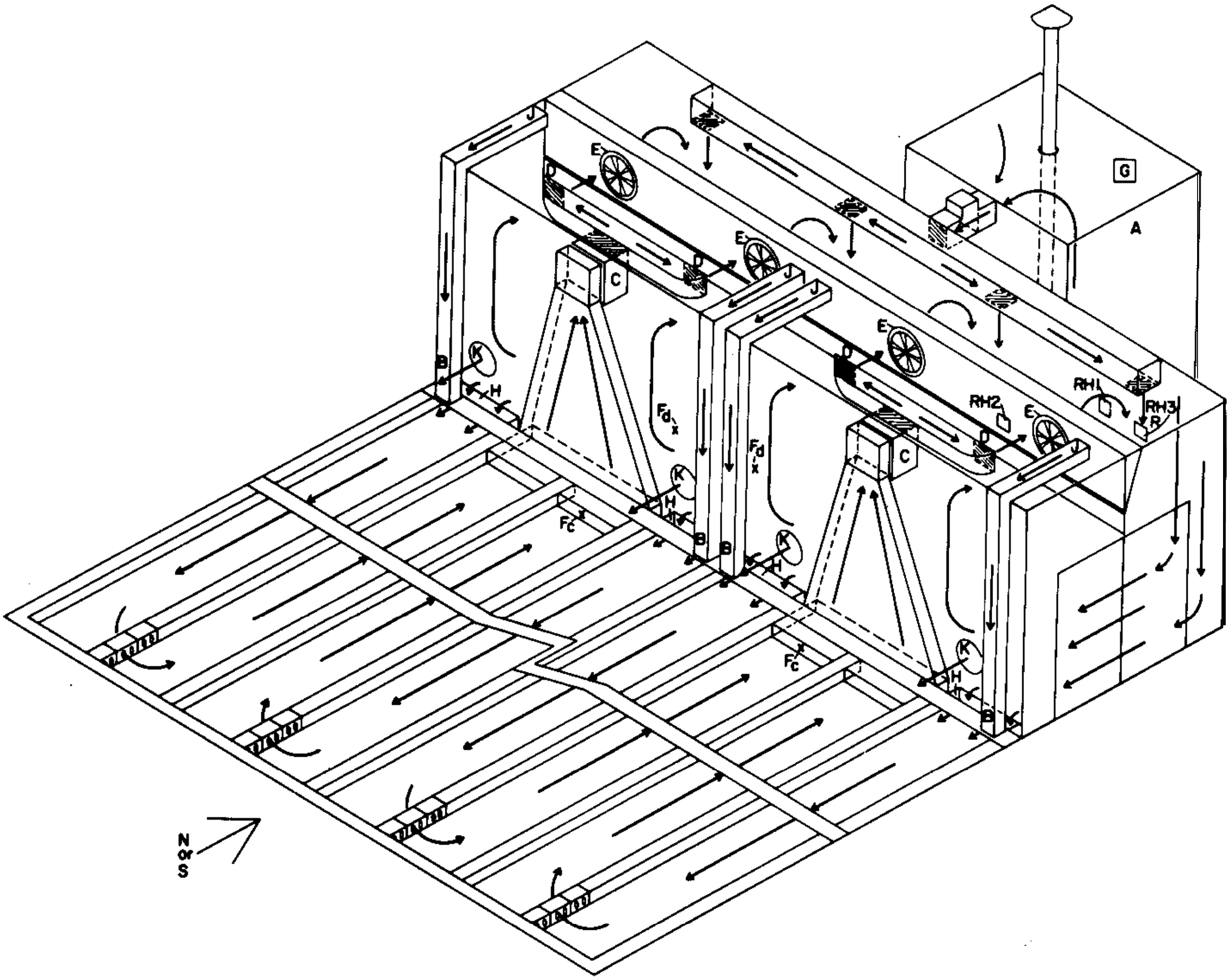


Figure 2-26—Schematic diagram of solar wood-residue dry kiln. A, furnace room; B, intake air enters collector; C, solar blower; D, manifold ducts for solar-heated air; E, internal fans; F_c, differential temperature sensor-collector; F_d, differential temperature sensor–dryer; G, humidifier; H, return-air duct from dryer to collector (dampered at night); J, entry point of intake air; K, exhaust vents; RH1, humidistat for exhaust vents K: RH2, humidistat for shutting kiln off at high humidity; RH3, humidistats for humidifier G. (ML88 5601)

value species, which can be safely dried in a vacuum kiln in a small fraction of the time required in a conventional kiln.

The main difference between the several types of vacuum kilns currently on the market is the way in which heat is transferred to the lumber. Convective heat transfer in a partial vacuum is almost nonexistent. In one common type of vacuum kiln, there are alternate vacuum and atmospheric pressure cycles. Heat is applied to the lumber convectively at atmospheric pressure, and then a vacuum cycle is applied to remove water at low temperature. These cycles are alternated throughout the drying. Another common type of vacuum kiln maintains a vacuum throughout the entire drying process, and the heat is transferred to the lumber by direct contact with steam-heated platens or by electrically heated conductive blankets that contact the lumber (fig. 2-27). A third type employs high-frequency electrical energy to heat the lumber. In all types, water is removed from the drying chamber by pumps.

Figure 2-27—Vacuum-kiln type in which heat is supplied to the lumber by contact with electrically heated blankets. (M85 0351-10)

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Table 2-1—Annual average of daily solar radiation available at various locations in the United States

City	Solar radiation (Btu/ft^2-day)
Albuquerque, NM	1,915
Ames, IA	1,273
Atlanta, GA	1,454
Boise, ID	1,456
Boston, MA	1,148
Corvallis, OR	1,255
Davis. CA	1,598
Fort Worth, TX	1,638
Grand Junction, CO	1,675
Greensboro, NC	1,410
Indianapolis, IN	1,273
Lexington, KY	1,506
Little Rock, AR	1,432
Shreveport, LA	1,458

Chapter 3
Dry Kiln Auxiliary Equipment

Chapter 3 was revised by R. Sidney Boone, Research Forest Products Technologist.

Certain auxiliary equipment is needed to operate a dry kiln in the most economical manner and to obtain good drying results. Drying schedules based upon moisture content cannot be successfully applied unless the moisture content of the stock is known. Therefore, equipment should be available for determining the moisture content of the stock. Equipment should also be available for determining the temperature, humidity, and velocity of air in the kiln to maintain uniform conditions for fast drying.

Equipment for Determining Moisture Content

Such items as balances, scales, saws, drying ovens, and electric moisture meters are used in determining the moisture content of wood. Distillation equipment is used for accurate determination of moisture content of woods that hold relatively large amounts of oil, resins, wood preservative, or fire-retardant chemicals.

Balances and Scales

Triple-Beam Balance

One of the most commonly used types of balances for weighing small moisture sections is the triple-beam balance, shown in figure 3-1. Balances best suited for weighing the recommended sizes of moisture sections (see preparation of kiln samples and moisture sections in ch. 6) should have a maximum capacity of at least 1,000 g and weigh to an accuracy of at least 0.1 g (0.01 g is preferable).

Electronic Top-Loading Balance

Electronic top-loading balances are available in a wide range of weighing capacities, precisions, styles, and price ranges. Models with printers that provide a written record of the weights and portable battery-operated models are also available. Two types suitable for weighing small moisture sections are shown in figure 3-2. Because of the size of the pieces to be weighed and the precision to which they need to be weighed, the same balance cannot be used to weigh the small moisture sections and the much larger sample boards (see preparation of kiln samples and moisture sections in ch. 6). For weighing moisture sections, the balance should have a maximum capacity of at least 1,000 g and weigh

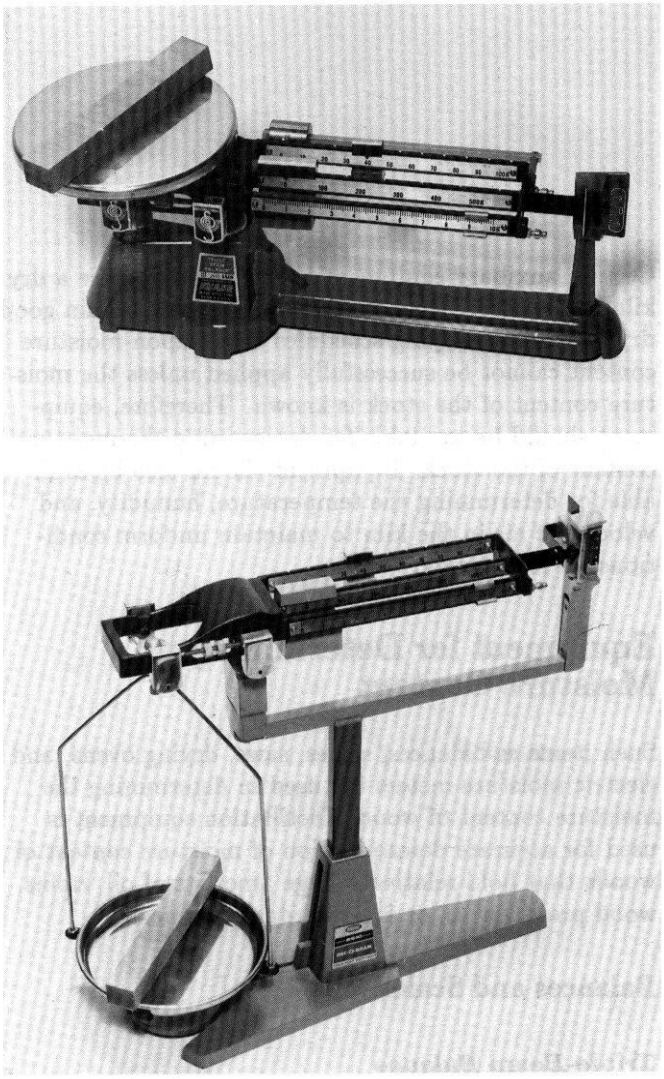


Figure 3-1*—Two types of triple-beam* balances suitable for weighing moisture sections. *(M87 0198, M87 0169)*

to at least 0.1 g (0.01 g is preferable). A type of balance suitable for weighing sample boards is shown in figure 3-3. For weighing sample boards, the balance should have a maximum capacity of at least 15,000 g and weigh to 1.0 g. Operations drying wide boards of higher density hard woods should consider having a maximum capacity of 20,000 to 30,000 g.

Self-Calculating Balance

To calculate moisture content, it is necessary to know the original and the ovendry weights of the wood sections. The loss in weight is divided by the ovendry weight (see ch. 6 for procedure). Self-calculating balances, similar to the one shown in the upper part of figure 3-4, have been developed to speed up these calculations or to eliminate them entirely. As shown in the lower part of figure 3-4, the moisture readings can be estimated to the nearest 0.5 percent when the values are less than 10 percent, and to the nearest 1.0 per-

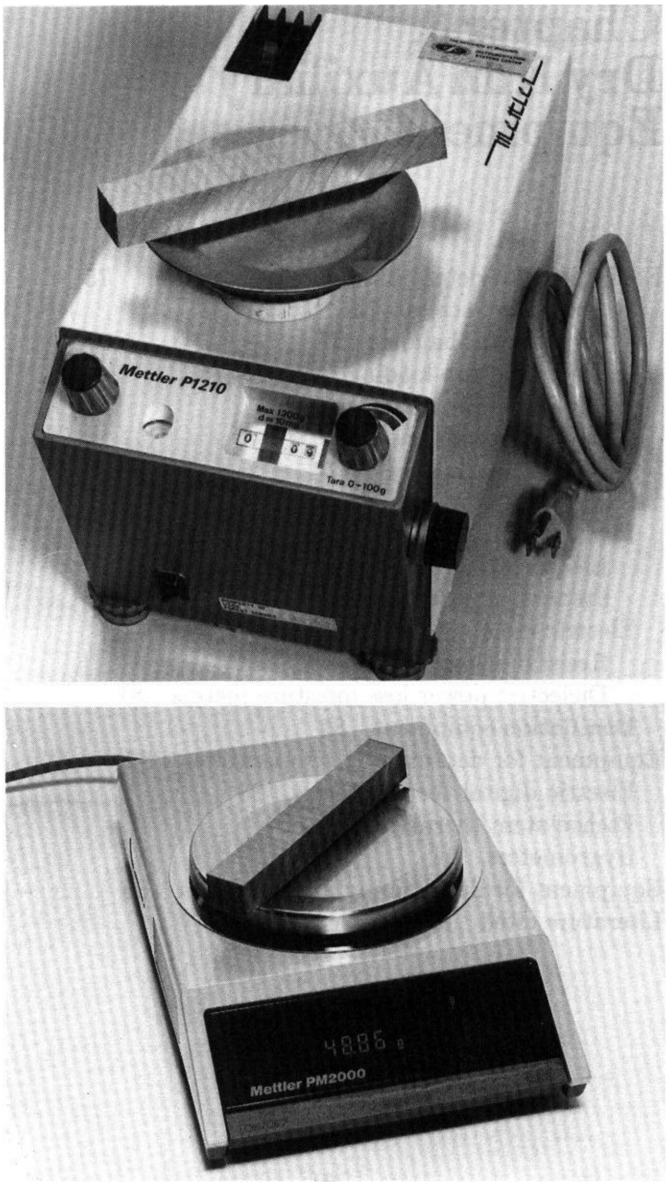


Figure 3-2*—Electronic top-loading balances suitable for weighing small moisture sections. (M87 020,M87 0175)*

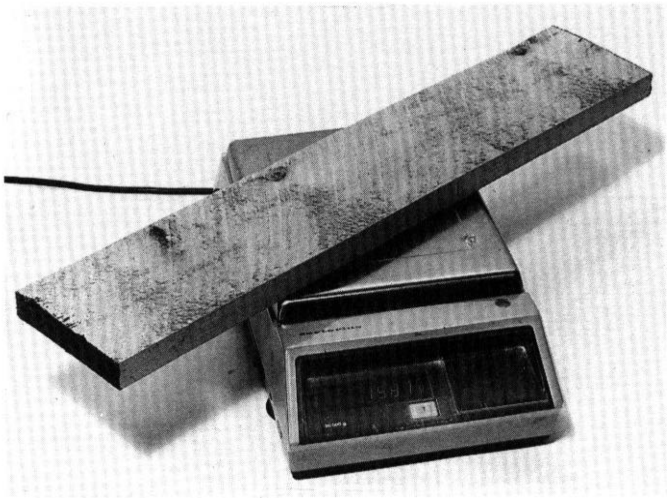


Figure 3-3—Electronic top-loading balance for weighing *sample boards. (M87 0174)*

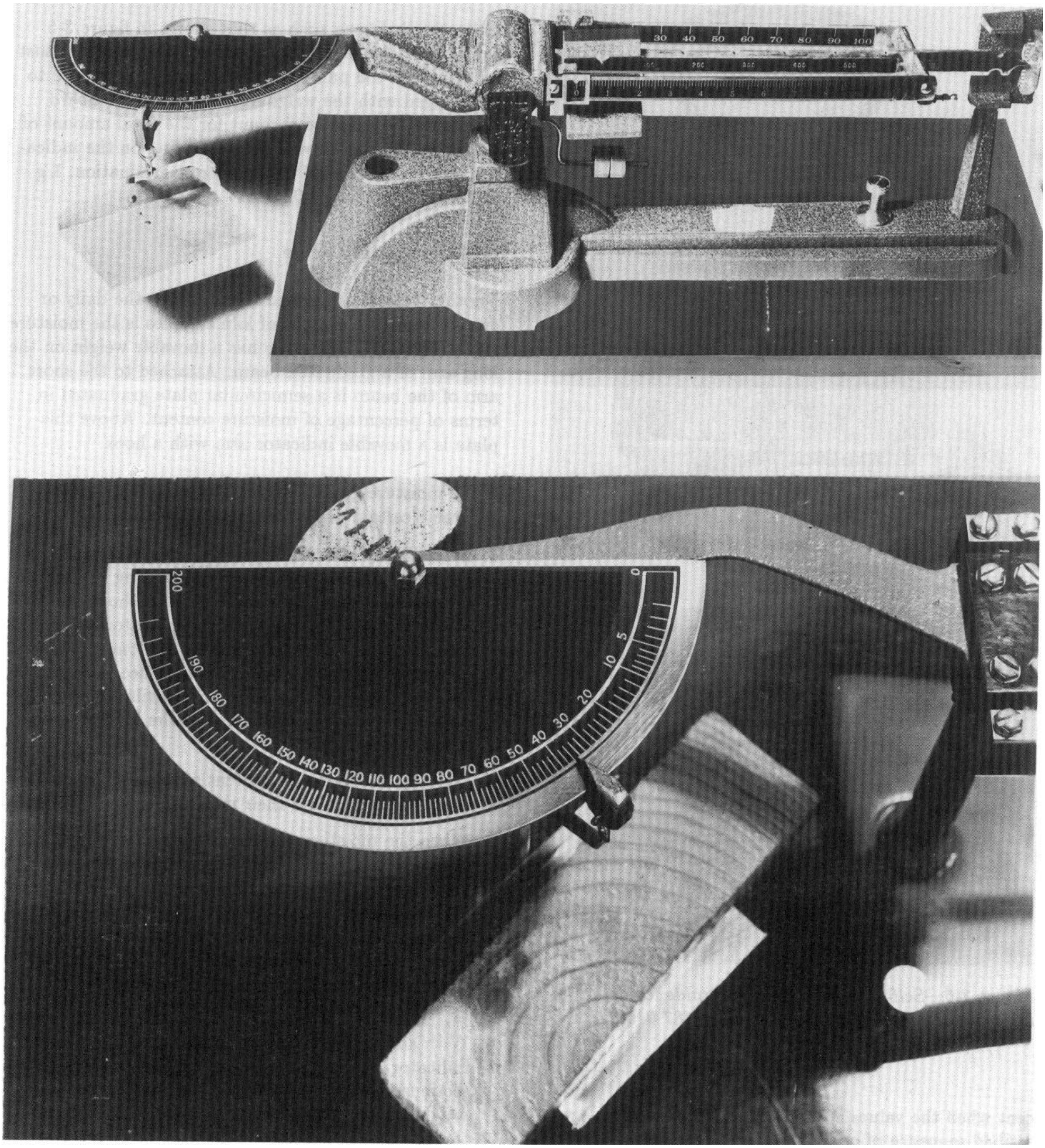


Figure 3-4—*Self-calculating moisture balance. Top: Triple-beam balance with special scale on specimen pan used to calculate moisture content of moisture section after ovendrying. Bottom: Specimen pan is carried on revolving indicator that indicates moisture content directly on scale. (M 90343)*

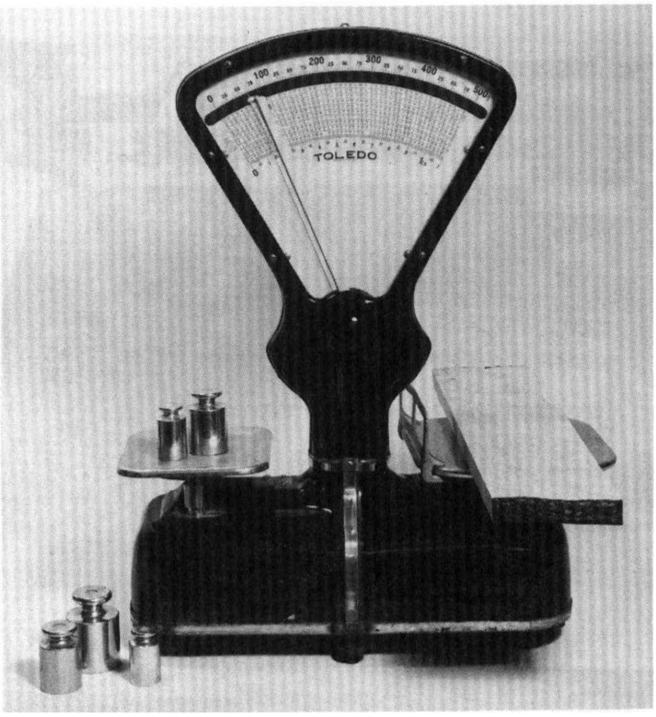


Figure 3-5—*Indicating balance. (M87 0199)*

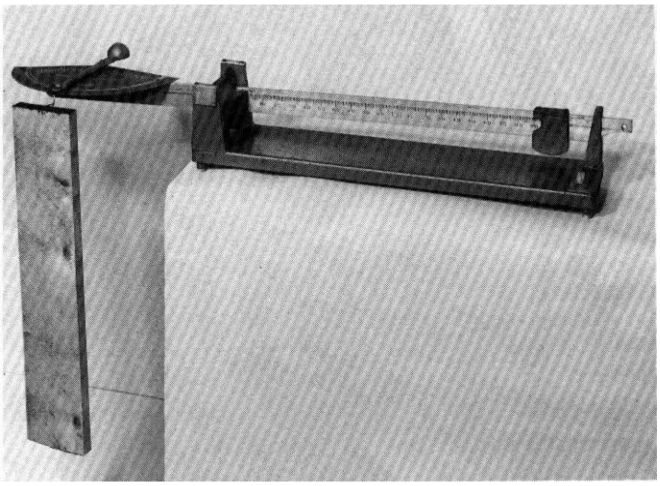


***Figure** 3-6—Self-calculating scale or guide for determining moisture content of kiln sample. (M87 0168)*

cent when the values are more than 10 percent. A prescribed sequence of operating steps, supplied by the manufacturer, must be followed in carrying out a moisture content determination for moisture sections with this balance.

Indicating Balance

Indicating balances such as that shown in figure 3-5 can be used for weighing sample boards. Weights must be placed on the pan on the left side and may need to be changed with the weighing of each sample board. Care must be taken to account for the total amount of weight on the pan as well as the reading on the indicator, which can be read to the nearest graduation, 1 g or, on some models, 0.01 lb.

Self-calculating scale

Another type of scale used to determine the daily or current moisture content of kiln samples is the moisture guide (fig. 3-6). This scale has a movable weight on the long arm of a graduated beam. Attached to the short arm of the beam is a semicircular plate graduated in terms of percentage of moisture content. Above this plate is a movable indicator arm with a hook.

If the moisture guide is to be used with reasonable accuracy, certain procedures must be followed:

1. Immediately after the moisture content sections have been cut and weighed, apply end coating to the kiln sample, and hang the sample from the hook on the movable indicator arm, with the indicator set at zero. Move the sliding weight on the long beam to a point that brings the beam into balance. Record the value of the balancing point on the kiln sample, and place the sample in the kiln with the load of lumber it represents.

2 Ovendry the moisture content sections to constant weight and calculate their moisture content values.

3. When the moisture content of the sections has been obtained, remove the kiln sample board from the kiln, hang it on the movable indicator hook with the indicator set at zero, and move the sliding weight on the long beam to the setting determined in step 1. Then place metal weights, such as washers or lead slugs, on the end of the kiln sample until the long beam balances.

4. With added metal weights in place, set the movable indicator arm to the moisture content value of the sections determined in step 2, and move the sliding weight on the long beam until balance is again obtained. Erase or cross out the previously recorded value on the kiln sample and record the new balance value. This new value will be the setting of the sliding weight on the long beam used for all subsequent moisture determinations.

5. Remove the metal weights from the sample. With the sliding weight set at the new value obtained in step 4, move the indicator arm until the long beam balances. The current moisture content of the kiln sample can then be read on the semicircular plate.

6. Subsequent moisture content values of the samples are obtained by setting the sliding weight on the long beam at the new balance value obtained in step 4, hanging the kiln sample on the movable indicator hook, and moving the indicator arm until the long beam is balanced. The current moisture content is read on the semicircular plate.

Saws

Band, table, radial arm, swing, and portable saws are generally used for cutting moisture sections. Hand saws are not recommended. A band saw is particularly suitable for slotting and slicing small sections for moisture-distribution and casehardening tests. Saws should be sharp, have the proper set, and be provided with suitable safety devices. Saws that are not sharp or have improper set tend to overheat or burn the wood, thereby changing the moisture content of the section.

Drying Ovens

Several kinds of ovens are used for drying moisture sections. Drying ovens should be large enough to provide adequate open spaces between the sections of wood being dried. The temperature of the oven should be controlled with a thermostat or other means so it will stay within the desired setting (212 to 218 °F, 215 ± 3 °F). Excessive temperature will char the sections and may also start fires. Temperatures below 212 °F will not drive off all the water in the sections. The oven should have ventilators on the top or sides and bottom to allow the evaporating moisture to escape.

Electrically Heated Ovens

Electrically heated ovens are commonly used in kiln drying (fig. 3-7). Ovens containing fans to circulate the air and speed up drying are generally recommended, especially if large numbers of moisture sections are dried frequently. Natural draft ovens, those depending on the heat rising to create air circulation, are usually less efficient and require more time to remove all the moisture from the sections. Check the thermostat setting when the oven is empty, using a thermometer inserted in the hole provided in the top of the oven. When wet or moist wood is placed in the oven, the temperature will fall at first and then rise as the wood dries. Do not reset the thermostat higher after placing the wood in the oven or it will be above set point when the wood is dry.

Recently, an increasing number of operators have successfully used home-type microwave ovens to ovendry moisture sections. Considerable care must be used when drying moisture sections in a microwave oven. Although sections can be dried in minutes rather than hours, it is rather easy to overdry the section (burn it in the center) or to underdry the section (not remove all the moisture), resulting in an inaccurate ovendry weight of the moisture section. One procedure suggests using a medium-low to low power setting and an oven with a carousel tray to prevent uneven drying (Wengert 1984). Suggested time for ovendrying is about 10 min for dry pieces and about 20 min or longer for green pieces.

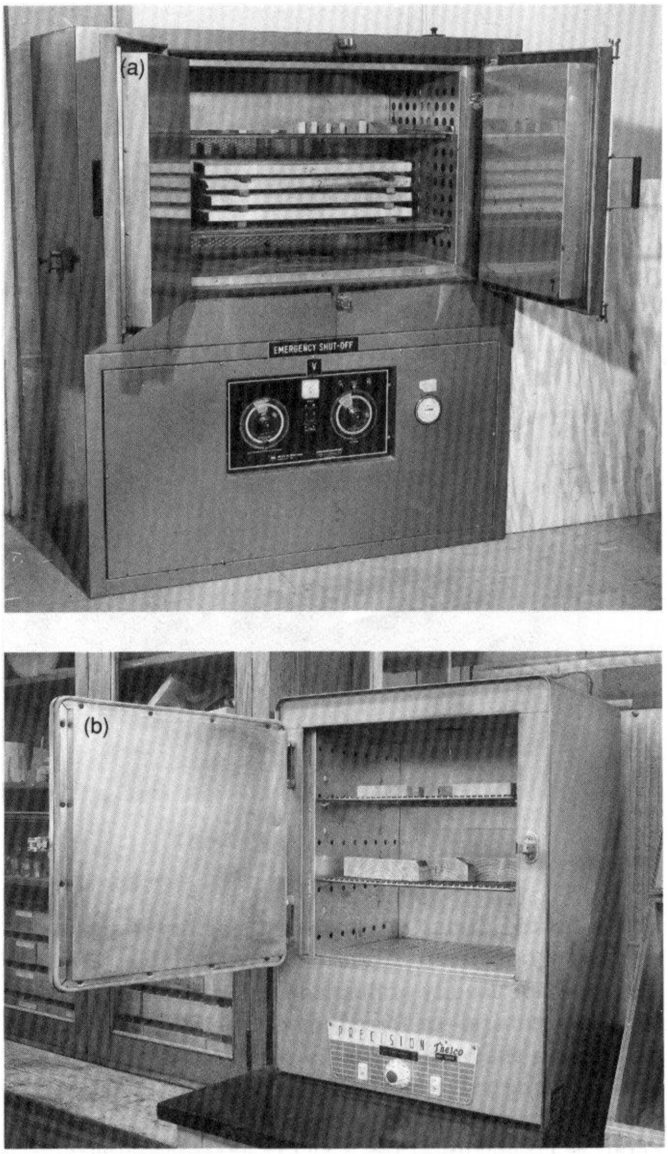
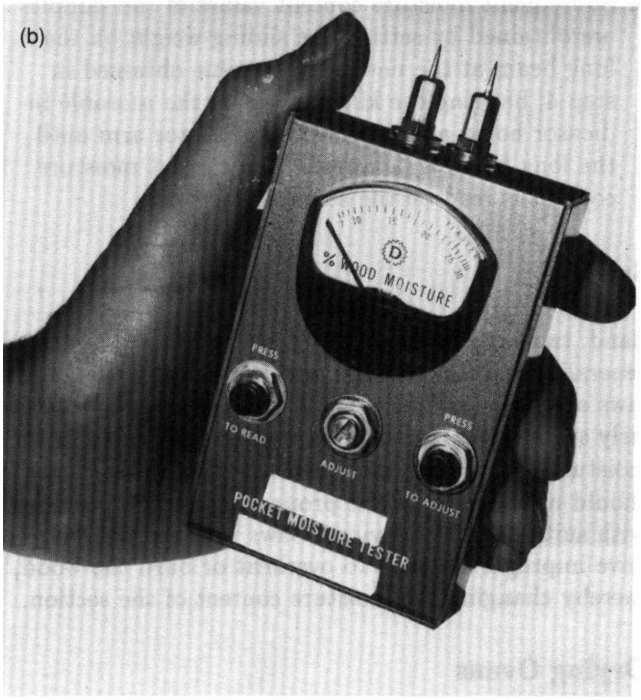


Figure 3-7—Electrically heated ovens for drying moisture sections: (a) large floor model, (b) smaller tabletop model. (M87 0193-1, M87 0193-16)



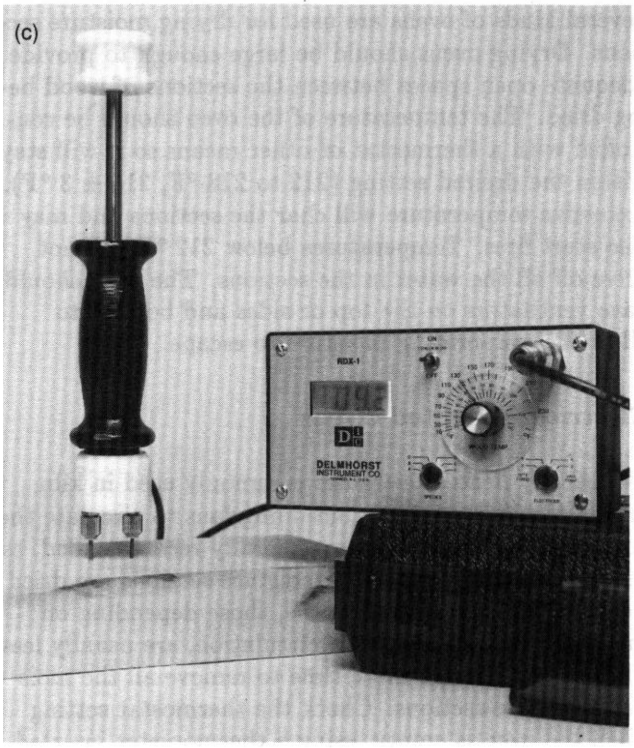


Figure 3-8—*Selected models of resistance-type moisture meters: (a) meter with insulated two-pin electrodes, dial readout; (b) meter with uninsulated two-pin electrodes; (c) meter with insulated two-pin electrodes, digital readout. (MC88 9030, M88 0131-13)*

Steam-Heated Ovens

Steam-heated drying ovens are satisfactory if a suitable supply of steam is continuously available. Ovens of this type are usually homemade and may be equipped for either natural- or forced-air circulation. The temperature in the oven is usually regulated or controlled by a reducing valve on the steam feed line. The reducing valve is adjusted to maintain the desired temperature (typically 215 ± 3 °F) in accordance with a thermometer inserted through the top of the oven. As with the electrically heated oven, set the temperature when the oven is empty, not after the moist wood has been placed in the oven. Shelves for the moisture sections should be made of perforated metal or large mesh, heavy wire. Provide ventilators to remove the moisture-laden air.

Electric Moisture Meters

Electric moisture meters, if properly used, provide a rapid, convenient, and, for most purposes, sufficiently accurate means of determining moisture content when it is less than 30 percent (James 1988). Woods treated with salts for preservation or fire-retardant purposes will generally, give meter readings that are too high, and the use of electric moisture meters to determine moisture content is not recommended. Electric moisture meters are available as portable hand-held units or as stationary units used to monitor moisture content of material moving along conveyor lines. In many situations, temperature and species corrections must be applied for accurate readings; correction data are usually supplied by the manufacturer of the equipment. There are two types of meters commonly available, resistance (or conductance) and dielectric.

Resistance Moisture Meters

The most common type of portable hand-held moisture meter is the resistance-type (also known as conductance-type) meter. Resistance-type meters use pin-type electrodes that penetrate the wood. The useful operating range of most meters of this type is between about 7 and 30 percent. Although some instruments have scales that read above the fiber saturation point (usually taken to be 30 percent moisture content), the accuracy above 30 percent is questionable. Selected models of resistance-type meters are shown in figure 3-8.

When using resistance-type meters on pieces of lumber with rectangular cross sections, pins should be driven one-fourth to one-fifth of the thickness of the piece to indicate an average moisture content. For circular cross sections, the depth of the pins should be one-sixth of the diameter. For the most accurate readings, orient pins so that the current flows parallel to the grain, with pins driven in the wider face of the piece. Pins driven parallel to the grain in the narrow face of the piece will give acceptable readings when ready access to the wide face is not convenient. If readings drift, take the reading immediately after the electrode is driven into the specimen. Actual moisture readings (subject to temperature and species correction) appear on the meter dial or readout.

Two-pin electrodes are quite commonly used with lumber, posts, or poles. Electrodes using l-in-long insulated pins are the type most commonly used (fig. 3-8a,c). Insulated pins are helpful in avoiding false readings if wood has been surface wetted with rain, snow, or dew. Also, by using pins that are insulated except at the tip, some indication of moisture content gradient can be determined as the pins are driven to differing depths in the wood. To get an estimate of the average moisture content of a pole or heavy timbers, extra long pins (2-1/2 in) are available. Short (5/16 in) uninsulated pins are used on models such as shown in figure 3-8b, and when inserted to the proper depth, these pins give accurate average moisture contents for stock up to 2 in thick.

Four-pin electrodes are more commonly used with veneer and sawn lumber less than 1 in. in thickness. As with two-pin electrodes, accurate readings can be obtained on stock up to 2 in thick using short (5/16 in) uninsulated pins.

Dielectric Power Loss Moisture Meters

A hand-held moisture meter of the dielectric power loss type is shown in figure 3-9. The surface-contact electrodes are nonpenetrating and may vary in design according to the material on which they are to be used.

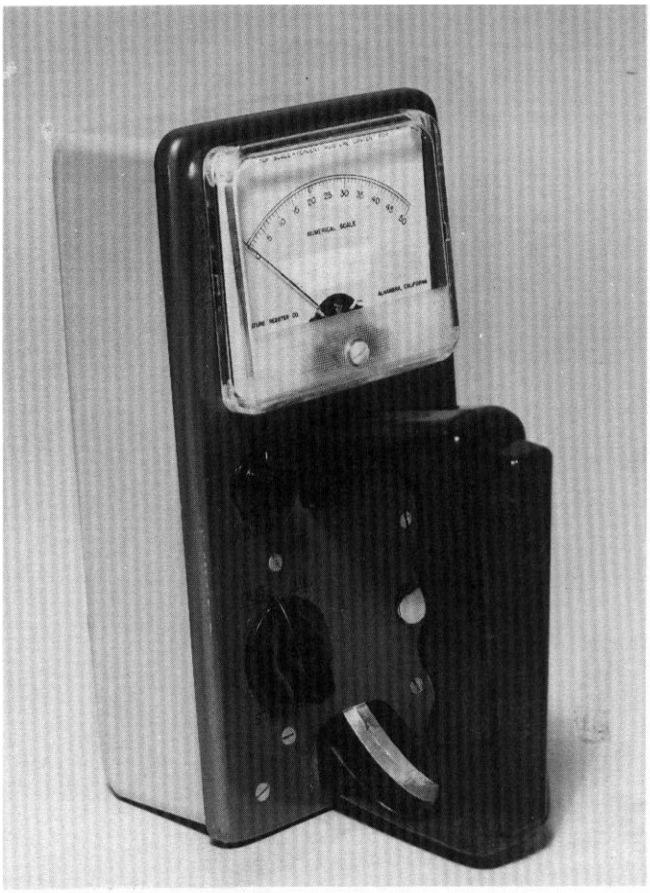


Figure 3-9—*A radiofrequency power loss type electric moisture meter. (M 133689)*

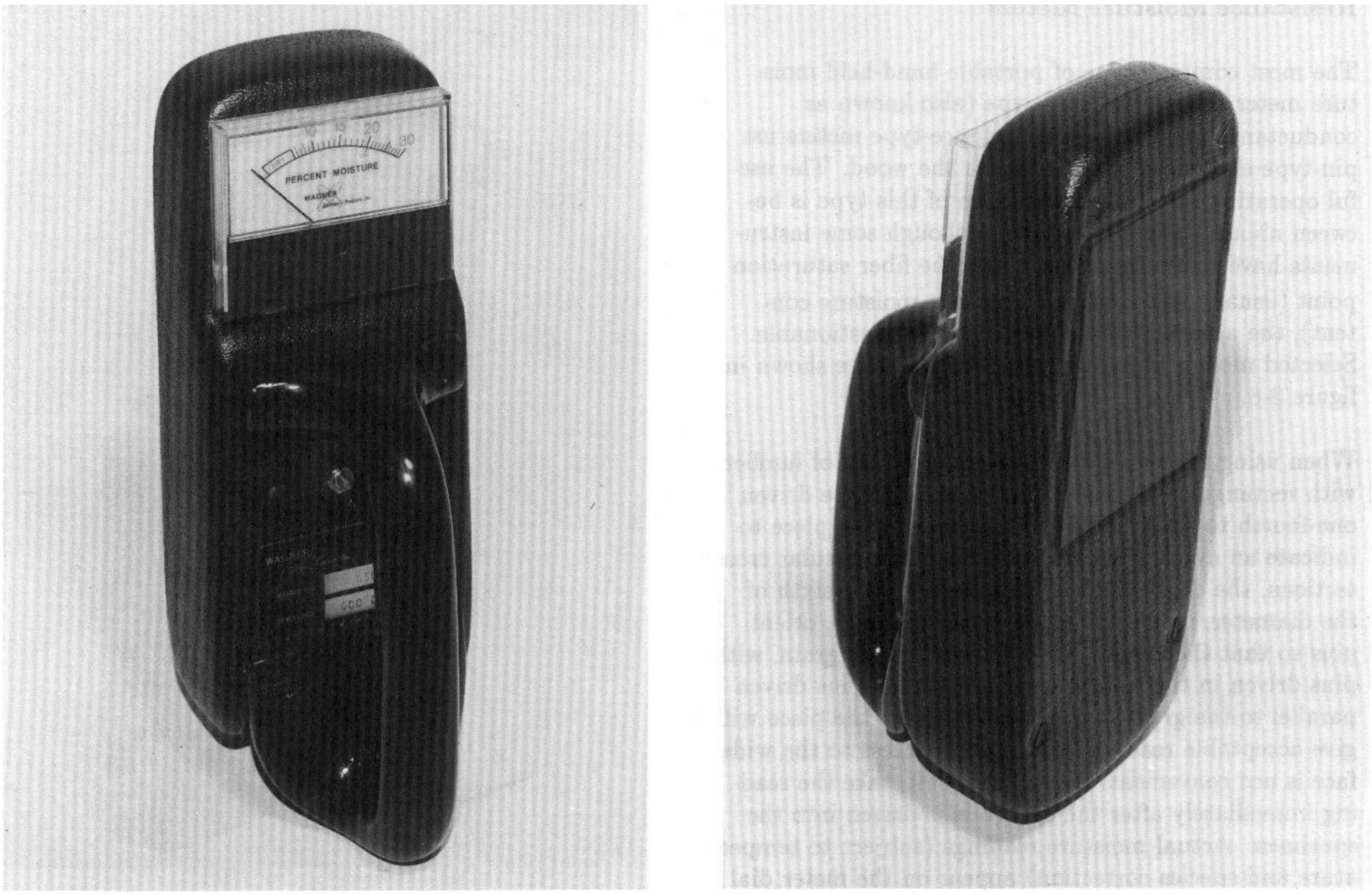


Figure 3-10—*A dielectric electric moisture meter with smooth surface electrode. (M88 0239, M88 0238)*

The instrument shown has eight spring-cushioned contact points equally spaced on the circumference of a circle. This design is for use primarily on rough lumber. The electric field from this electrode penetrates about 3/4 in, so that specimen thicknesses up to about 1-1/2 in may be read. With surface-contact electrodes, the surface layers of the specimen have a predominant effect on the meter readings. Other electrode configurations are used for surfaced lumber and veneer. An example of a smooth surface electrode is shown in figure 3-10.

The range of these power-loss meters is from 0 to about 30 percent moisture content. Some manufacturers offer meters where actual moisture content is read on the dial. For others, the actual moisture content value is not read directly from the dial, but must be equated with moisture content from a separate table.

Stationary meter systems using noncontact sensors are available to monitor moisture content of moving lumber on a dry chain (fig. 3-11) or at the outfeed from a planer. Such systems can be equipped to mark or eject, or both, individual pieces that are outside preset moisture specifications. Some equipment offers a summary printout showing such items as total piece count, average moisture content of all pieces, and distribution of moisture content at specified moisture content intervals

Distillation Equipment

Some woods contain a high percentage of volatile compounds or are impregnated with oily preservatives. The volatiles will be driven off in the ovendrying process, resulting in an incorrect moisture content value. Distillation equipment should be used for determining the moisture content of such woods (American Society for Testing and Materials 1986).

Equipment for Determining Temperatures

Checking temperatures in a dry kiln is frequently necessary to determine the causes for nonuniform drying and the differences in temperature between the areas around the control bulbs and other areas in the kiln. Occasionally, it may be desirable to verify that the temperature indicated by the sensor for the recorder-controller is an accurate value. These temperature measurements are usually made on the entering-air side

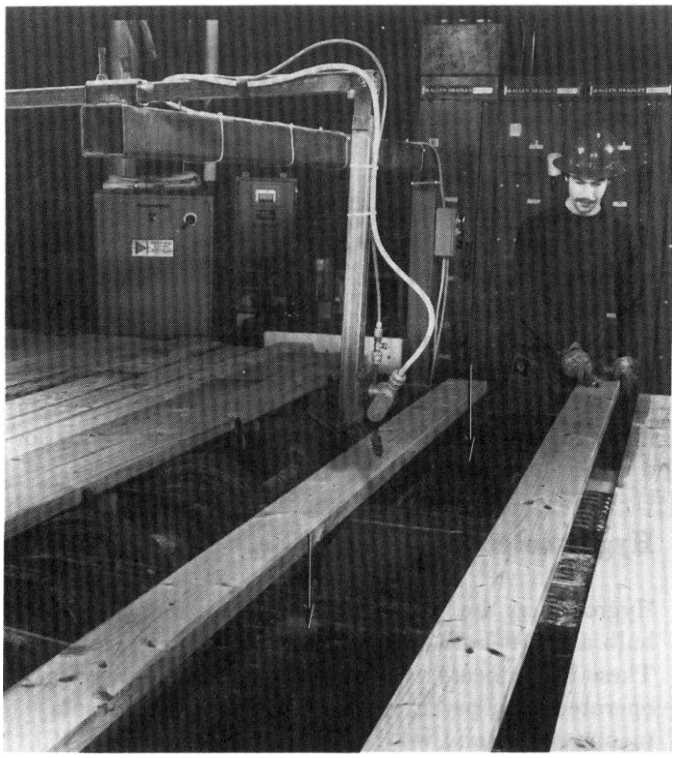


Figure 3-11—Stationary inline moisture meter located on dry chain. Arrows show location of noncontact sensors. Note spray nozzle for marking pieces beyond preset limits. (MC88 9035)

of the loads, although at times leaving-air temperatures are simultaneously obtained so that the temperature drop across the load can be determined. Electric digital thermometers, etched-stem glass thermometers, and occasionally hygrometers are used for this purpose.

Electric Digital Thermometers

Electric digital thermometers, using either thermocouples or resistance temperature detectors (RTD) as sensors or probes, are rapidly becoming a common way of measuring temperatures in dry kilns. They are available as portable hand-held models (fig. 3-12), or as panel or bench-top models, which can be mounted in the control room (fig. 3-13). For those designs using thermocouple sensors, type **T** (copper—constantan) thermocouple wire is commonly used in dry kiln environments, although type **J** (iron—constantan) or type **K** (chromel—alumel) is sometimes used. Thermocouple connections at the sensor should be soldered or fused together to make the junction. Some commercially prepared thermocouple sensors are enclosed in a metal sheath and look somewhat like RTD sensors. Resistance temperature detectors are usually of the platinum type, with all leads enclosed in a metal sheath (fig. 3-14).

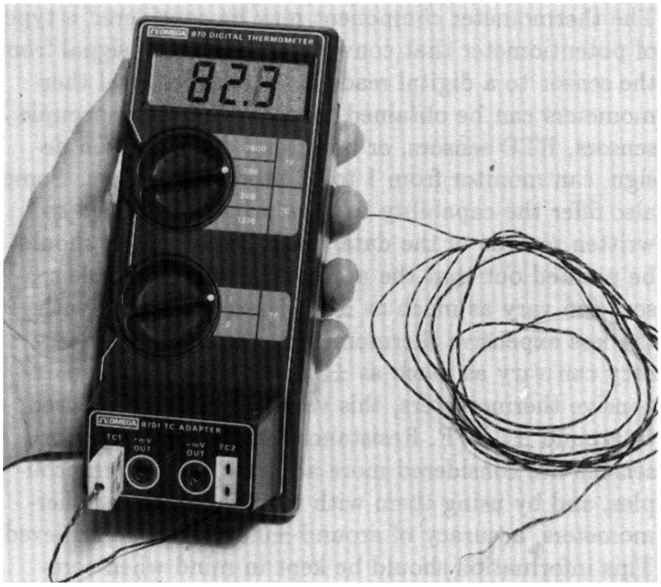


Figure 3-12—Hand-held digital thermometer *(M87 0171)*

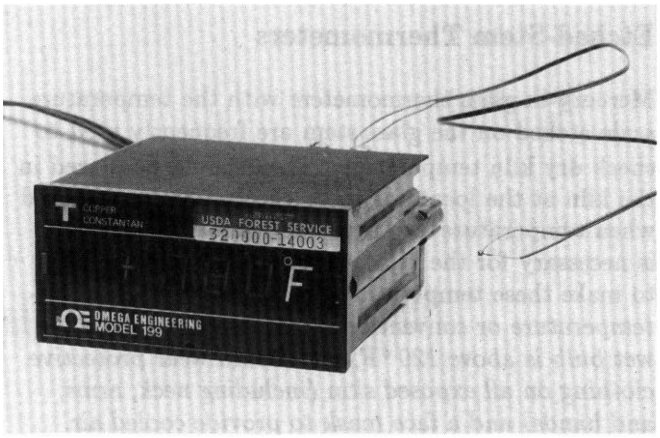


Figure 3-13*—Panel-mounted digital thermometer (M87 0197)*

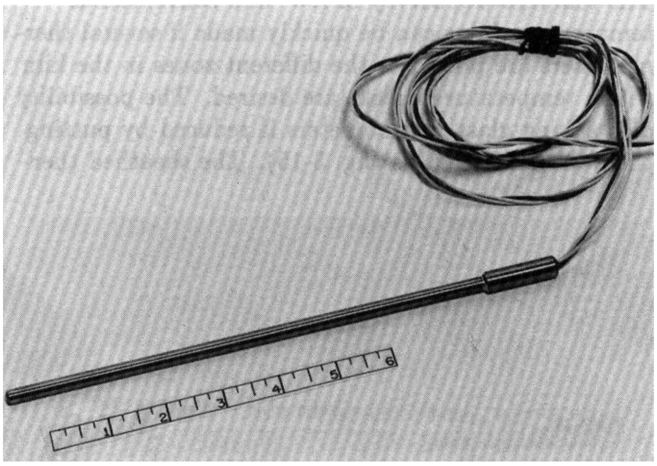


Figure 3-14*—Resistance temperature detector (RTD) sensor. (M87 0167)*

The thermometer component may be considered a type of potentiometer that converts the electrical signal from the sensor to a digital readout. These electrical thermometers can be obtained to work with thermocouple sensors, RTD sensors, or both, and depending on design, can monitor from 1 to 12 probes or sensors. Some also offer the capability to have printers attached so written records of the data can be obtained. It should be pointed out that the accuracy of thermocouple sensors can vary as much as ±2 °F and when used with the less expensive thermometers, the combined accuracy can vary as much as ±3.6 °F. By using more expensive thermometers, this variability can be reduced to around ±1.5 °F. Resistance temperature detector sensors are considered more accurate than thermocouples, and by using them with moderately priced thermometers, accuracy of around ±0.6 °F can be achieved. This information should be kept in mind when comparing temperature values from sensors located in the same area of the kiln or when comparing thermocouple readings to readings from the recorder-controller.

Etched-Stem Thermometers

Mercury-in-glass thermometers with the temperature scale etched on the glass stem are frequently used to check dry kiln temperature. They should be placed in the kiln at the locations to be checked and not moved when temperature readings are taken. Obviously, it is necessary for the kiln operator to go into the kiln to make these temperature readings. Note: In a low-temperature or conventional-temperature kiln, if the wet bulb is above 120 °F, one should wear protective clothing on all exposed skin (including neck, arms, and hands) and a face mask to provide cooled air. It is not recommended that elevated-temperature or high-temperature kilns be entered while the kilns are running.

The temperature survey of low- and conventional-temperature kilns can be quickly made if several thermometers are placed at the different zones in the kiln where temperature checks are desired. The possibility of breaking glass thermometers is reduced by putting them in metal sheaths (fig. 3-15). The sheathed thermometer is suitable for making dry-bulb measurements, but if wet-bulb temperatures are also being measured, the sheath must be removed so that a wick can be applied directly over the mercury bulb of the thermometer.

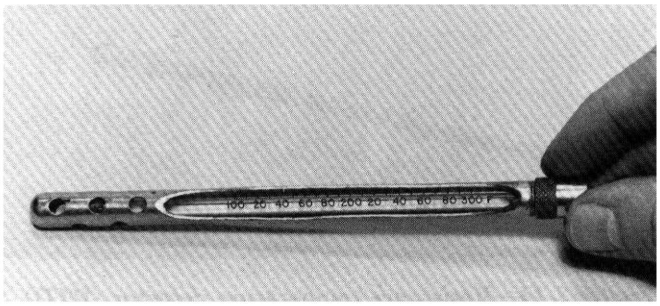


Figure 3-15—Etched-stem glass thermometer in metal protecting case. (M87 0195)

Maximum thermometers are also used for checking kiln temperatures. By mounting two maximum thermometers on a frame and supplying one with a wick and a water supply, both the maximum wet- and dry-bulb readings can be obtained. Care should be taken in choosing the location in the kiln for the thermometers as they will read the hottest temperature sensed, even for very brief periods, and thus there is a tendency for a biased high reading.

Hygrometers

Hygrometers are instruments for measuring the dry-bulb and wet-bulb temperatures of circulated air. These instruments vary from the hand-held and hand-operated sling psychrometer (fig. 3-16) to stationary mounted dry- and wet-bulb thermometers (fig. 3-17). Instruments that directly read relative humidity may also be considered hygrometers.

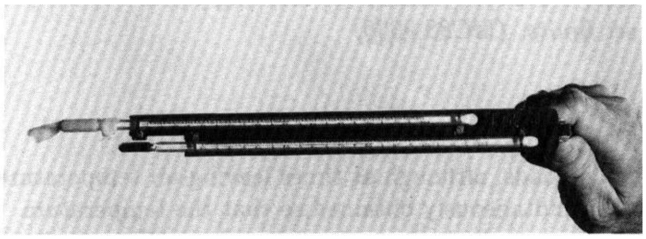


Figure 3-16—Sling psychrometer for determining relative humidity. (M87 0196)

Hygrometers similar to that shown in figure 3-18 are sometimes used to check kiln temperatures. Such hygrometers may use etched-stem thermometers or those with the calibrations on adjacent metal strips. One bulb must be continuously supplied with water to get wet-bulb readings. Using these data with the psychrometric chart in the appendix to chapter 1, equilibrium moisture content and relative humidity values can be determined. Sling psychrometers are helpful in spot checking wet- and dry-bulb temperatures (thereby determining relative humidity and electric moisture content) in a dry kiln or storage area. Hygrothermographs are instruments that measure and record temperature and relative humidity. They are helpful in providing a continuous written record of conditions in storage sheds or other areas where the temperature does not exceed about 120 °F (fig. 3-19).

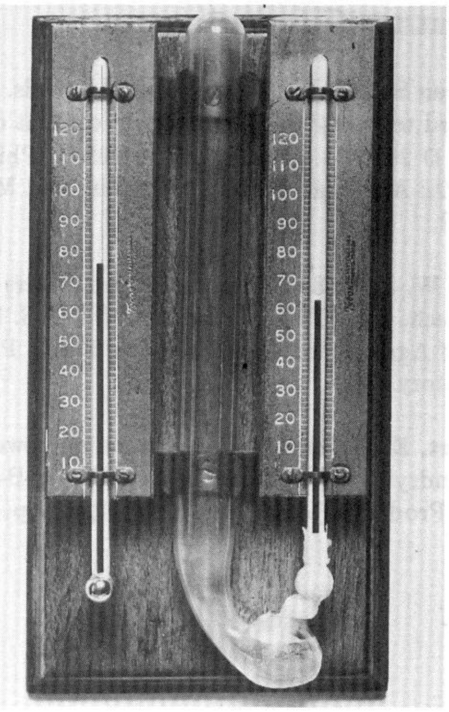


Figure 3-17*—Stationary mounted dry- and wet-bulb thermometers. (M 137003)*

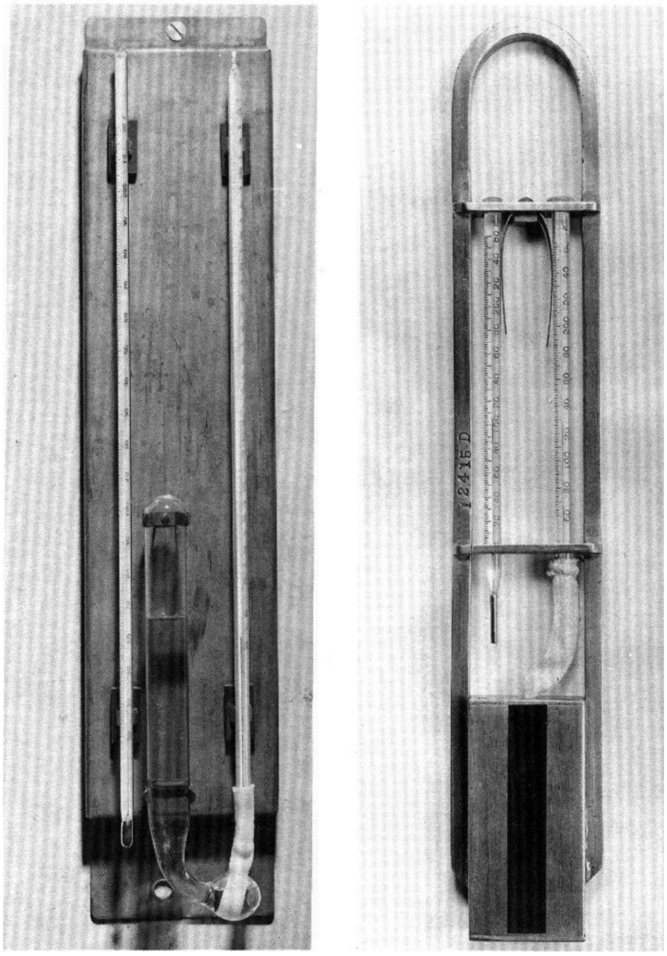


Figure 3-18*—Hygrometers: left, wet- and dry-bulb hygrometer made from two etched-stem glass thermometers; right, wet- and dry-bulb hygrometer with maximum thermometer. (M 86250, M 90337)*

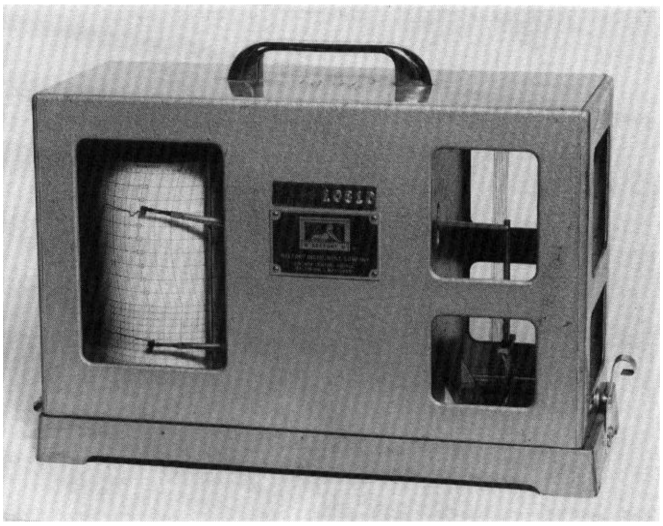


Figure 3-19*—Hygrothermograph for measuring and recording temperature and relative humidity (M87 0172)*

Equipment for Determining Air Movement

Since the direction and rate of airflow are important in the operation of a dry kiln, means of determining these factors are necessary. Rate of airflow may be measured with anemometers and the direction of flow may be inferred from these measurements.

Anemometers are instruments for measuring the velocity or force of air. Several types of anemometers, also called air meters, can be used to determine the velocity of air in dry kilns. One commonly used type is called a hot-wire or thermal anemometer (fig. 3-20). The wire in the probe is heated by electricity from a battery in the unit. The amount of cooling of the hot wire is proportional to the velocity of the air passing over the wire. Velocities are indicated directly on a scale calibrated in feet per minute.

In another commonly used type of anemometer, the air enters the instrument through a port or shutter, and velocity is read directly in feet per minute on a calibrated dial. This type, known as a deflection anemometer, is shown in figure 3-21.

Another type of anemometer occasionally used in dry kilns is the rotating vane anemometer. The sensor of this instrument is a disk fan mounted on pivot bearings and provided with a revolution counter. Air velocities, in feet per minute, are read directly on a dial or in some models on a digital readout.

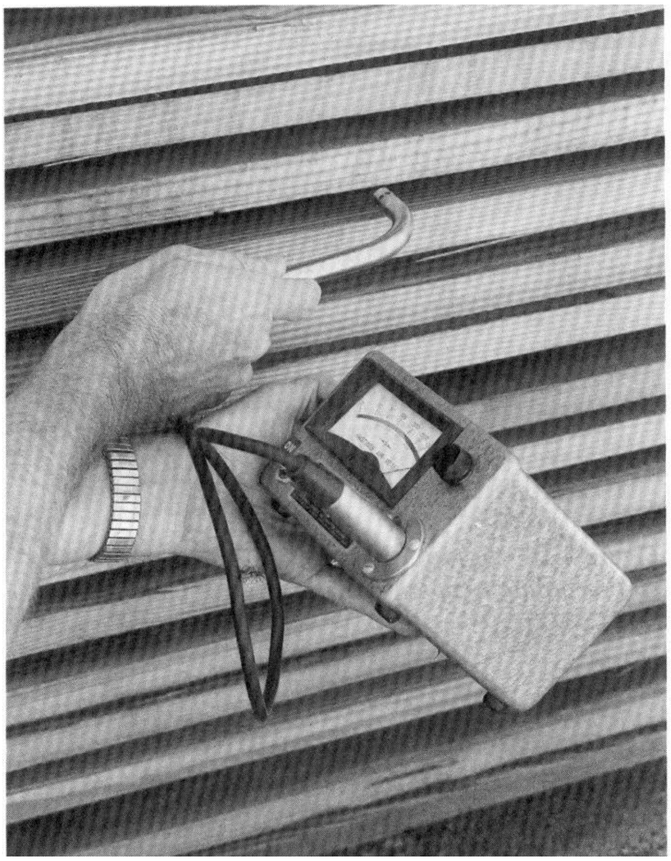


Figure 3-20—*Hot-wire air meter. (M87 0194-18)*

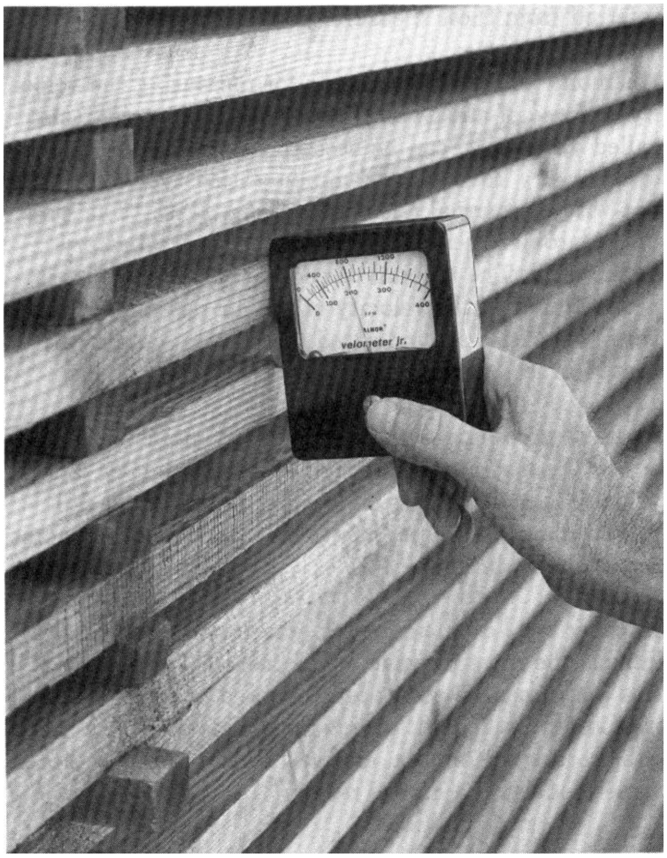


Figure 3-21—*Deflection anemometer. A type of air velocity meter. (M87 0194-13)*

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Chapter 4
Inspection and Maintenance of Dry Kilns and Equipment

Chapter 4 was revised by R. Sidney Boone, Research Forest Products Technologist, and William T. Simpson, Supervisory Research Forest Products Technologist.

Adequate kiln maintenance is as essential to efficient dry kiln operation as good design and construction. Adequate maintenance can be accomplished only through regular, frequent inspections of the kiln and auxiliary equipment. If inspections reveal the need for repairs or replacements, they should be made as soon as possible to avoid drying problems.

Regular, systematic inspections should cover such items as the kiln structure; doors; floor; tracks; control equipment; heating, spraying, and venting system; trucks; lumber-handling equipment; and general housekeeping. To make sure that inspections are thorough, the operator should note the condition of the kiln structure and the equipment on a checklist. The checklist at the end of this chapter can be made to fit any specific kiln installation.

Kiln Structure

Dry kilns are required to withstand much harsher conditions than those conditions that ordinary buildings are subjected to, regardless of the materials used in construction. Kilns must withstand not only extreme external weather conditions but also even more extreme internal conditions. Relative humidity can vary from 5 to 95 percent, and temperatures can change from -20 °F (ambient) to 250 °F during operation of a high-temperature kiln. In addition, vapors that arise from the woods being dried are often corrosive. Structural components of the kiln and the internal protective coatings must be capable of withstanding this broad range of operating environments.

Walls, Roofs, and Ceilings

The majority of today's commercially built steam-heated or direct-fired dry kilns are made of either (1) prefabricated aluminum panels on a steel or aluminum structural frame or (2) masonry, primarily concrete block or light-weight aggregate block and sometimes precast concrete. Although aluminum prefabricated kilns require a larger capital investment, the amount of maintenance required is considerably less than that required by a concrete block structure.

Prefabricated Aluminum Panels

The prefabricated aluminum panel for walls and roofs of dry kilns was developed in the mid-1950's, and by 1960 it had received rather widespread acceptance. Early designs used the type of insulation board then in common use in residential and commercial buildings. Later designs used fiberglass insulation, and more recent designs use a rigid foam insulation. The design and construction of panels for walls, roofs, and doors are frequently the same, although in some cases panels for roofs are thicker and have more insulation. The aluminum panels generally are not affected by the expansion and contraction that occurs in a kiln cycle, even those cycles in which dry-bulb temperatures go as high as 250 to 300 °F. At operating temperatures above about 215 °F, some manufacturers prefer fiberglass insulation; others prefer rigid foam insulation in the aluminum panels.

Insulation values for aluminum panel kilns range from an R value of about 16 for 2-in-thick panels to about 32 for 4-in-thick panels. In contrast, concrete block kilns have R values ranging from only 1 to 3, depending on thickness, type of aggregate, and whether or not the cores are filled with insulation. A wood-frame wall will have an R value of 4 to 5 when the stud space is not filled with insulation and a value of about 12 when filled with insulation.

Maintenance of aluminum panels usually requires only ensuring that moisture does not get past the skins and wet the insulation, reducing its value. This means repairing (sealing) any holes or tears in the skins as soon as they are noticed. Care should also be taken to repair any separation between the aluminum skin and the metal frame around each panel. Moisture can enter the interior of the panel and wet the insulation through this avenue as well as through holes in the skins. Weep holes are usually put in the bottom of the panels for draining water that may build up in the panel, but the weep holes must be kept open and free from sawdust or dirt.

Steel components of a dry kiln must be protected from water vapor as well as corrosive vapors that are emitted from certain woods during drying, such as oak and hemlock. This is commonly done by painting or spraying a vapor- and corrosion-resistant paint or coating on the steel members. Recoating is usually necessary every 2 to 5 years. Suitable coatings can be obtained from dry kiln manufacturers.

Masonry

Masonry kilns may develop cracks from expansion and contraction caused by temperature changes inside the kiln during the drying run. This problem is sometimes exaggerated by a large temperature difference between the inside and outside environments. Most concrete, including concrete blocks, is rather porous and can adsorb large quantities of water vapor from the kiln atmosphere. If cracks are not sealed when small, they will increase in size, which leads to excessive heat and vapor losses and premature failure of the entire structure. Large cracks may also cause cold zones in the kiln that slow up drying and permit mold and stains to develop on the lumber located in those zones.

Proper maintenance of concrete kilns or concrete parts of a kiln consists of prompt recognition and repair of problem areas. Some good maintenance practices for concrete kiln structures are as follows:

1. For all kilns constructed of masonry or wood (or lined with plywood), coat the inside surfaces with a vapor- and corrosion-resistant material before the kiln is used and whenever required thereafter. Usually recoating is necessary every 2 to 5 years. Suitable coatings can be obtained from dry kiln manufacturers or other knowledgeable suppliers. Never put vapor-resistant coatings on the exterior surfaces of masonry or wooden dry kilns, though a water-repellent coating can be applied if desired.
2. As soon as possible, seal cracks that develop in the structure as a result of repeated expansion and contraction of the building material. If the cracks are small, a coating of kiln paint may be sufficient, but larger cracks should be filled with mastic, mortar, or cement. Coat the mortar or cement fillers with a kiln paint after they have set.
3. Cracks that develop because of settling of the structure can be temporarily repaired in the same manner as expansion and contraction cracks. To reduce future maintenance costs, however, determine the cause of the settling and correct it as soon as possible.
4. Openings in the kiln structure for steam lines, tubing, fan shafts, and the like should be as small as possible. Insert sleeves in the openings and plug the space not occupied by pipe with epoxy or silicone compounds or some similar material.
5. Promptly caulk with a nonhardening filler any open joints and splits that occur in wood or plywood dry kilns. Refasten all loosened boards as soon as possible.
6. Use noncorrosive metal fastenings if possible.
7. Immediately repair or replace failed supporting members of the structure

Steel components of a dry kiln must be protected from water vapor as well as corrosive vapors that are emitted from certain woods during drying, such as oak and hemlock. This is commonly done by painting or spraying a vapor- and corrosion-resistant paint or coating on the steel members. Recoating is usually necessary every 2 to 5 years. Suitable coatings can be obtained from dry kiln manufacturers.

Doors

Doors are frequently the weakest and most troublesome part of a kiln structure. They are often damaged when they are opened or closed carelessly, when a forklift operator does not pay attention when loading or unloading the kiln, or when an improperly blocked truckload of lumber in a track-loaded kiln rolls into the doors. The common use of prefabricated aluminum doors, on both aluminum prefabricated kilns and masonry kilns, has solved many of the problems associated with doors on the dry kilns of the 1930's, 1940's, and 1950's. During that time, it was difficult to design and build a large door that was strong, lightweight, easy to handle, well insulated, and resistant to corrosion.

Doors, door hangers, stops, rollers, roller tracks, and gaskets that are poorly maintained cause excessive losses of heat and vapor and are difficult to open and close. Lower temperatures occur near damaged or poorly fitted doors because of cold air infiltration, and drying is slower in that zone. In high-temperature kilns, large amounts of condensate form on the framework near the doors when they are opened at the completion of the kiln run. Steel members should be adequately protected to prevent excessive corrosion and rust. Neglect of doors and door equipment may also create a hazard to workers. Some good maintenance practices for door and door equipment are as follows:

1. Immediately repair or replace damaged door hangers, rollers, and roller tracks.
2. Lubricate parts in accordance with the manufacturer's recommendations.
3. Repair or replace torn or missing gasket material or gaskets that no longer provide an adequate seal.
4. Instruct or warn lift truck operators to be alert to minimizing damage to doors (also to walls and baffles) when loading or unloading the kiln.
5. In package-loaded kilns, ensure that piles are stable and will not tip over into doors or walls.
6. In track-loaded kilns, block wheels of standing loaded kiln trucks, so that the trucks cannot roll into the kiln door.

Floors

The floors of most commercial dry kilns are constructed of concrete. In some small kilns, usually operated on a part-time basis and perhaps home designed, the floor may be crushed stone, lumber, or even dirt or sand. All types of floors require maintenance.

Good maintenance practices for kiln floors include the following:

1. Provide a waterproofing treatment on new concrete floors to prevent spalling or scaling. Treat again when necessary.
2. Repair and seal cracks in concrete floors that develop because of settling or expansion and contraction of the concrete.
3. For stone, dirt, or sand floors, maintain an even floor level, filling holes and leveling as needed.
4. Provide proper drainage of site so that rain and surface runoff do not flood kiln floor.

Rails and Rail Supports

Generally, rails and rail supports in kilns with fans or blowers located above or on the sides of the drying compartment are not troublesome, since the rails are usually well supported and anchored. Weak rails or rail supports in old converted natural-circulation kilns and in older design forced-circulation kilns, where the fans or the air-supply ducts are located below track level, may collapse or spread under heavy loads. Failure of the rails or rail fastenings can seriously damage kiln equipment, injure workers, and result in lost drying time.

Good maintenance practices for rails and rail supports include the following:

1. Immediately replace or tighten broken or loose rail fastenings.
2. Promptly realign spread rails and securely fasten them to the rail supports.
3. Leave a break in the rails under the doors to minimize rail corrosion caused by condensate dripping from the doors.
4. As needed, apply corrosion-resistant paints to the rails, metal rail supports, and rail fastenings.

Recording–Controlling Instruments

Accurate control of both the dry- and wet-bulb temperature (or dry-bulb and relative humidity) is essential for efficient kiln operation. The most common and the best method of control is the use of semiautomatic or fully automatic recording-controlling instruments. (See Equipment to Control Drying Conditions section in ch. 2 for a detailed description of control instruments.) Although these instruments are usually efficient, they are at times troublesome. Some problems are associated with improper location of the sensors or bulbs. Once sensors and bulbs are properly located, problems may arise from improper calibration, faulty flow of water to the wet-bulb pan, and dirty wet-bulb wicks. The efficiency of air-operated instruments may be seriously impaired by oil, water, and dirt in the compressed air. Approximately 25 percent of pneumatic instrument failures can be attributed to a contaminated air supply.

Proper Location of Control Sensors or Bulbs

Dry-Bulb Sensors

To accurately sense temperature, the sensor must be mounted in the main airstream flowing in the plenum. It cannot be too close to the wall or to the load of lumber. Care must also be taken not to place the sensors and capillary tubes too close to steam pipes or other sources of heat that may give false readings. The traditional approach has been to have at least two dry-bulb sensors and one wet-bulb sensor in a kiln. Longer kilns usually have four dry-bulb sensors and one wet-bulb sensor. This is known as a dual end control system; one set of dry-bulb sensors is located about one-fourth to one-third the length of the kiln from one end and the other set, one-fourth to one-third the distance from the other end. The dry-bulb sensors are mounted on opposite walls of the kiln and are hooked up such that the bulb on the entering-air (hottest) side of the load provides the signal that is sent to the instrument. When the airflow is reversed by the fans, the bulb on the opposite side of the kiln becomes the controlling bulb. Dry bulbs that are improperly located may result in very high temperatures that increase drying losses or in very low temperatures that prolong drying time and result in mold and stain.

Although it is common to locate one of the dry-bulb sensors near the wet-bulb sensor, never locate the dry-bulb sensor below the wet-bulb sensor. If the wet-bulb water reservoir overflows, or if liquid water falls on the dry-bulb sensor, it will be cooled and will thus sense a temperature that is lower than the actual temperature. This false lower temperature causes the heat valves to open, resulting in kiln overheating and the potential for degrade. Using brackets furnished by the kiln manufacturers and following the instructions for installation should ensure satisfactory readings from the sensors.

Wet-Bulb Sensors

The wet-bulb sensor must be located so that air circulates around it at all times. Experience suggests that air speeds as low as 150 ft/min are satisfactory, but more reliable readings are obtained at air speeds of 300 to 600 ft/min or higher. Only one wet-bulb sensor is located in each kiln because the wet-bulb temperature is essentially the same throughout the kiln and is not as variable as the dry-bulb temperature. The wet-bulb sensor should be located about the middle of the kiln lengthwise and at a height above the floor that allows convenient inspection of wick and water level. Improper location and care of the wet-bulb sensor result in poor control of the wet-bulb temperature. When the kiln is operating, the wick must be kept wet by a constant supply of clean water to the water pan or reservoir. A dry or partially dry wick will result in an actual wet-bulb temperature *in* the kiln lower than that recorded or indicated on the instrument. The instrument then signals the vents to open in an effort to reduce humidity. Therefore, occasional cleaning of the water reservoir and flushing of the supply line are recommended. The flow of water to the water reservoir is usually controlled by a needle valve, which needs to be regulated from time to time. If the flow of water is too rapid, its temperature may be too low when it reaches the bulb, and the thermometer can give a false reading.

In some steam-heated kilns, condensate from the drain end of the coils is used to supply water to the wet-bulb wick. The condensate is piped from the drain line through a coiled copper tube for cooling and then piped to the water reservoir. In using this system, care must be taken to assure that the water is adequately cooled, for water that is too hot will also give false readings.

The wet-bulb sensor itself should never, under any circumstances, touch the water in the reservoir nor should water drip directly on the sensor.

The water reservoir should be equipped with an overflow line that has its discharge end outside the kiln, and the water supply should be regulated so that the discharge is a very slow drip, not a steady flow. The overflow line must be kept open to prevent water spilling over the top of the pan into the kiln. If the kiln is shut down for a day or more, shut off the water supply; if the temperature in the kiln is likely to drop below freezing during this time, drain the water lines and water reservoir. After a shutdown, the wick should be replaced when the kiln is restarted.

A dirty or badly encrusted wick affects wet-bulb control. The wet-bulb wick should be made of highly absorbent cloth. Replace the wick frequently with a new or laundered one whenever the kiln is loaded with a new charge of lumber or more frequently if necessary.

The wet-bulb sensor in a gas-filled or liquid-vapor system is frequently plated to minimize corrosion. When changing the wick, check the bulb for pitting or other surface deterioration. When necessary, have the bulb replated or replaced by the instrument manufacturer.

Because of the cooling effect of evaporation, the wet-bulb temperature in a dry kiln is usually lower than the dry-bulb temperature; at no time can it be higher. If the reading is higher, the instrument is out of calibration.

Equilibrium Moisture Content and Relative Humidity Sensors

Some recorder-controllers and some drying systems use sensors that tense equilibrium moisture content or relative humidity directly, rather than indirectly through wet-bulb thermometry. While the manufacturer's instructions should be followed to the letter, the same general principles for locating dry-bulb sensors apply to wet-bulb sensors.

Care of Recording–Controlling Instruments

The period of reliable performance of control instruments can be greatly increased by proper care. The parts of a recorder-controller are precision built and can be easily damaged. However, they are well protected against injury and dust, and they will give troublefree service for many years if the case is not left open too long at a time. Replace broken cover glass immediately. Never use compressed air, brushes, or cloth to clean off dust that may settle within the instrument case.

Generally, repairs of gas-filled or liquid-vapor systems should not be attempted in the field. Instrument repair and cleaning require special tools, skills, and equipment. Such work should be done at the manufacturer's plant or by an authorized serviceperson.

The only part of the control instrument that requires lubrication is the clock, and this should not be done too frequently. Never lubricate the pivot points on the linkage arms.

The compressed air flowing into an air-operated instrument must be free of oil and moisture. The quality of the compressed air is very important. For this reason, the air is passed through a filter dripwell or trap before entering the instrument. The trapped oil or moisture is blown from the dripwell or trap at least once daily by opening a blowoff valve. Usually the elements in filters must be replaced once a year or more frequently if they become discolored.

Repairs to electronic or computerized recorder-controllers should be made only by an experienced technician or authorized serviceperson. The skills and tools needed are different from those used in gas-filled systems. For those instruments controlling air-actuated valves, the compressed air supply must be clean and protected from oil and moisture. The clock must be lubricated occasionally. The slide wires on the servo motors may need to be cleaned if pen response becomes sluggish.

Calibration of Recording–Controlling Instruments

When instruments are out of calibration, the actual drying conditions within the kiln differ from those recorded on the chart, and serious kiln-drying defects or increased drying time may result. Because a new instrument may be jarred during shipment, check calibration at two or three points over total range at the time of installation. Thereafter, check it for accuracy frequently by using thermometers.

Recalibration of a recorder-controller found to be in error is not difficult, but it should be done carefully. The equipment required includes a liquid container and an accurate temperature-measuring device. Because the difference in height between bulbs of gas-filled systems and the recorder-controller case affects the recorded temperature, verify that the bulbs are at the correct height in relation to the instrument by checking the notation on the information plate inside the instrument case. Calibrate the instrument with the bulbs at about the same height above or below the instrument case as they will be in service. Height does not affect resistance temperature detectors (RTD). Two people are required for the calibration-one at the sensor in the liquid container and one at the instrument.

The procedure for calibration is as follows:

1. Fill the liquid container with water or oil at least as deep as the sensors are long, so that the sensors can be completely submerged. Heat the water to 200 °F or the oil to about 280 °F, and place the container near the sensors.
2. Remove the sensors from their fastenings and completely submerge in the heated liquid. If the dry- and wet-bulb sensors are located together in the kiln, calibrate them together. Avoid sharp bends in the tubing of gas-filled systems. The sensors should

not touch the sides or bottoms of the container. In a dual dry-bulb system, only one sensor usually needs calibration. If there has been a difference in the temperatures recorded by the dry-bulb thermometers at fan reversal during kiln operation, check each sensor separately. The person stationed at the liquid container should gently and constantly stir the liquid during calibration.

3. After about 10 min, the person at the liquid container should take a temperature reading of the hot liquid with the thermometer or other device. The person at the instrument then records this reading together with the corresponding temperature indicated by the instrument.
4. Record these two temperatures every 20 °F as the liquid gradually cools. If cool liquid is added to reduce calibration time in gas-filled systems, let 5 to 10 min elapse before temperatures are taken, so that the temperature change is reflected at the instrument, Resistance systems stabilize almost immediately. Make periodic check readings until the liquid temperature drops to below the lowest kiln temperatures used at the plant.
5. If the indicated temperatures on the instrument chart are consistently lower or higher than the water temperatures by a constant amount, adjust the recorder pen arms upward or downward by that amount by turning the small screw located on the pen arm or the pen arm pivot. If the differences between the indicated temperatures and the water temperatures are not constant, a trained technician should make the adjustment. A correction chart can be made so that the instrument can be used in the interim until it is adjusted.
6. The next step, the adjustment of the control-setting indicator, should be made only by a knowledgeable, experienced person. The indicator is adjusted while the compressed air or electricity is on. Lower the temperature-setting indicator to a temperature below that indicated by the pen on the chart and then move the indicator slowly upward until the motor valve it controls begins to open. Record the temperature shown by the setting indicator. Then move the setting indicator slowly downward until the motor valve begins to close and record the indicated temperature. If the average of the two recorded temperatures is different than the temperature indicated by the pen, move the control-setting indicator- by means of adjustment screws on the indicator- upward or downward by the amount of the difference.

Some kiln operators prefer not to adjust the instrument pens or control-setting indicators. Instead, they list the calibration data and place this list near the face of the instrument. These data are used as a guide for setting the instrument in kiln runs.

Resistance sensors can be calibrated as outlined above, or they can be calibrated quickly with precision electrical resistors. (For a more complete discussion, see the section on semiautomatic control systems in ch. 2.)

Dry kiln operators should be familiar with the manufacturer's instructions for the care and maintenance of recorder-controllers. If the instrument should fail, trained service people should be contacted for advice and service.

Heating Systems

A correctly designed and properly maintained heating system produces uniform drying conditions in a kiln. Unfortunately, the maintenance of heating systems is often neglected, and the consequent nonuniform drying conditions cause kiln degrade, extended drying time, nonuniform moisture in the lumber, and increased drying cost. On the other hand, frequent inspection and prompt corrective action can minimize, if not eliminate, many adverse effects.

Steam-Heated Kilns

Problems that occur with steam-heated kilns include improperly insulated feedlines, leaking pipes and unions, sagging and distorted pipes, defective valves and regulators, faulty pressure gauges, faulty automatic and manual control valves, and faulty steam traps.

Improperly Insulated Feedlines

Insulate all main feedlines from the boiler to the kiln to reduce losses in steam temperature, pressure, and consumption. In control rooms or other areas frequented by workers, steam lines, headers, and valves should be insulated for safety. The insulation on many steam feedlines is either improperly installed or damaged. Replace deteriorated or damaged insulation as soon as possible.

Leaking Pipes and Unions

Leaking pipes, caused by corrosion or mechanical damage, increase steam consumption. If the leak occurs within the kiln, this will affect the wet-bulb temperature. Repair or replace leaking pipes. When necessary, clean all pipes and fittings.

Sagging and Distorted Pipes

Feedline and coil supports frequently fail, causing the pipes to become distorted and to sag. Condensate and scale accumulate in the sagged pipes and eventually plug them. Sagging coils will become water logged, thereby drastically reducing their ability to transfer heat to the kiln. Straighten or replace sagging and distorted pipes. Protect pipe supports against corrosion, and reinforce or replace them when examination shows they are failing.

Defective Valves and Regulators

Fluctuations in steam pressure caused by faulty pressure-reducing valves and regulators result in nonuniform drying conditions. If adjustment does not correct the condition, repair or replace the defective parts.

Faulty Pressure Gauges

The pressure gauges used in conjunction with the reducing valves and regulators occasionally go out of calibration. Recalibrate the gauges at intervals against a gauge known to be accurate or replace them.

Faulty Automatic and Manual Valves

Automatic valves that control steam flow may leak or fail to open or close properly. Failure of an air-operated motor valve to open is usually associated with a leak in the air supply line, a damaged diaphragm, or an overtight packing nut that causes mechanical binding. Some valves have a compression spring that facilitates opening; others have springs that facilitate closing. The springs should be checked periodically for proper adjustment and functioning. Failure of electrically operated valves may be associated with power failure, damaged wiring, or faulty motor. A valve that leaks because of worn parts or the presence of scale on the seat can usually be detected by a slow, continuous rise in temperature above the set point. A valve that is slow to open or fails to open can be detected by a slow drop in temperature below the set point when the instrument is calling for heat.

Repair or replace faulty valves. Keep a spare motor valve on hand as well as extra motor valve parts, including diaphragms, springs, packing compound, valve stems, and valve seats. If leaks occur around the valve-stem packing nut, tighten the nut or replace the packing.

Manual valves are used extensively on steam heating systems. These valves, which are usually of the gate type, should be operated wide open or completely closed. Open or close the valves occasionally to keep them from rusting or corroding in the open or closed position. If leaks occur around the valve-stem packing nut, follow the procedure outlined for faulty automatic valves. Keep replacement valves and spare parts on hand.

Faulty Steam Traps

Consult kiln manufacturers, engineers, and steam-trap manufacturers on trap installations to minimize failures in the trapping system. The following summary will assist the operator in locating and correcting trap problems.

The failure of a steam trap to discharge may be due to (1) excessive operating pressures, (2) failure of condensate to reach the trap, (3) a plugged bucket vent (in the case of bucket traps), (4) dirt in the trap, (5) worn or defective parts, or (6) excessive back pressures in the condensate return line. Excessive operating pressures in the steam feedline may be caused by the failure of the reducing valve or pressure regulator, by inaccurate readings on the pressure gauge, or by the raising of steam pressures beyond the operating range of the trap. Failure of the condensate to reach the trap may be due to a closed motor valve on the feedline, a closed manual valve in the line between the coils and the trap, open or leaking bypass valves that allow the condensate to flow around the trap, or water-logged steam lines. Dirt, rust, or scale in the condensate may plug the bucket vent. This problem can be minimized by installing a strainer ahead of the trap and cleaning it at frequent intervals. A strainer will also prevent the trap body from becoming filled with dirt. Install blowoff valves on all traps, and blow out the traps for a short period each day the kiln is in operation.

Continuous discharge of water from a trap can be caused by the inadequate size of the trap or trap orifice (that is, an opening too small for the steam pressure used), rust or scale under the seat in a disc trap, a worn seat that prevents proper closing, or a rusted bellows. These difficulties can be prevented by installing a trap that has been sized correctly and is large enough to handle the peak condensate load, which will usually occur during the warmup period.

If the trap blows live steam, the discharge valve may not be seating. A bucket-type trap that blows live steam may have lost its prime. A badly worn valve seat or dirt lodged between the valve and valve seat will cause improper seating of the valve. A trap that loses its prime is usually subjected to sudden or frequent drops in steam pressure. If this occurs frequently, install a good check valve ahead of the trap. Maintaining a fairly constant supply of steam pressure will also minimize this problem.

Worn or defective trap parts may cause complete failure. Some parts can be easily replaced on the job with very little, if any, loss in operating time. Replacement is even simpler if a bypass line has been installed around the trap. When a defective trap cannot be repaired on the job, replace it with a new or reconditioned trap. Repair the defective trap at the first opportunity. Annual cleaning and overhaul of all traps is recommended.

Trap failure can be detected by observing discharge from the trap, obtaining temperatures on the supply and discharge sides, or listening to the action of the trap. The discharge action of most traps can be observed from test outlets. These should be opened frequently. If steam discharges continuously from a correctly sized trap, the trap is not functioning properly; determine the cause and correct it. Do not confuse flash steam with live steam. Flash steam, which is due to pressure changes, is white as it leaves the test valve. Live steam generally appears in a continuous flow, and it is transparent as it leaves the test valve.

By listening carefully to traps during operation, traps can be checked without visual observation of the condensate discharged. This method is, therefore, much more convenient when working with a closed condensate return system. The necessary equipment consists of an industrial stethoscope or a homemade listening device such as a 2-ft length of 3/16-in steel rod in a file handle, a piece of wood dowel, or a screwdriver (table 4-1). With a little practice, the operation of the internal components of the trap can be heard with any of these homemade devices merely by placing one end of the tool against the trap bonnet and the other end to your ear.

A steam trap is essentially an automatic condensate valve, the only function of which is to pass condensate and hold back steam. This definition implies that a significant temperature differential exists between the upstream and downstream sides of a properly functioning trap. Trap performance, therefore, can be checked by measuring temperatures on the pipeline immediately upstream and downstream of the trap. Two requirements for this method are a simple contact pyrometer for making the measurements on the surface of the pipe and a knowledge of line pressure upstream and downstream of the trap. For each steam pressure, there is a corresponding steam temperature. Table 4-2 shows typical pipe surface temperature readings corresponding to several operating pressures.

Let us assume the upstream pressure in the piping system is 150 lb/in^2-gauge, and the pressure downstream of the trap is 15 lb/in^2-gauge. The pyrometer measures an upstream temperature of 335 °F and a downstream temperature of 225 °F. (File or wire-brush the pipe at points of measurement to provide good contacts for the tip of the pyrometer.) Table 4-2 shows that for an upstream pressure of 150 lb/in^2-gauge, a pyrometer reading between 348 °F and 329 °F should be obtained. For a downstream pressure of 15 lb/in^2-gauge, a pyrometer reading of between 238 °F and 225 °F is desirable. We can conclude, therefore, that the trap is functioning properly.

Now let us assume the same pressures, but a pyrometer reading of 335 °F upstream and 300 °F downstream of the trap. The insufficient spread between the two temperatures indicates that live steam is passing into the condensate return line. The trap has failed while open, and it needs to be repaired or replaced.

In still another example, suppose the pyrometer readings are 210 °F on both sides of the trap. Such a reading is all right downstream, where we know the pressure is 15 lb/in^2-gauge. However, this reading is too low upstream where we know the pressure is 150 lb/in^2-gauge. The low upstream temperature probably indicates a restriction in the line that is reducing the pressure to the trap. A clogged strainer may be the culprit; blow out the trap before looking any further for a cause for the problem.

Although these examples deal with a closed return system, the temperature measurement method can also be used to check traps that discharge to the atmosphere. In this situation, of course, the downstream pressure is always atmospheric.

Direct-Fired Kilns

In direct-fired kilns, the hot gases produced by burning gas, oil, or wood waste are discharged directly into the kiln. Burners commonly have electrically or pneumatically modulated fuel valves. Temperature-limit switches are located on the inlet and discharge ends of the combustion chamber and are set to shut down the burners if they overheat beyond the predetermined set point. Careful attention should be paid to proper monitoring and maintenance of all sensors, temperature-limit switches, and safety equipment associated with the burner. Manufacturer's recommendations and instructions and State safety codes should be closely followed.

Humidification Systems

Steam Spray

Steam sprays supply moisture to the kiln atmosphere when required to maintain the desired relative humidity. Saturated or “wet” steam is preferable to superheated or “dry” steam for this purpose. Using low pressure steam or installing a desuperheater in the steam line are common ways of obtaining saturated steam (see discussion of humidification in ch. 2). Manual or automatic valves controlling the flow of steam spray into a kiln require the same maintenance as those used in steam-heating systems. Follow the inspection and maintenance procedures as discussed for heating systems. A flow of steam or condensate from the steam spray line when the valves are closed indicates leakage through the control valve. A falling wet-bulb temperature when the control instrument is calling for steam spray indicates there is an inadequate supply of spray into the kiln or the steam spray motor valve has failed to open. Repair or replace defective valves immediately.

The steam spray lines usually slant downward from the feed end. Usually a small drain line discharging outside the kiln is provided to drain off the condensate that collects at the low end. Keep this drain line open. Inspect the steam spray line itself periodically to see that the discharge holes or nozzles are open and that the pipe has not been bent or turned so that the spray discharges onto the lumber or the instrument control bulbs.

Water Spray

Occasionally water spray lines are installed in kilns to supply moisture when required for humidification. Generally, water spray cannot supply sufficient water vapor required for effective conditioning treatments. Inspect the valves frequently that control the flow of water into the spray line and repair or replace defective valves immediately. Open plugged spray holes or nozzles and repair or replace damaged lines.

Venting systems

Most kilns are provided with ventilators for exhausting hot, moist air from the kiln and taking in fresh air. Excessive venting increases heating and humidification requirements, and it should be avoided by proper adjustment and maintenance of the venting system. An effective and low-cost method for preventing excessive venting is the installation of an air exhaust valve on the air line at the vent control valve. The controller and the vent systems should be adjusted so that venting and spraying cannot occur at the same time. This obviously wastes energy, and in cold climates the spray can condense on contact with cold air and cause accelerated corrosion of any steel surface with which the condensate or “rain” comes into contact.

Although vents can be manually or automatically operated, automatic ones are recommended. To prevent excessive venting, frequently inspect the system and keep it in good repair. This generally means going on the kiln roof rather than observing the vents from groundlevel. The inspection and maintenance of vents require the following:

1. Keep the linkage system connecting two or more vent lids or dampers lubricated and inspect it periodically for damage and excessive wear at pivot points. Straighten, repair, or replace bent, broken, or excessively worn pins, hinges, rods, chains, and levers.
2. Inspect the vent lids or dampers when they are in a closed position. If the lids or dampers are partially open, adjust the linkage so that the lids or dampers fit tightly. This adjustment can be made quickly and easily on most kilns.
3. Install gaskets around vent openings if there is excessive leakage when the vent lids are closed.
4. Avoid overventing. Adjust the linkage so that the lids or dampers are open just wide enough to obtain the desired venting. High winds will often keep vent lids open even if no air is supplied to the control valve. This can be corrected with a counterweight.
5. Examine air lines or electric circuits connecting the vent mechanism to the control instrument for air leaks and short circuits.
6. Keep the compressed air used to operate the vent mechanism dry and free of oil. Water in the air supply line may freeze the motor valve during cold weather. If dry compressed air cannot be obtained, protect the air supply line against freezing.

Air-Circulation Systems

The uniform circulation of air in a kiln is extremely important for proper drying, and it is dependent on well-maintained air-circulation equipment. Any failure or damage to the component parts of the air-circulation system extends drying time and may also result in nonuniform drying. Therefore, the maintenance and care of the component parts of the air-circulation system are essential.

The items to be checked in the periodical inspection of the air-circulation system and some of the maintenance procedures include the following:

1. Fan motors
   a. Lubricate fan motors in accordance with the manufacturer's instructions. Replace leaky bearing seals.
   b. Keep windings and armatures free of dust. Dry compressed air may be used for blowing out dust.
   c. Keep motor mounts and anchor bolts tight.
   d. Protect fan motors located outside the kiln from the weather.
   e. Properly ventilate the control room to avoid overheating fan motors.
   f. In the kiln, use fan motors designed for high temperatures and high relative humidities.
   g. Protect fan motors against overloading. Relays should be set to kick out under small overload.
   h. Repair or replace damaged or badly worn motors.
   i. Have a qualified electrician inspect all elements of the electrical circuits periodically and keep them in good condition.
2. Fan shafts
   a. Lubricate shaft bearings according to the manufacturer's instructions and replace leaking oil seals.
   b. Keep bearing supports tight and aligned with the shaft. Misalignment may overload the fan motor and damage the fan shaft and bearings.
   c. Keep fans shafts aligned, both horizontally and vertically.
   d. Keep friction and babbitt bearings tight.
   e. Replace damaged or badly worn bearings.
   f. Replace or repair badly worn keys or keyways.
   g. Keep shaft couplings tight.
   h. Replace damaged fan shafts.
3. Pulleys and belts
   a,. Keep pulleys tight on the shafts.
   b. Replace badly worn or damaged pulleys to prevent excessive belt wear or belt slippage.
   c. Tighten belts according to manufacturer's recommendations. Do not overtighten.
   d. Replace badly stretched or damaged belts.
   e. Keep all belts uniformly tensioned or tight on multibelt systems.
4. Fans
   a. Repair minor damage to fans; replace badly damaged fans.
   b. Keep fans tight on fan shafts.
   c. See that the clearance between the tips of fan blades and the fan shroud conforms to the manufacturer's recommendations.
   d. Ensure that all fans are rotating in the same direction and that all reverse at the proper time. This is especially important to check in cross-shaft fan arrangement.

      Caution: Exercise extreme care when fans must be inspected while they are running. Do not stand on fan deck when fans are running; rather, stand on ladder and look over edge of fan deck. Serious injuries have resulted from carelessness during the inspection of moving fans.
5. Fan baffles and floor
   a. Repair or replace damaged fan baffles and floors.
   b. Keep anchor bolts in fan baffles tight to minimize vibration and possible damage to fans.
6. Load baffle system (includes top, floor, and end baffles)
   a. Repair or replace damaged baffles.
   b. Lubricate baffle hinges.
   c. Maintain pulleys and cables on hinged baffle systems in good condition.
7. Oil lines, connections, and bearings
   a. Leaking oil lines, connections, and bearings increase safety and fire hazards, create an adverse working environment, and may stain the lumber.
   b. Make a systematic inspection for oil leaks and tighten loose connections.
   c. Repair or replace damaged lines.

Kiln Trucks

Frequent inspection and proper maintenance of kiln trucks can minimize downtime and accidents. Proper lubrication will help extend truck life. Recommended maintenance procedures are as follows:

1. Repair or replace damaged truck frames, axles, and bearings promptly.
2. Keep bolts and rivets in truck frames tight.
3. Repair or replace damaged metal or wood cross supports.
4. Provide enough trucks so that no truck is loaded over its capacity.

Use of Protective Coatings

Since ferrous (iron) metal in a dry kiln will rust or corrode, frequent inspection of metal parts is essential. Remove rust and coat the affected surface with a suitable protective paint. Such paints can be obtained from dry kiln manufacturers. (If manufacturers do not have these paints, they may furnish names of suppliers.) Typical areas of rapid corrosion are around doors, the lower 16 to 24 in of structural support columns (H or I beams) in aluminum prefabricated kilns, any location where a steel column or beam attaches to or extends through the kiln floor or wall, and any other location where condensation can occur for a prolonged period. Heat- and vapor-resistant kiln paint or coating is necessary for the inside of block and concrete kilns to protect masonry against humidity and condensation and to reduce heat and vapor transmissions. Do not apply to the outside of masonry kilns as the moisture will be trapped in the wall and speed deterioration of the structure.

Housekeeping and Maintenance Around Dry Kilns

Good housekeeping around dry kilns is essential. The possibility of injuries, damage to equipment, derailment of kiln trucks, and fires can be minimized by keeping the dry kiln, operating room, and surrounding area clean and free of safety and fire hazards. Good housekeeping practices include the following:

1. Immediately pick up stickers that have fallen from loads of lumber and place them in conveniently located sticker racks.
2. Pick up lumber that has fallen from loads and repile it on the loads or return it to the storage area.
3. Remove sawdust and other debris that collects on kiln roofs or sifts into the kiln.
4. Keep kiln walkways free of debris.
5. If possible, push any stickers or lumber that project into walkways back into the load to prevent injuries to workers. Boards projecting into plenum spaces or between vertical stacks of lumber can also cause nonuniform air velocities through the loads of lumber.
6. Stop oil or grease leaks around bearings, fans, blowers, and motors, and wipe up spilled oil or grease as soon as possible. Use drip pans to catch oil or grease that drips from bearings. Place oily or greasy rags in closed containers.
7. Keep control rooms clean, free of accumulated debris. and well ventilated at all times.
8. Keep transfers, tracks, and tramways on the loading and unloading ends of dry kilns in good alignment and repair.
9. Inspect stairways and ladders frequently and replace weak members at once.
10. Keep walkways along roof in good repair to provide access for inspection of vents, vent motor valves, vent linkages, oil cups for bearings, and other parts of the kiln.

Locating Problems in Kiln Maintenance and Operation

To assist the dry kiln operator in rapidly finding the causes of poor drying, the common sources of trouble are outlined in this section.

If the dry-bulb temperature does not reach the set point in a reasonable length of time, the causes may be as follows:

1. Steam pressure is too low.
2. Heat transfer is insufficient.
3. Heating coil is damaged, waterlogged, air-bound, or plugged.
4. Manual valves on steam supply or drain lines are closed or only partially open.
5. Automatic motor valve fails to open.
6. Steam trap is defective.
7. Valves are open on bypass line around steam trap.
8. Back pressures in return line to boiler are excessive.
9. Venting is excessive.
10. Leakage from kiln structure and around doors is excessive.
11. Recorder-controller system is malfunctioning because
    - a. air or electrical signal fails to travel from controller to motor valve or
    - b. sensor bulb (gas-filled or RTD) is not working properly.

If dry-bulb temperature continues to climb above the set point, the causes may be as follows:

1. Automatic motor valve is leaking.
2. Motor valve remains open.
3. Heat is being transferred through a common wall from an adjacent kiln.
4. Heat from steam spray is excessive (more common at low wet-bulb depressions or during conditioning phase of schedule).

If the wet-bulb temperature fails to reach the set point in a reasonable length of time, the causes may be as follows:

1. Insufficient steam is entering the spray line because
    a. steam supply to spray system is insufficient,
    b. automatic motor valve fails to open,
    c. manual valve on feedline is closed or only partially open, or
    d. holes or nozzles in spray line are plugged.
2. Leakage of heat and vapor from kiln structure or around doors is excessive.
3. Venting is excessive.

If the wet-bulb temperature continues to rise above the set point, the causes may be as follows:

1. Motor valve on steam spray line is leaking.
2. Motor valve on steam spray line remains open.
3. Water is standing on kiln floor.
4. Steam or water lines in kiln are leaking.
5. Valve in bypass line around motor valve is open.
6. Venting is insufficient.
7. Wet-bulb wick is dry, dirty, or crusty.

If the lumber is not uniformly dried or has excessive degrade associated with hot or cold zones within the kiln, the causes may be as follows:

1. Hot zones may be caused by
    a. higher than average air velocities across heating coils because of faulty stacking and inadequate baffling,
    b. leakage of heat through a damaged wall common to two kilns, or
    c. leakage in heating coils.
2. Cold zones may be caused by
    a. infiltration of colder air through cracks in the kiln wall or around doors,
    b. damaged fans or fan motors,
    c. short circuiting of the air because of faulty stacking or inadequate baffling,
    d. improper drainage of condensate from coils, or
    e. downdrafts through the vents.

Incorrect recording of dry- and wet-bulb temperatures may be caused by

1. control instrument that is out of calibration or damaged,
2. improper air circulation over control bulbs,
3. exposure of control bulbs or capillary lines to direct radiation from heating coils and feedlines or heat from steam spray,
4. water on the dry bulb,
5. dirty or dry wet-bulb wick or wet-bulb wick made of improper cloth,
6. too fast or too slow waterflow to wet-bulb water pan,
7. absence of wick on the wet bulb,
8. misplacement of wick on dry bulb instead of wet bulb,
9. wrong recorder chart, or
10. excess capillary tubing on gas-filled or liquid-vapor systems rolled up in kiln (best to roll up excess capillary tubing in control room rather than kiln).

Table 4-1—Operating sounds of various types of traps

Trap type	Operating sounds of properly functioning trap	Operating sounds of failed trap
Disc (impulse or thermodynamic)	Opening and snap-closing of disc	Normally fails while open—cycles in excess of 60/min
Mechanical (bucket)	Cycling sound of bucket as it opens and closes	Fails while open—sound of steam blowing through Fails while closed—no sound
Thermostatic	Sound of periodic discharge if on medium-to-high load; possibly no sound if light load (throttled discharge)	Fails while closed—no sound

Table 4-2—Pipe surface temperatures at various steam pressures

Steam pressure (lb/in^2-gauge)	Steam temperature (°F)	Pipe surface termperature range (°F)
15	250	238-225
50	298	283-268
100	338	321-304
150	366	348-329
200	388	369-349
450	460	437-414

Appendix-
Kiln Inspection Checklist

(Where maintenance or replacement is recommended, indicate kiln number.)

I. Kiln Structure

1. **Doors and door hangers,** present condition:

Do door hangers operate properly: __________

Do doors fit properly: __________

Do gaskets adequately seal door: __________

What maintenance a replacement is recommended: __________

2. **Walls,** present condition:

IS protective coating adequate (masonry kilns): __________

Are cracks repaired or holes patched: __________

What maintenance or replacement is recommended: __________

3. **Structural steel** members, present condition:

Is protective coating adequate: __________

What maintenance or replacement is recommended: __________

4. **Roof or ceiling,** present condition:

Is protective coating adequate to minimize corrosion and vapor transmission: __________

What maintenance or replacement is recommended: __________

5. **Floors and walkways,** present condition:

What maintenance or replacement is recommended: __________

6. **Rails and supports,** present condition:

What maintenance or replacement is recommended: __________

II. Control system

1. **Recorder-controller,** present condition:

Is correct chart paper on instrument: __________

Is recorder-controller properly calibrated: __________

Are capillary tubes protected: __________

Are leads and connections of RTD adequately protected: __________

Are bulbs or sensors properly located and mounted for accurate reading of kiln conditions: __________

Does cellulose EMC wafer need replacing: __________

What maintenance or replacement is recommended: __________

2. **Water supply:**

Is water supply line to wet bulb open: __________

Is wet-bulb water pan clean: __________

Is water supply unusually hot or cold: __________

Is drain line from water pan open: __________

Is wet-bulb wick replaced regularly:

What maintenance or replacement is recommended:

3. **Air supply:**

Is compressed air supply at correct pressure, clean, and uninterrupted:

Is compressor in good condition:

Are water and grease traps in good condition:

What maintenance or replacement is recommended:

III. Heating and Humidifying System

1. **Steam feedlines and headers,** present condition:

Are feedlines and headers properly insulated:

What maintenance or replacement is recommended:

2. **Heating coils or ducts,** present condition:

Are all pipes open to full flow of steam:

What is the condition of supports:

Is ductwork bent or otherwise damaged:

What maintenance or replacement is recommended:

3. **Traps, present condition:**

Are traps in best possible location:

What maintenance or replacement is recommended:

4. **Condensate return line,** present condition:

Are condensate pumps working properly:

Is line properly sized for volume carried:

What maintenance or replacement is recommended:

5. **Automatic and manual control valves,** present condition:

Are automatic control valves working properly:

Are springs and diaphragms working properly:

Are manual blowdown-valves provided for traps:

Are manual valves provided for shutting off individual coils:

Are check valves working properly:

What maintenance or replacement is recommended:

6. **Spray lines,** present condition:

Are spray holes or nozzles open:

Does condensate from spray line drip on lumber:

Is spray line properly trapped:

What maintenance or replacement is recommended:

7. **Vents,** present condition:

Do all vents open and close properly:

Do air motors and linkages work properly:

What maintenance or replacement is recommended:

IV. Air Circulation System

1. **Fans and motors,** present condition:

What is the condition of electrical connections and switches:

Are fans slipping on shafts:

Are all fans turning in proper (same) direction:

What maintenance or replacement is recommended:

2. **Shafts and bearings,** present condition:

Are motors and shaft bearings properly lubricated:

What maintenance or replacement is recommended:

3. **Fan baffles, cowling, and fan floor,** present condition:

What maintenance or replacement is recommended:

4. **Load baffles,** present condition:

Can load baffles be improved:

What maintenance or replacement is recommended:

5. **Air passageways (including ductwork in direct-fired kilns):**

Are air passageways open and unobstructed:

Could air movement be improved:

What maintenance or replacement is recommended:

V. General Condition of Yard, Kilns, and Control Room

Does grading and surface of yard provide for good drainage directed away from kiln(s):

Are alleys adequate for maneuvering lift truck:

Are kiln trucks in good condition:

What maintenance or replacement is recommended:

Is control room neat and clean:

Are good kiln records kept:

Are kilns and surrounding area neat and clean:

Chapter 5
Stacking and Loading Lumber for Kiln Drying

Chapter 5 was revised by William T. Simpson, Supervisory Research Forest Products Technologist.

Much of the degrade, waste, and moisture content variation that occurs during kiln drying results from poor stacking and loading. Well-stacked lumber and properly loaded and baffled kilns result in faster and more uniform drying, less warp, and less sticker loss. Stacking and loading procedures vary widely for hardwoods and softwoods, differences in plant layouts, type of material to be dried, and types of kilns and stacking equipment. However, certain principles apply to all stacking and loading. The purpose of this chapter is to describe these principles.

Sorting

Sorting lumber before drying simplifies stacking and also aids in placing material of similar drying characteristics in the same kiln charge. The extent of sorting depends on practical considerations--some sorts are almost unavoidable, whereas others are sometimes omitted. Lumber can be sorted by species, moisture content, heartwood and sapwood, wetwood, grain, grade, thickness, and length.

Species

Some species of wood have markedly different drying characteristics than others. For example, the time required to kiln dry green 4/4 red oak to a final moisture content of 7 percent is two to three times that required to kiln dry 4/4 hard maple. Furthermore, a milder drying schedule must be used for the oak to avoid drying defects. If these two species were dried in the same kiln charge, the hard maple would have to be dried by the milder oak schedule. Consequently, the hard maple would be in the kiln longer than necessary, which increases drying costs. On the other hand, the drying characteristics of hard maple and yellow birch do not differ greatly. Thus, if the lumber has the same thickness and moisture content, these species can be dried together economically. Similarly, in softwoods the cedars and redwood might take three to five times as long to dry as Douglas-fir or the true firs. So, whenever possible and practical, a kiln charge should consist of the same species or of species with similar drying characteristics.

Moisture Content

It is not desirable to mix air-dried, partially air-dried, and green lumber in the same kiln charge. Wetter lumber requires milder initial drying conditions and longer drying time than drier lumber. For example, 4/4 cypress air dried to a moisture content of 25 percent can be kiln dried to 7 percent moisture content in about one-half the time required to dry green lumber to the same final moisture content. Similarly, 4/4 red oak can he kiln dried from 25 to 7 percent moisture content in about one-quarter the time required to kiln dry red oak from green to 7 percent.

Because of the many variables involved, specific recommendations cannot be made as to the maximum allowable difference in initial moisture content between the driest and wettest lumber in a kiln charge. This difference must be determined by each kiln operator on the basis of production needs and the quality of drying desired. In general, the difference in moisture content between the driest and wettest lumber in a kiln charge should be smaller (1) for air-dried or partially air-dried lumber than for green lumber, (2) for shorter expected drying times than for longer times, and (3) for a narrow range in the desired final moisture content.

Heartwood and Sapwood

In many hardwood species, sapwood has a higher green moisture content than heartwood (ch. 1, table 1-4). In addition, sapwood generally dries faster and has fewer defects than heartwood. Thus, sapwood and heartwood usually reach the final moisture content at different times, Because of these differences, it would often be advantageous to separate heartwood from sapwood, but this is usually impractical.

Wetwood

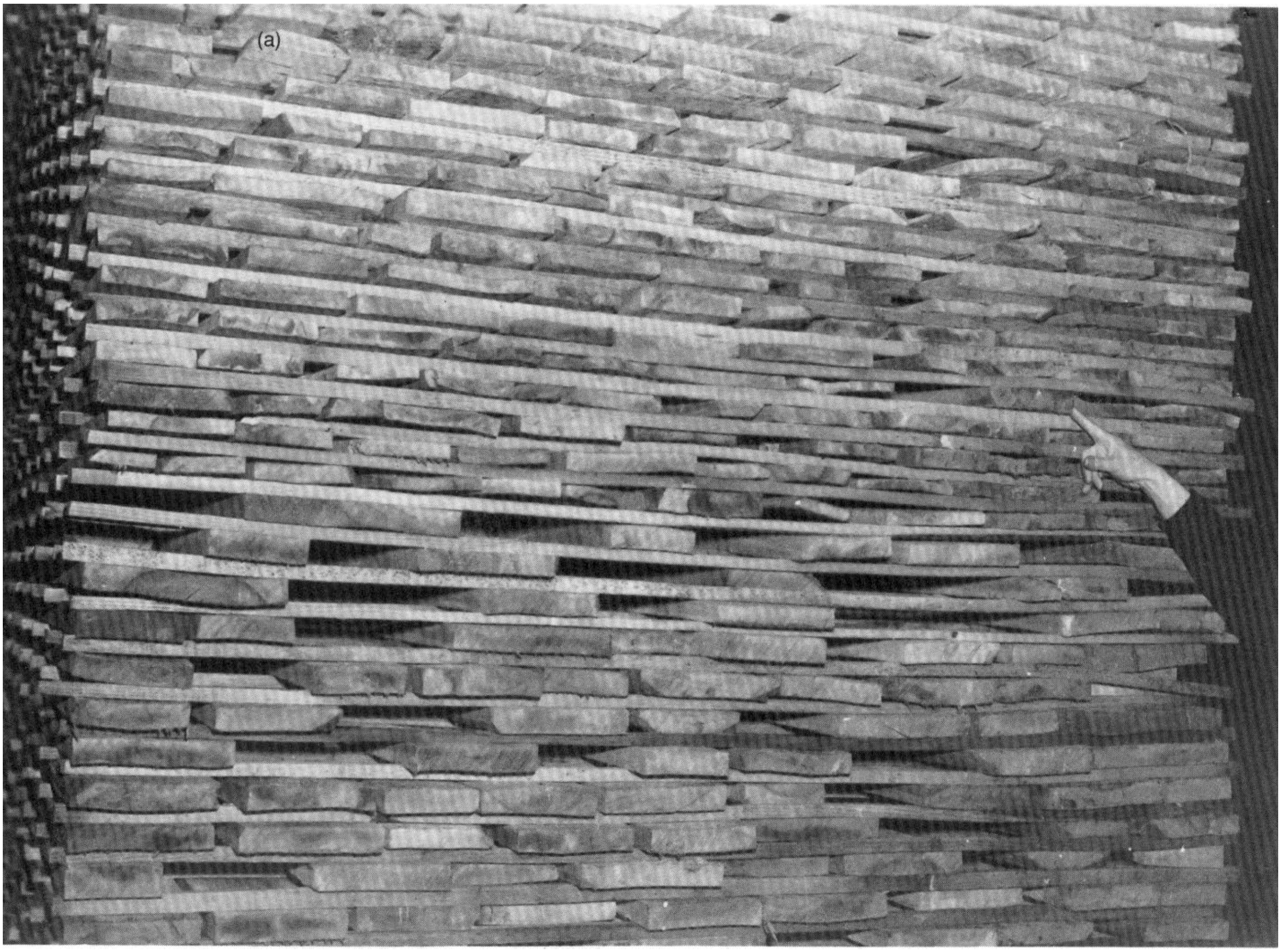
Wetwood, sinker stock, and wet pockets are terms used to describe wood that has a green moisture content higher than that of the normal wood of the species (see ch. 8 for additional discussion). The higher moisture content is sometimes confined to areas that are surrounded by normal wood. The condition is usually confined to heartwood, but also often occurs in the transition zone between sapwood and heartwood. In addition to higher green moisture content, wetwood usually dries considerably slower and often with more drying defects than normal wood of the species. The net result is that final moisture content after kiln drying is quite variable, and drying defects sometimes occur when wetwood and normal wood are kiln dried together. Some affected species are the hemlocks, true firs, aspen, oak, and cottonwood. For example, typical kiln-drying times to 19 percent moisture content for western hemlock dimension lumber are 78 h for normal heartwood (65 percent green moisture content), 115 h for sapwood (170 percent green moisture content), and 160 h for wetwood (145 percent green moisture content). Sorting techniques on the green chain, which transports lumber between the edger and the lumber stacker, are possible, but they are not always accurate or practical. Faster and more reliable techniques need to be developed for effective, practical sorts.

Grain

Flatsawn lumber (ch. 1, fig. 1-6) generally dries faster than quartersawn lumber, but it is more susceptible to such drying defects as surface checks, end checks, and honeycomb. For practical purposes, large quantities of quartersawn lumber may be segregated from flatsawn lumber and dried under relatively severe kiln conditions, using a shortened drying time.

Grade

The upper grades of lumber, both hardwood and softwood, are generally used in products that require higher strength, closer control of final moisture content, and better appearance than the lower grades. Therefore, higher grade lumber is usually sorted out and kiln dried by different schedules than the lower grades.



Thickness

Sorting for thickness is essential. Uniform thickness of lumber simplifies stacking and drying. It also reduces warping in the lumber as well as breakage and distortion of stickers. Warping of lumber and sticker distortion resulting from stacking lumber with different thicknesses are shown in figure 5-1a. Cupping and twisting in the thinner boards is caused by lack of contact between the boards and stickers. Without the restraint of the weight of the lumber pile, boards are very likely to warp. Warping and distortion also disrupt airflow through the lumber pile, resulting in nonuniform drying. A stack of uniformly thick and well-piled lumber is shown in figure 5-lb.

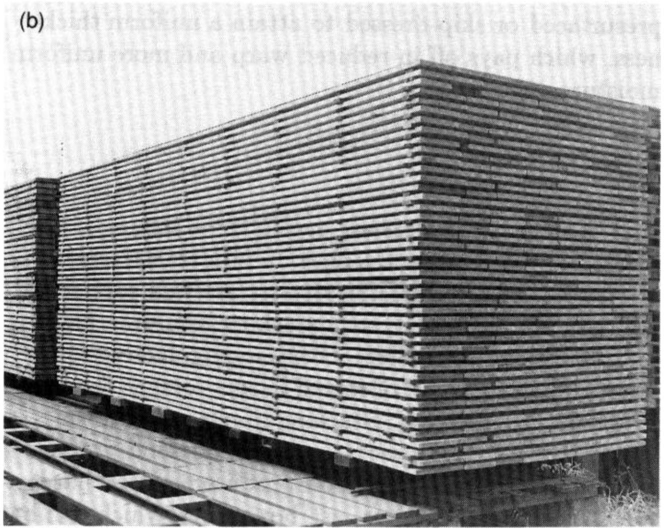


Figure 5-1—(a) Stacking lumber of different thicknesses in the same stack results in warping of lumber and deformation and breakage of stickers. (b) Lumber of uniform thickness and stickers remain flat during drying. (M 115549, M87 929)

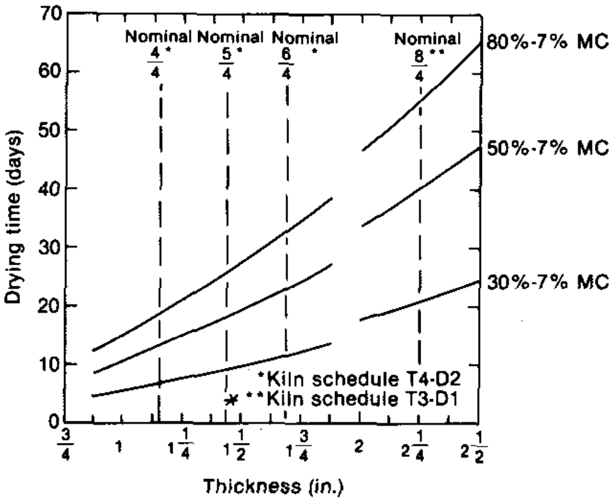


Figure 5-2—Effect of thickness and initial moisture content on kiln-drying time of red oak. (ML88 5562)

Another reason for sorting for thickness is the variation in drying time with thickness. Figure 5-2 shows the effect of thickness on kiln-drying time of red oak. For example, kiln drying from green to 7 percent moisture content might range from 18 days for 4/4 lumber to 32 days for 6/4 lumber to 55 days for 8/4 lumber.

Lumber that is miscut is likely to vary considerably in thickness across the width and along the length of the piece. Not only is miscut lumber difficult to stack, the thinner part of boards cannot be kept flat. Moreover, the thicker parts dry more slowly and may develop more defects than thinner parts. Lumber is sometimes presurfaced or skip-dressed to attain a uniform thickness, which pays off in reduced warp and more uniform moisture content.

Length

One of the best and easiest methods for sorting is to stack lumber of a single length on kiln trucks or in packages (fig. 5-lb). If the stickers are well supported and in good alignment, such stacking results in flatter and straighter lumber. Overhanging ends of longer boards in a truckload of mixed-length lumber are likely to warp during drying. Stacking lumber of uniform length is a common practice among softwood producers and some larger hardwood producers. Most hardwood producers, however, use box piling, which will be described later in this chapter.

Sorters

Lumber is often sorted by grade and size on the green chain between the edging and stacking operations. Different categories of boards are held in bin or sling sorters until the lumber is stacked for drying. Different types of sorters are the slant bin, vertical bin, sling, and buggy. A sling and a slant-bin sorter are shown in figure 5-3.

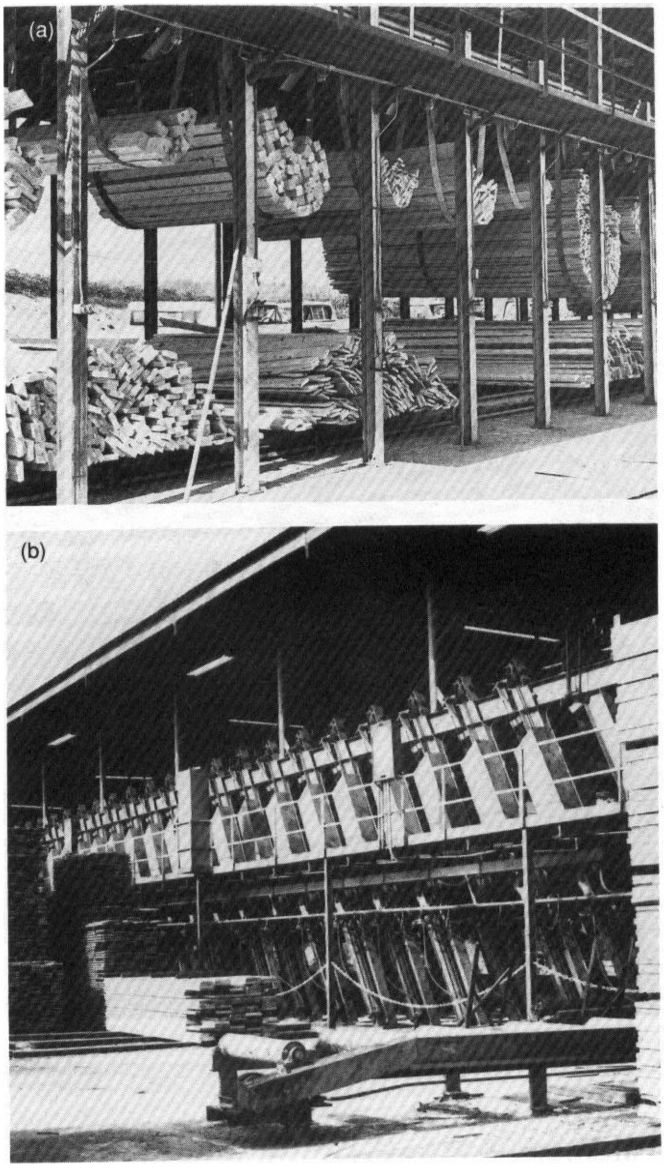


Figure 5-3—Sling sorter (a) and slant-bin sorter (b) for holding sorted lumber prior to stacking for the dry kiln. (MC88 9029, MC88 9031)

Stickering Lumber

The purpose of stickers is to separate each board surface so that air can flow over each surface and evaporate water. Stickers must be selected and placed so that they give adequate support to minimize warping of the lumber and breakage and distortion of stickers. In most applications, stickers should also be chosen to minimize stains that sometimes develop in the lumber that contacts the stickers. Important considerations of stickering include species and grade of wood used for stickers, moisture content of stickers, sticker size and placement in stack, and load supports.

Sticker Material

Many stickers are required in a kiln-drying operation, and replacement is costly. Practical measures for lengthening sticker life are therefore worthwhile. Stickers are often made from clear, straight-grained lumber rather than from low-grade lumber. The initial cost of such stickers may be higher, but their longer service life usually offsets this cost. Straight-grained stickers made from the harder woods stay straighter, break less, and generally last longer than irregular-grained stickers from softer woods.

Species such as hickory, hard maple, beech, oak, Douglas-fir, and larch make good stickers. However, for practical reasons, the species being dried at the plant are usually used for stickers.

Moisture Content of Stickers

Stickers should be made from kiln-dried lumber. They should be protected from readsorbing moisture during storage or holding between kiln charges. This reduces the chance of sticker stain, which is a discoloration on the surface of or deeper within the lumber where it contacts the sticker. Kiln drying the stickers kills mold spores that cause the stain, and protection from readsorption minimizes pickup of new spores. The use of heartwood for stickers also reduces staining. In addition, kiln drying reduces the distortion and thickness shrinkage of stickers that could occur in use.

Sticker Size

Width

Wide stickers slow the drying of lumber in the areas of contact; these areas may remain at a higher moisture content than areas of the lumber not in contact with the stickers. If stickers are too narrow, the lumber or stickers are liable to be crushed. Stickers for hardwoods are usually 1-1/4 to 1-1/2 in wide and should not exceed 1-1/2 in. Stickers for softwoods are generally about 2 in wide and sometimes up to 3 in wide for softer species such as sugar, white, and ponderosa pine.

Thickness

Stickers are usually 3/4 to 1 in thick, although 1/2-in-thick stickers are sometimes used. The thinner stickers increase the capacity of a kiln and may be adequate for slow-drying species. They increase air velocity through the lumber stack and tend to make airflow more uniform. However, the increased number of layers of boards in a kiln causes a decrease in the volume of air passing over each board face. In fast-drying species, the volume of air per unit time may be inadequate to hold the amount of moisture evaporating from the board surfaces. In some species, such as eastern white pine, this lower evaporation rate may cause staining of the surface. In addition, thinner stickers break and deform more readily, and sagging boards are likely to obstruct airflow.

Regardless of size of thickness, all stickers within a kiln charge should be surfaced to a uniform thickness Thickness and width should be sufficiently different to avoid sticker misorientation (for example, a sticker placed on edge rather than flat).

Load Supports

Unless lumber stacks are properly supported, sagging and distortion in the lower courses will result (fig. 5-4a). On the other hand, lumber stacked as in figure 5-4b will not sag because the load supports are directly under tiers of stickers. The schematic in figure 5-5 shows the proper alignment of load supports and stickers.

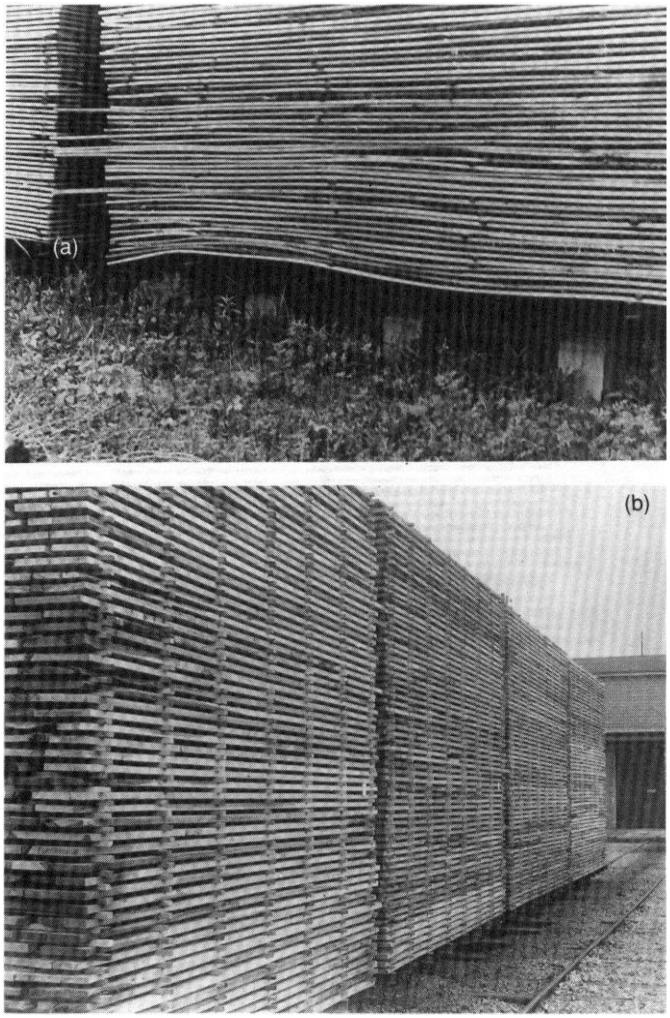


Figure 5-4—(a) An insufficient number of load supports, improperly placed, causes sagging in this stack of lumber. (b) Properly aligned load supports prevent sagging of the stack and distortion of the lumber. (M 115545, M 115696)

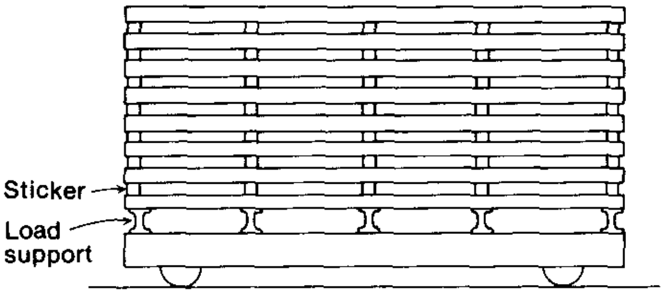


Figure 5-5—Typical lumber truck showing alignment of load supports and stickers. (ML88 5566)

The thinner the lumber, the greater the number of load supports required. A bottom course of thick dunnage sometimes can be used instead of additional supports. The usual spacing for load supports is 2 ft. The distance between load supports can be increased for thick lumber, but it is better to use too many than too few supports.

Sticker Location, Spacing, and Alignment

Good location, spacing, and alignment of stickers reduce warping and minimize end checking and splitting.

Location

Stickers should be placed flush with or very near the ends of boards whenever possible (fig. 5-5). This will minimize warping at the ends of boards and will also retard end drying to some extent, thus helping to minimize end checking and splitting.

Spacing

Optimum sticker spacing is governed by the lumber's tendency to warp, its thickness, and its resistance to crushing. In general, hardwoods require closer sticker spacing than softwoods. Some particularly warp-prone species like sweetgum and the elms benefit by spacing of less than 2 ft. The stickers of hardwoods that are thinner than 1 in should also be spaced less than 2 ft apart. Also, to avoid crushing stickers between the bottom courses of heavy loads, sticker spacing may need

Figure 5-6—Package of lumber raised by forklift truck. Short tiers of stickers above point of contact with forks reduce sag in the lower courses of lumber and help prevent the end stickers from falling out of the stack, (M 115553)

to be reduced. Modern lumber-stacking machines typically have sticker guides adjustable in 1-ft increments. However, these machines are commonly operated with the guides set for 2-ft sticker spacing for both hardwoods and softwoods.

Alignment

For the best control of warp during drying, the tiers of stickers should be aligned vertically (figs. 5-4b and 5-5). Misaligned stickers (fig. 5-4a), particularly in stacks of green lumber, invariably cause nonuniform distribution of weight and result in sharp kinks in the lumber where the stickers contact it. The thinner the lumber, the greater the possibility of kinking. Considerable waste results from incorrectly aligned stickers in 4/4 lumber.

Auxiliary *Stickers*

Packages of lumber are commonly transported around dry kilns with forklift trucks and straddle carriers. When lifted by this kind of equipment, lumber in the lower courses of a package often sags, and stickers at the ends may fall out. One way to avoid this problem is to use short tiers of stickers above the forks (fig. 5-6) or the carrier bunks. The number of stickers needed in these extra tiers depends upon the thickness of the lumber and the weight of the package. Usually stickers are interlaid between the bottom 6 to 10 courses of lumber.

Sticker Guides

Sticker guides are devices that force stickers to be placed in exactly the same vertical alignment tier after tier. They ensure good spacing and alignment of stickers and are used almost universally. Sticker guides vary in type and are used in both manual and automatic stacking. One type used in manual stacking is shown in figure 5-7. Vertical channel irons equal in length to the height of the load are positioned along each guide at points corresponding to the desired sticker spacing. The stickers, cut about 2 in longer than the desired width of the load, are held in place by the guide channels.

Semiautomatic stackers have built-in sticker guides (figs. 5-8, 5-9). They are similar to the guide described above except that they do not need to be as tall as the stack because the level of the top course changes as the stack is built, and there is no need to pivot the guide away from the stack. Most plants use semiautomatic or automatic stackers.

Figure 5-7—Sticker guides for stacking lumber on kiln trucks. (M 134969)

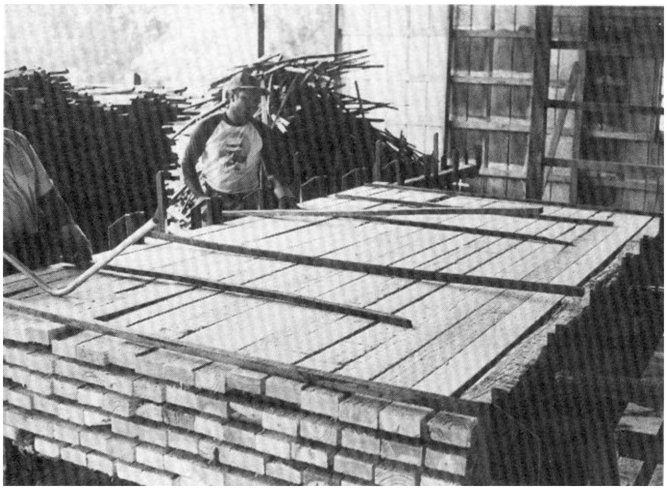


Figure 5-8—Semiautomatic stacker. Lumber stack is located on hydraulic lift so that the level of the top course is always at working level for the sticker crew. Stickers are placed by hand. (MC88 9013)

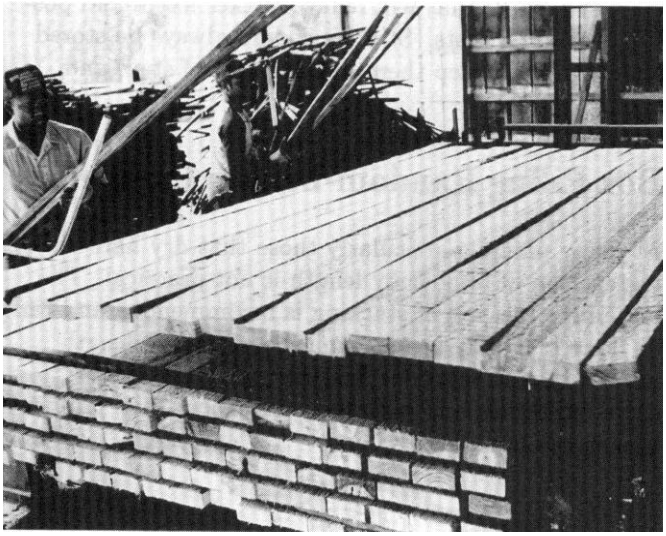


Figure 5-9—Semiautomatic stacker. Lumber stack is located on hydraulic lift so that the level of the top course is always at working level for the sticker crew. Stacker arm moves course to a position over stickers and lowers it into position. (MC88 9012)

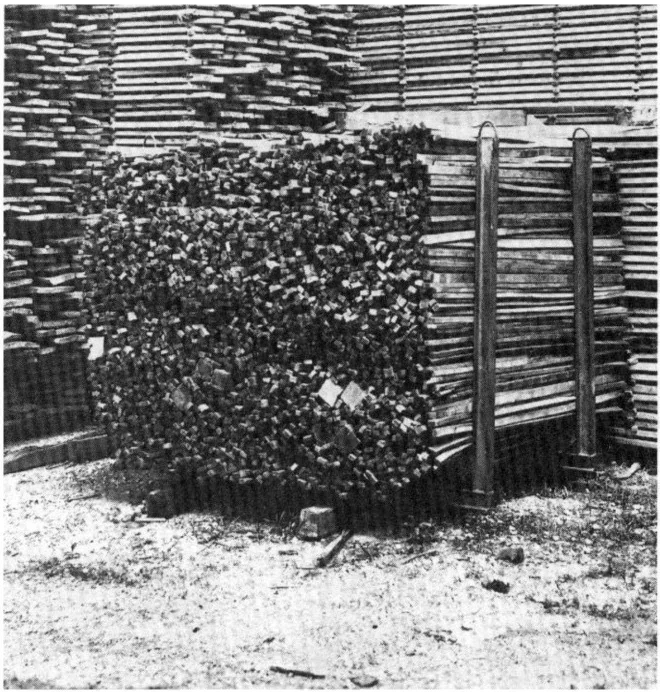


Figure 5-10—The handling of stickers is facilitated if they are racked for transport by carrier or forklift truck. (MC88 9011)

Care of Stickers

The primary concerns in the care of stickers are to prevent breakage in handling, distortion in handling or storage, and excessive pickup of water in storage that could support the growth of molds that could cause stain. Large plants often invest considerable money in sticker-handling equipment, such as conveyors, to reduce handling costs without damaging the stickers. Smaller plants can construct racks or other holding devices (fig. 5-10) that will reduce sticker losses and possibly handling costs. Stickers should always be stored under cover to keep them dry and free of stain and decay.

Box Piling Random-Length Lumber

At many plants, particularly those that dry hardwoods, segregation of lumber by length is not practical. The box-piling method of stacking is recommended and can be done manually or mechanically. Random-length lumber that is box piled will dry straighter, flatter, more uniformly, and with less sticker loss than lumber that is not box piled.

In box piling, the length of the outside boards in each course is equal to the full length of the stack. Thus, in figure 5-11, boards numbered 1 and 7 in all courses are as long as the stack. Other full-length boards, when available, are usually placed near the center of the courses, such as board 4 in course A and B. The shorter boards in the same course are alternately placed with one end even with one or the other end of the load. The shorter boards in all courses in the same tier of boards are all placed with one end even with the same end of the load. For example, in figure 5-11 all even-numbered short boards (with the exception of board 6, course D) are placed even with the front end of the load and all odd-numbered boards even with the rear end. Occasionally, two narrow, short boards, such as boards 5 and 6 of course D, are placed over a wider board, such as board 5 of course C. Also, two or more short boards can sometimes be laid end to end in the same tier of lumber. For example, 6- and 8-ft boards could be laid end to end in a load of lumber 14 to 16 ft long.

The column effect obtained by box piling ensues that all boards are well supported and held down; warp, particularly cup and bow, is thereby lessened, along with sticker deformation and breakage. The unsupported ends of the short boards within the stack may warp to some extent.

If enough full-length boards are not available for placement on the sides of the load in occasional courses, shorter boards laid end to end can be used. When this is done, filler blocks should be placed in any gaps between the stickers above and below the course of lumber, particularly when the gaps occur at the ends of the load. These blocks will keep the ends and sides of the loads from sagging and will also reduce sticker breakage. The blocks should be the same thickness as the lumber.

Mechanical Stacking and Unstacking Equipment

Most plants use semiautomatic and automatic equipment for stacking and unstacking lumber. Several types of equipment are available, and they ail eliminate any manual handling of lumber.

Stackers

With both semiautomatic and automatic stackers, a solid package of lumber is placed on a tilting breakdown hoist from which the lumber slides onto a conveyor where the courses are assembled. The stacked lumber, in some cases on the kiln trucks, is placed on a hydraulic lift controlled by the stacker crew and el-

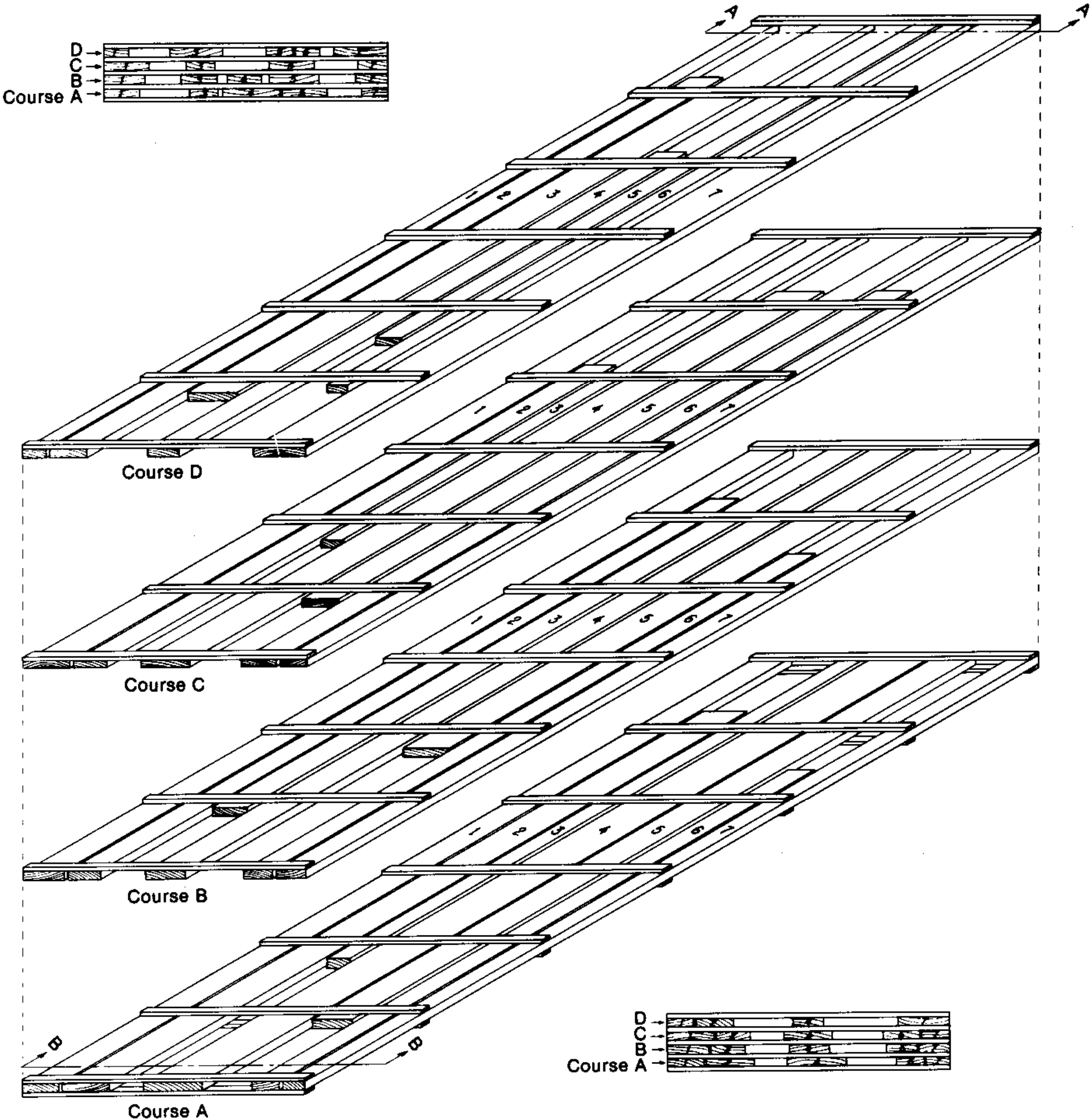


Figure 5-11—Box piling of random-length lumber. (ML88 5565)

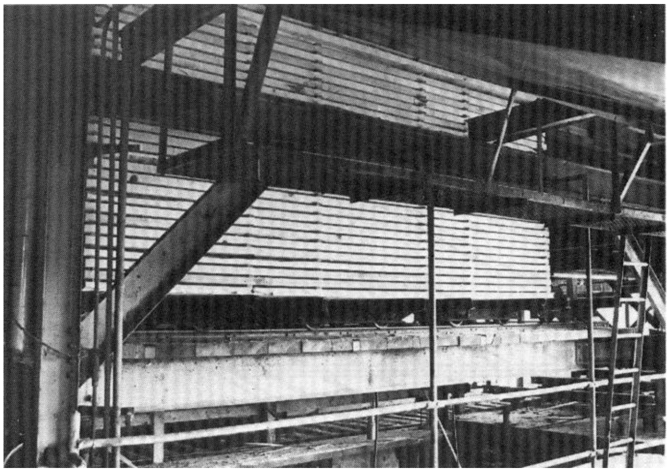


Figure 5-12—Lumber stacker showing hydraulic lift that keeps the top of the stack at working height. (MC688 9010)

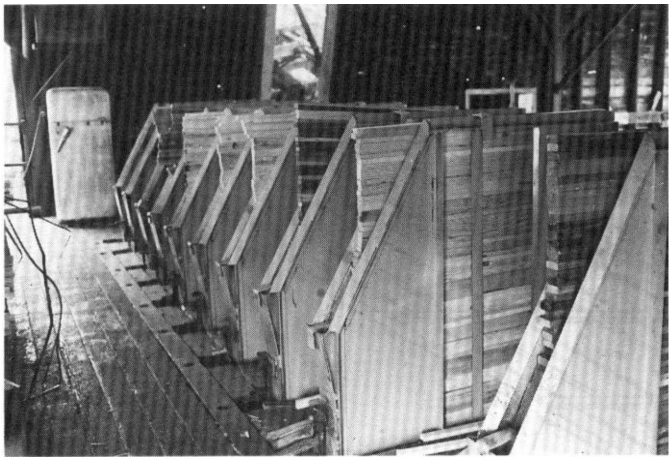


Figure 5-13—Sticker magazines located above automatic lumber stacker. (MC88 9009)

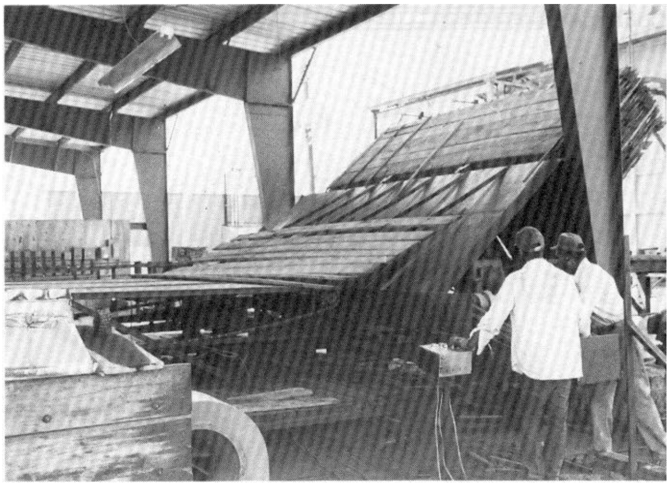


Figure 5-14—Lumber unstacker showing boards sliding onto a conveyor and stickers sliding away from the lumber. (MC88 9008)

evated to a comfortable working height (fig. 5-12). As courses of lumber are mechanically moved onto the lift, the load is lowered a distance equal to the thickness of the boards, stickers are placed, and another course of lumber is moved into position.

Semiautomatic stackers require that each sticker be placed by hand (figs. 5-8, 5-9). A stationary guide located on the lift facilitates alignment of the stickers. In automatic stackers, the stickers are typically loaded in a set of magazines located above the load of lumber on the lift (fig. 5-13). The stickers are positioned automatically on the course of lumber.

Unstackers

With one common type of unstacker, the load of dried lumber is placed on a tilting hydraulic lift (fig. 5-14). The lift is raised and tilted, and the top course of lumber slides by gravity to the dry chain. The stickers slide down a ramp to a sticker bin or conveyor. The lift is then raised to the next course of lumber and the cycle repeated.

Stacking Lumber for Various Types of Dry Kilns

Modern dry kilns are almost universally internal fan kilns where airflow is across the width of the lumber stack. In the past, there were other types of kilns, such as natural circulation and external blower kilns and kilns where air flowed along the length of the stacks or sometimes even vertically. For optimum airflow, stacking procedures had to conform to the type of kiln used. Since few of these older type kilns remain in service, stacking procedures for them will not be discussed here. The earlier version of this manual (Rasmussen 1961) contains these stacking procedures.

Kiln Samples

Kiln samples, that is, boards used to estimate the progress of drying, will be described in detail in chapter 6. Although other process-control techniques are beginning to be applied, the use of sample boards is still widespread in hardwood kiln drying. Moreover, some of the newer automatic kiln-control schemes still depend on the selection and placement of kiln samples.

Kiln samples are placed in the lumber stack in one of three possible ways: (1) kiln sample pockets are built into the stack, (2) kiln sample pockets are cut into the stack, and (3) kiln samples are placed in the bolster space.

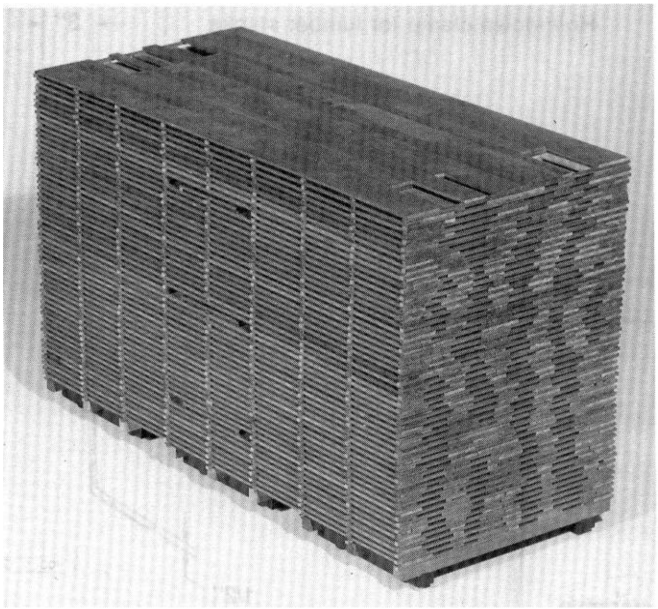


Figure 5-15—Box piling of random-length lumber showing sample pockets and kiln samples. (M 75804)

Kiln Sample Pockets Built Into Stack

Ideally, kiln samples are placed in pockets in the lumber stacks (fig. 5-15). These pockets can be built in at the time of stacking. Since the kiln samples are usually longer than the space between tiers of stickers, the sticker or stickers immediately above the sample should be shortened by the width of the kiln sample. Otherwise, these stickers will bear on the sample and make it impossible to remove the sample for periodic weighing and examination. Two short stickers, the width of the sample pocket, are used to support the kiln sample and allow air circulation across both faces.

Kiln Sample Pockets Cut Into Stack

If it is not feasible to make kiln sample pockets at the stacker, the kiln operator can create sample pockets after stacking. If appropriate safety precautions are taken, kiln samples can be cut from stacked lumber with a small chain saw. Care is necessary because the small space requires cutting with the tip of the saw, which can cause kickback of the blade. Guides can be attached to the saw bar to help steady the blade and prevent cutting adjacent boards. Unfortunately, the recommended length of kiln samples is greater than normal sticker spacing. Removing the cut kiln sample from the stack is relatively easy if the sample is shorter than the sticker spacing because there are no stickers above and below the sample to hold it in place. However, when the sample is longer than the sticker spacing, there will be one point on the sample where it is held in place above and below by stickers. In this situation, it is necessary to pry or jack up the board above the sample to relieve the sticker pressure and remove the sample. A simple forklike tool can be fitted over the end of the sticker that is left when the sample is removed; the end of the sticker can be snapped off with a sideways motion of the tool.

Kiln Samples in Bolster Space

A shortcut taken by some kiln operators is to place kiln samples in the bolster space between packages of lumber in package-loaded kilns. This avoids the necessity of making pockets at the stacker or cutting them into the stack. However, airflow through the bolster space is not the same as airflow through the lumber stack, and the drying rate of kiln samples placed there is not representative of lumber in the stack. Holding racks for samples can be made with boards above and below the sample, thus simulating a sample pocket, but the samples are not at the same moisture content as boards in the stack, which will affect their drying rate somewhat. Kiln operators who have placed kiln samples in the bolster space successfully have carefully correlated the drying rate of the samples with the drying rate of lumber in the stack. These samples dry a little faster than they would if properly placed in the stack, and the operators adjust kiln conditions accordingly. Particular care must be taken if the lumber is at a high moisture content upon entering the kiln. In this case, airflow is particularly important in determining drying rate, and disastrous errors in estimating moisture content of the lumber in the stack are possible. When the lumber entering the kiln has been air-dried or predried to 25 percent moisture content or below, airflow becomes less important in determining drying rate, and fewer errors result from using samples in the bolster space to estimate moisture content of lumber in the stack.

Protecting Stacked Lumber

Kiln trucks or packages of lumber stacked for kiln drying are often air dried first or held at the loading end of the kiln for some period of time before entering the kiln. Such lumber should be protected from rain and direct sunshine to prevent checking and warping of the upper layers. Portable roofs made of simple building materials, such as corrugated metal, can be used for this purpose (fig. 5-16). An open shed or roof over the green end of the kiln is also an effective means of protection.

Weights and Restraining Devices

Weights placed on top of a load of lumber or restraining devices that exert pressure are frequently used to reduce warp in the top layers of a stack. Concrete slabs are often used for top weighting, and at least 50 $\mathrm{lb/ft^2}$ is necessary for effectiveness. Top loading has been found effective in reducing bow and twist, but less so

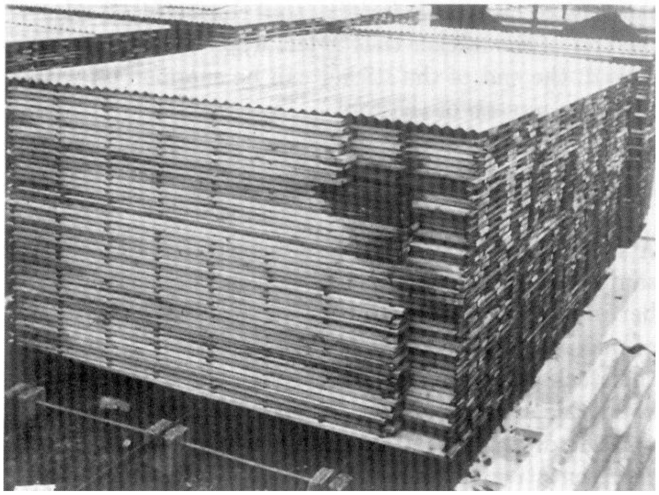


Figure 5-16—Corrugated pile covers for kiln trucks of lumber stored outdoors prior to kiln drying. (M 115539)

in reducing crook. Serrated or pinned stickers (stickers with metal pins that protrude vertically along the length of the sticker and are spaced a little further apart than the width of board) have been found effective against crook in laboratory experiments, but have not been used commercially.

Spring-loaded clamps are also used to reduce warp in top layers (fig. 5-17). One common device consists of wire rope and tension springs attached to each end of light I-beams that extend across the load directly over the stickers and about 6 in beyond each edge. The spring is pulled into tension and hooked into a sticker opening about 5 to 6 ft below the top of the load. The spring extension usually accommodates the load shrinkage, but it sometimes requires adjustment during drying.

Loading and Baffling Dry Kilns

Overloading and underloading affect the quality of drying achieved in a given kiln. A capacity load assumes not only that the lumber is properly stacked in the kiln but also that the loads or packages of lumber are of lengths that provide suitable overall dimensions. That is, the spaces between truckloads and between the charge and walls and ceiling are those called for by the kiln design. If these spaces are changed by overloading or underloading, air circulation is changed as well, with consequent effects on drying time and quality.

The higher the air velocity in a kiln, the greater the possibility that air will short circuit through gaps. The basic principle of airflow through lumber in a kiln is that the fans cause air pressure to build up in the plenum chamber on one side of the load. This static pressure causes airflow through the load; ideally the pressure is uniform, so that airflow is also uniform. Any gaps in, around, over, or under the load provide flow paths for air and prevent the buildup of uniform air pressure. Kilns are usually engineered with specific fan characteristics and plenum chambers, and they should not be altered without careful consideration.

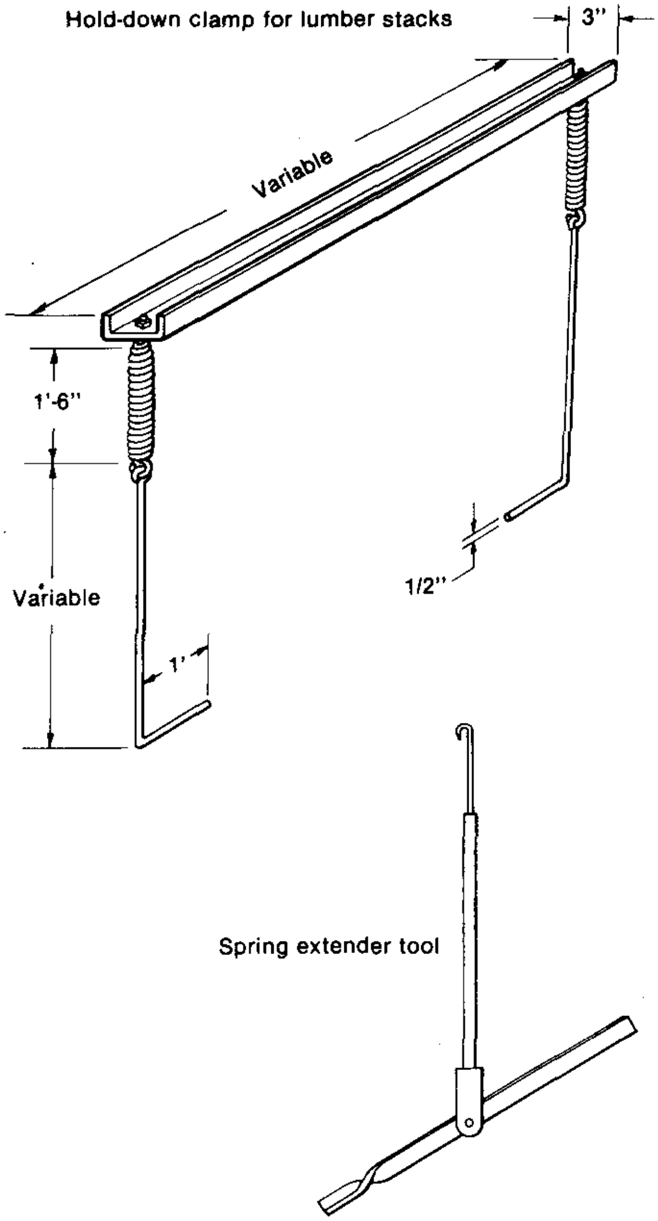


Figure 5-17—Spring-loaded hold-down clamp for reducing warp in top layers of lumber and spring extender tool. (ML88 5564)

Although a particular dry kiln is not limited to only certain lengths of lumber, a kiln operator must consider how overloading or underloading affect air circulation and thus plan the loading patterns to the best advantage, deviating as little as possible from the overall charge dimensions best suited for the kiln. When circumstances demand that the loading pattern must be

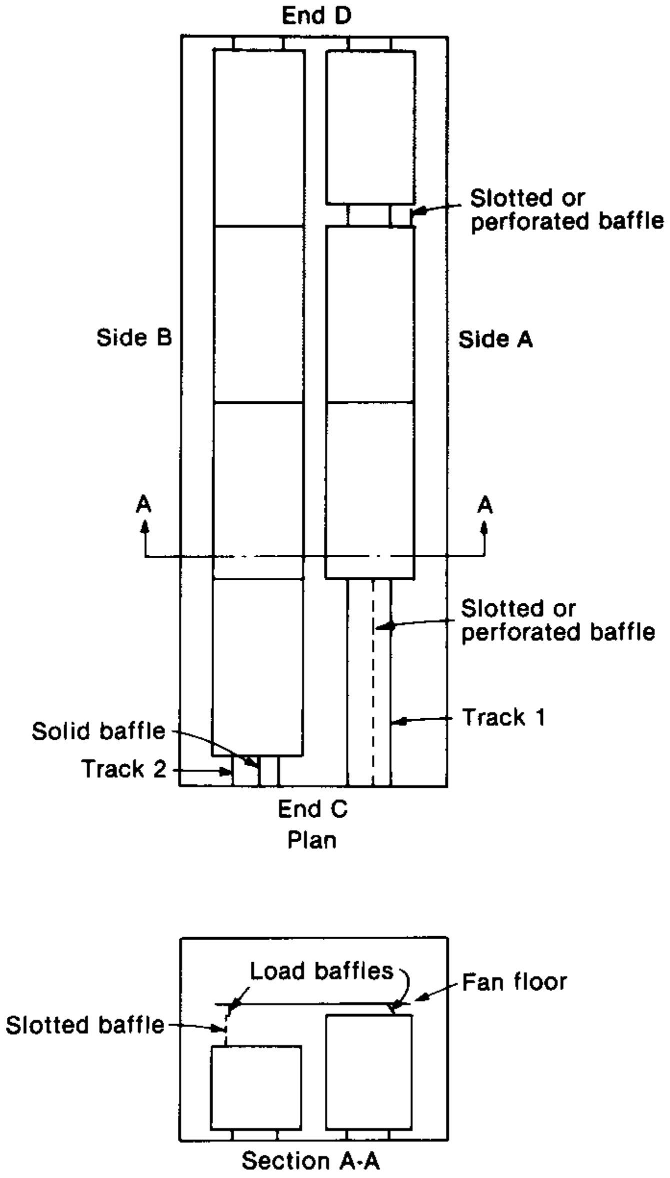


Figure 5-18—A method of baffling voids in a charge of lumber in a double-track kiln. (ML88 5563)

considerably changed from the norm, the kiln operator should exercise special care to keep air circulation as uniform as possible by adding auxiliary load baffles.

Track-Loaded Kilns

In single-track kilns, the distance between the loads of lumber and top load baffles should not exceed 4 in. The ends of the kiln trucks of lumber should be butted snugly together. If this is not possible because long boards overhang from the ends of the loads, the voids created should be blocked. If the kiln charge lacks one or more lumber trucks, the entire charge should be pushed to one end of the kiln, and the empty area should be closed by solid baffles extending from the track level to the kiln ceiling, the fan floor, or the top load baffle. If the kiln has doors on one end only, a charge that is short one or more kiln trucks should be pushed toward the closed end rather than the door end of the kiln.

More care is required in loading multiple-track kilns (ch. 2, fig. 2-2) than single-track kilns with the same type of loading. Short circuiting through voids in a charge of lumber in a single-track kiln can be controlled with solid baffles. In a multiple-track kiln, however, a solid baffle blocking a space in one track of lumber may reduce airflow through some of the lumber on the other tracks.

A method of baffling voids in a double-track kiln is illustrated in figure 5-18. Track 1 has three trucks of lumber, one of which is a short load, and track 2 is fully loaded. The void spaces on both tracks between kiln-end D and the loads are small, about 1 ft wide. A temporary solid baffle extending from the kiln floor to the fan floor can be installed in this opening if desired, but since the opening is quite small, the value of a baffle here is questionable. The larger voids between the short and long loads on track 1 and between kiln-end C and the ends of the loads are blocked off by temporary baffles to prevent excessive short circuiting of the air. The baffles shown on track 1, however, should not be solid. A solid baffle here would block off track 2 from air circulating through the loads from side A to side B, and the lumber on this track would be shorted of air and dry more slowly than the rest of the charge. Slotted or perforated plywood baffles have been used in a situation like this. Snow fence has also been used successfully. Perforated baffles do not provide the same resistance to airflow as a load of lumber, but they reduce short circuiting considerably. The space on kiln-end C, track 2, is blocked off with a temporary solid baffle.

The low load illustrated on track 2 (section A-A) would produce a large void that would permit excessive short circuiting of air if it were not baffled. The slotted or perforated baffle shown between the load baffle and the top of the low load permits air to move across the loads on both tracks in both directions of airflow with very little short circuiting.

If a charge in a double-track kiln is short two lumber trucks, each track should be loaded one truck short. The trucks should be butted together. Both tracks should be loaded as closely as possible to the same end of the kiln so that most space occurs at the opposite end. Then, with both tracks evenly loaded, two solid, temporary baffles can be placed to block out the space on each track.

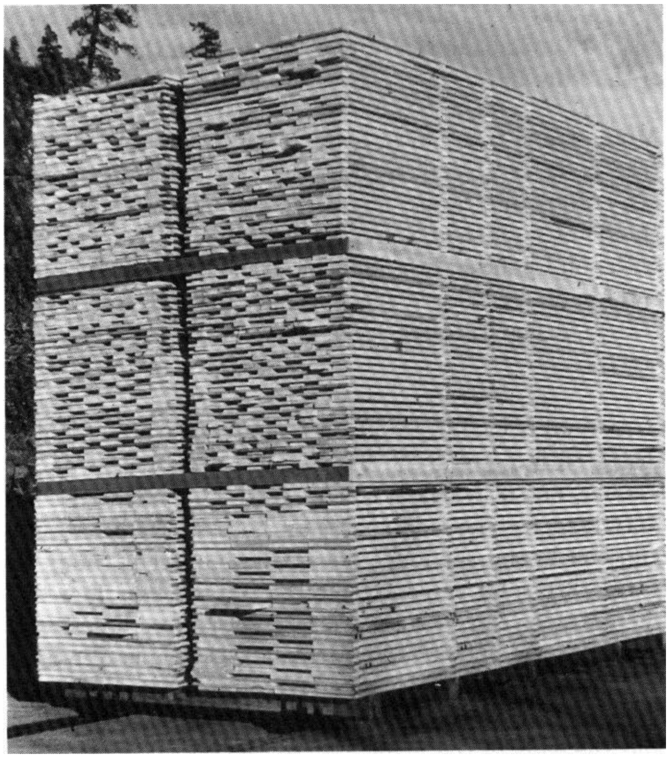


Figure 5-19—Packages of lumber properly spaced side by side on kiln trucks for kiln drying. (M 100902)

Sometimes lumber is stacked in packages, and the packages are loaded by forklift and placed two-wide on kiln trucks (fig. 5-19). The sides of adjacent packages should be spaced 3 to 4 in apart. If this is not done, the sticker openings between courses of lumber may not line up as drying progresses because of nonuniform shrinkage between loads. When this happens, the circulating air may be blocked off. Note also in figure 5-19 that strips of lumber are fastened to the ends of the bolsters separating packages. This practice is recommended because large volumes of air can short circuit through these openings, which are usually 4 in wide.

Package-Loaded Kilns

Careful placement of packages and baffles is particularly important in package-loaded kilns (fig. 2-6) to prevent short circuiting of airflow. Short circuiting is more critical in this type of kiln than in track-loaded kilns because of the generally longer distance air must travel from the entering-air to the leaving-air side of the load. In general, the greater the capacity of package-loaded kilns, the more difficult it is to prevent short circuiting. When loading a package kiln, the initial back row of packages should be placed tight against one wall. The second row should be "side-shifted" so it is tight against the opposite wall. The placement of packages should be alternated from one wall to the other until all rows have been loaded. This will leave a minimum of air space along either wall for short circuiting of air.

Kiln operators are sometimes tempted to add an extra tier of packages to increase the kiln capacity. This narrows the plenum space from the design width and causes nonuniform airflow through the load. It is poor practice and not recommended.

The spaces between adjacent tiers of packages are sometimes made smaller or larger than recommended. If the spaces are too small, circulation through the sticker openings may be impaired because the openings are misaligned during load shrinkage. If the spaces are too large, air will short circuit through the openings or around the ends of the tiers of packages.

The installation of additional top- and side-load baffles reduces short circuiting over or around the ends of the tiers of packages and increases kiln efficiency. Temporary solid or slotted baffles may be required when large voids occur in a kiln charge that is short one or more packages or in which the tiers of packages are incomplete. Solid baffles should never be placed so that they block airflow to any packages.

Because air generally travels a long distance across a charge of lumber in package-loaded kilns, blocking the bolster space (fig. 5-19) helps to prevent the short circuiting of air through the bolster space.

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Chapter 6
Kiln Samples

Chapter 6 was revised by William T. Simpson, Supervisory Research Forest Products Technologist.

Lumber is dried by kiln schedules, which are combinations of temperature and relative humidity applied at various times or at various moisture content levels during drying (see ch. 7). When moisture content levels are the determining factor for adjusting temperature and relative humidity in the kiln, some means of estimating moisture content of the lumber in the kiln during drying is necessary. These estimates are made with kiln sample boards, which are weighed or otherwise sensed during drying.

Kiln samples are not used in drying softwood dimension lumber and are rarely used for drying lumber for higher quality softwood products. Kiln samples are usually used in hardwood lumber drying because incorrect kiln conditions have more severe consequences for hardwood lumber than for softwood lumber.

Traditionally, kiln samples have been removed from the kiln periodically and weighed manually for moisture content estimates. This manual procedure is still used in the majority of hardwood operations, but automated methods are beginning to be developed. One such method utilizes probes that are inserted into sample boards to measure electrical resistance as an estimate of moisture content (ch. 1, table 1-11). This electrical resistance signal can then be fed into a computer control system that makes scheduled changes in kiln conditions automatically. Another system uses miniature load cells that can continuously weigh individual sample boards; the weights are fed into a computer control system.

Whether kiln samples are monitored manually or automatically, the same principles of selection and placement apply. The main principle of selection is that the kiln samples be representative of the lumber in the kiln, including the extremes of expected drying behavior. It is impractical to monitor moisture content of every board in a kiln, so the samples chosen must represent the lumber and its variability. The main principles of placement are that the samples are spread throughout the kiln at various heights and distances from the ends of lumber stacks and that the samples are subject to the same airflow as the lumber.

The handling of kiln samples requires additional operator time, and some lumber is lost when kiln samples are taken. These disadvantages are more than offset by several advantages. The selection, preparation, placement, and weighing of kiln samples, if properly done, provide information that enables a kiln operator to (1) reduce drying defects, (2) obtain better control of the final moisture content, (3) reduce drying time and improve lumber quality, (4) develop time schedules, and (5) locate sources of trouble that affect kiln performance. All these advantages add up to lower drying costs and more uniformly dried lumber.

This chapter covers selection and preparation of kiln samples; the number of samples required in a kiln charge; determination of moisture content and ovendry weight of samples; how to use samples during drying; how to make intermediate moisture content estimates; tests for residual drying stresses; and recording and plotting of data.

Variability of Material

To make full use of known drying techniques and equipment and to assure good drying in the shortest time, each kiln charge should consist of lumber with similar drying characteristics. Differences between boards will invariably exist despite measures to minimize them, and kiln sample selection must include these differences. The following variables should be considered in selecting kiln samples: (1) species, (2) thickness, (3) moisture content, (4) heartwood and sapwood, (5) wetwood or sinker stock, and (6) grain (flatsawn or quartersawn).

Species

Wood of both native and imported species has a wide range of physical properties that can influence ease of drying (ch. 1 and USDA 1987). These properties include specific gravity, shrinkage, moisture diffusion and permeability, strength perpendicular to the grain, and size, distribution, and characteristics of anatomical elements. Such woods as basswood, yellow-poplar, and the pines are relatively easy to dry, with few or no serious drying defects. Others, such as the oaks, black walnut, and redwood, are more likely to check, honeycomb, and collapse during kiln drying. Consequently, it is usually advisable to dry only one species at a time in a kiln, or, at most, a few species that have similar drying characteristics. If mixed species are dried together, kiln samples should be taken from all species.

Thickness

When lumber dries, the moisture evaporates from all surfaces but principally from the wide faces of boards. Thickness, therefore, is the most critical dimension. The thicker the lumber, the longer the drying time and the more difficult it is to dry without creating defects (ch. 1). Lumber of different thicknesses cannot be dried in the same kiln charge without either prolonging the drying time of the thin lumber or risking drying defects in the thick lumber.

Kiln operators should recognize miscut lumber and either dress it to uniform thickness or choose kiln samples accordingly. Nominal l-in-thick lumber can vary from 3/4 in to over 1 in thick, even in the same board. The thinner parts will dry faster than the thick parts, resulting in uneven final moisture content or drying defects.

Moisture Content

The extent to which lumber has been air dried or predried before it is put in a kiln must also be considered, because moisture content often governs the drying conditions that can be used. If all the free water has already been removed, more severe drying conditions can be used in the initial stages of kiln drying, with little or no danger of producing drying defects. Furthermore, a uniform initial moisture content greatly accelerates drying to a uniform final moisture content. If boards vary considerably in initial moisture content, the kiln samples should reflect this variation.

Heartwood and Sapwood

Sapwood usually dries considerably faster than heartwood. Resins, tannins, oils, and other extractives retard the movement of moisture in the heartwood. Tyloses and other obstructions may be present in the pores of the heartwood of some species, principally white oak and the locusts. Sometimes, it is practical to segregate the heartwood and sapwood boards. The green moisture content of sapwood is usually higher than that of heartwood, particularly in the softwoods. For these reasons, heartwood lumber may not reach the desired final moisture content as soon as sapwood, or vice versa. Choice of kiln samples should be guided by the relative proportions of heartwood and sapwood in a kiln charge.

Wetwood or Sinker Stock

Wetwood or sinker stock (Ward and Pong 1980) is a condition (bacterial infection) that develops in the living tree and causes entire boards or parts of boards to be higher in initial moisture content, slower drying, or more susceptible to drying defects. Hemlocks, true firs, red oaks, aspen, and cottonwood develop this kind of wood. Ideally, wetwood should be segregated from normal lumber and dried separately by a different drying schedule. However, it is not always possible or practical to do so. From the standpoint of kiln sample selection, only the hardwoods are really relevant. Bacterially infected wood often has a disagreeable odor, especially in red oaks, or may be darkened (aspen and cottonwood).

If wetwood is suspected, the sample boards should be selected accordingly and observed carefully during drying to detect any drying defects.

Grain

Quartersawn boards generally dry more slowly than flatsawn, but they are less susceptible to surface checking. Thus, more severe drying conditions can be used on quartersawn lumber to reduce drying time. It is sometimes advantageous to segregate quartersawn and flatsawn lumber in drying. If not, kiln samples should reflect the relative amounts of the two grains in a charge.

Number of Kiln Samples

The number of kiln samples needed for any kiln charge depends upon the condition and drying characteristics of the wood being dried, the performance of the dry kiln, and the final use of the lumber. There are several reasons for using kiln samples, which may dictate the number as well as placement of the samples. Kiln samples are used when drying lumber by moisture content schedules and for developing time-based drying schedules.

Moisture Content Schedules

By far the most important purpose of kiln samples is to enable a kiln operator to dry a kiln charge of lumber by a specific moisture content schedule (ch. 7). This type of schedule calls for changes in drying conditions that are based on the moisture content of the lumber during various stages of drying.

Because many variables affect drying results, the specific number of kiln samples required when using moisture content schedules has not been firmly established. The requisite number is different for different species, initial moisture contents, and kilns, and it is best determined through experience. A rule of thumb given in the earlier version of this manual (Rasmussen 1961) is to use at least four samples in charges of 20,000 fbm or less. For charges of 100,000 fbm or more, 10 to 12 kiln samples per charge are usually sufficient. More samples should be used when (1) drying a charge of lumber of different species, thicknesses, moisture contents, grain, or mixture of heartwood and sapwood, (2) drying an unfamiliar species, (3) drying costly lumber, (4) obtaining drying data for modifying a drying schedule or developing a time schedule, and (5) using a dry kiln whose performance is unknown or erratic.

Since publication of the earlier edition of this manual, research has been conducted to better define the necessary number of kiln samples (Fell and Hill 1980). Although this research is not directly applicable to commercial practice, it provides some guidelines. In their scheme, which applies to hardwoods, Fell and Hill recommended using 10 to 12 kiln samples to monitor moisture content from green to 40 percent. Twenty to 23 samples are recommended for 40 to 12 percent moisture content because this range requires a more precise estimate of moisture content. Finally, only 7 to 12 samples are recommended for 12 to 6 percent moisture content. These recommendations call for considerably more kiln samples than the rule of thumb guidelines, but they are based on statistical sampling. Operators should use their experience and individual circumstances to weigh the value of the increased precision, at an increased cost, that comes with increasing the number of kiln samples.

Time Schedules

At plants where certain species and thicknesses of lumber from the same source are dried regularly, kiln operators can utilize kiln samples to develop time schedules for subsequent charges of the same material dried from and to the same moisture content. This may involve extra sampling work to measure the full range of variables, but after sufficient information and experience are obtained, kiln samples can be eliminated for future charges.

Time schedules are generally used in drying softwoods. It is possible, however, to develop satisfactory time schedules for some of the more easily dried hardwoods. Some samples should be used occasionally to check the performance of the kiln and the final moisture content of the lumber.

Checking Kiln Performance

Studies of kiln performance show that dry-bulb temperature and rate of air circulation throughout a kiln may vary considerably and affect the time and quality of drying. Variations in temperature and air circulation can be determined with testing equipment (ch. 3). But if such equipment is not available, kiln samples can be used to check variability of kiln performance. All samples for this purpose should be cut from the same board to minimize variation in drying characteristics between samples. The samples should be placed near the top and bottom of the stacks and on both sides, at intervals of 10 to 16 ft along the length of the kiln.

Kiln samples that dry slowly indicate zones of low temperature or low air circulation, and those that dry rapidly indicate zones of high temperature or high air circulation. If the drying rates vary greatly, action should be taken to locate and eliminate the cause. Differences in drying rates between the samples on the entering-air and leaving-air sides of the stacks will assist the operator in determining how often to reverse air circulation. The greater the difference in drying rate between these two, the more frequently the direction of air circulation should be reversed.

Selecting Kiln Samples

Ideally, segregation of lumber is based on all the factors that affect drying rate and quality. Since this is frequently not possible or practical, a kiln operator must be guided in the selection of kiln samples primarily by the drying rate of the most critical, slowest drying material. The largest number of samples should be selected from the slowest drying material. Some samples should also be selected from the fastest drying material, since these will determine when the equalizing period should be started (ch. 7).

The best time to select boards from which kiln samples will be cut is during stacking. Some boards are selected to represent the heavier, wetter, and thicker boards and to contain a relatively high percentage of heartwood. Usually one kiln sample is cut from each sample board to assure a representative group of kiln samples (fig. 6-1). Some kiln samples are also cut from boards that represent the drier and faster drying boards. Such boards are usually flatsawn, narrow, and scant in thickness, contain a high percentage of sapwood, or are drier than the rest of the lumber at the time of stacking.

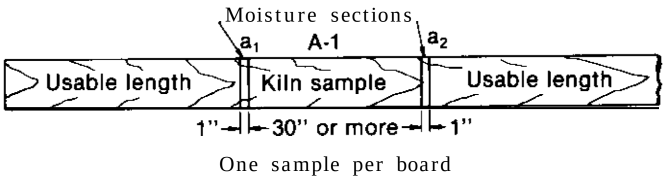


Figure 6-1—Method of cutting and numbering kiln samples and moisture content sections. (ML88 5587)

Preparing Kiln Samples and Moisture Sections

Kiln samples that will be weighed during drying and moisture sections are prepared as shown in figure 6-1. Kiln samples should be 30 in or more long. Moisture sections, cut for the purpose of estimating initial moisture content, should be about 1 in. in length along the grain. Knots, bark, pitch, and decay should not be included in the kiln samples, except when drying lumber of the common grades. The moisture sections that are cut from each end of the kiln sample must be of clear, sound wood. Any bark on the kiln sample or moisture sections should be removed before weighing because it causes error in the moisture content estimate and interferes with drying.

Cutting Kiln Samples and Moisture Sections

Mark the kiln samples and moisture sections for identification, as shown in figure 6-1, before they are cut. Usable lengths of lumber can be salvaged from each end of the board when the kiln samples and moisture sections are cut. If no usable lengths would be left, cut the samples and moisture sections about 20 in or more from the ends of the boards to eliminate the effects of end drying.

With certain exceptions, moisture sections are not cut less than 1 in along the grain and are cut across the full width of the board. It may be necessary to cut moisture sections less than 1 in. in length along the grain if a quick estimate of moisture content is needed. To minimize errors, take extra precautions in cutting, handling, and weighing these thinner sections. In dimension stock 1 in square or less in cross section, moisture sections are cut 2 in or more in length along the grain. A sharp, cool-running saw should be used and the sections weighed immediately. If it is necessary to cut a number of sections at a time before weighing them, the sections should be wrapped in aluminum foil or a sheet of plastic wrap.

Determining Moisture Content and Weight of Kiln Samples and Moisture Sections

The moisture content of a kiln sample is determined from the moisture sections cut from each end of the sample. The average moisture content of these two sections and the weight of the kiln sample at the time of cutting are used to calculate the ovendry weight of the sample. The ovendry weight and the subsequent weights of the sample obtained at intervals during drying-called current weights—are used to calculate the moisture content at those times.

Weighing Moisture Sections

After cutting the moisture sections, rapidly remove all bark, loose splinters, and sawdust, and weigh the sections immediately. Weigh each section on a balance that has precision of 0.5 percent of the weight of the section and that reads in grams. Triple beam or top loading pan balances are suitable for this (ch. 3). Balances with the precision to weigh moisture sections are somewhat delicate, and they require proper care and maintenance. The manufacturer's recommendations and procedures should be consulted to ensure accurate measurement.

To save weighing and calculating time, the two moisture sections cut from each kiln sample are sometimes weighed together. This technique, however, does not distinguish the difference in moisture content usually present between the two moisture sections; therefore, separate weighings are preferred. After weighing the moisture sections separately or together, mark the weight on each section with an indelible pencil or a felt-tip pen with waterproof ink and record the weight or weights on a data form.

Weighing Kiln Samples

After cutting the kiln samples, remove all bark, loose splinters, and sawdust. Then, immediately apply an end coating. Most kiln companies offer an end-coating product, and asphalt roofing compounds are effective and readily available. Immediately after end coating, weigh the kiln samples on a balance that is sensitive to 0.01 lb or approximately 5 g. The balance capacity should be about 35 lb (15 kg). Weight should be expressed in either metric units or in pounds and decimals of pounds (not ounces). Mark the weight with a waterproof pencil or ink on the kiln sample and also record it on a data form. The weight of the end coating can usually be disregarded. If for some reason the kiln sample has to be shorter than recommended and is made from a low-density species, it may sometimes be desirable to consider the weight of the end coating. If so, weigh the kiln sample immediately before and after end coating; the difference, which is the weight of the end coating, should be subtracted from all subsequent sample weights.

Ovendrying Moisture Sections

After weighing the moisture sections, they should be dried until all water has been removed in an oven maintained at 214 to 221 °F (101 to 105 °C). This usually takes 24 to 48 h in a convection oven. To test whether the sections are thoroughly dry, weigh a few sections, place them back in the oven for 3 to 4 h, and then reweigh. If no weight has been lost, the entire group of sections can be considered completely dry. A typical electric oven for drying moisture sections is shown in chapter 3.

The moisture sections should be open piled in the oven to permit air to circulate freely around each section (ch. 3, fig. 3-7). Avoid excessively high temperatures and prolonged drying because they cause destructive distillation of the wood. The result is that ovendry weights are too low, and thus the estimate of moisture content is too high. If newly cut sections are placed in an oven with partly dried sections, the newly cut sections may cause the drier sections to absorb some moisture and unnecessarily prolong drying time.

Microwave ovens can also be used for ovendrying moisture sections. Such ovens are much faster than a convection oven (moisture sections can generally be dried in less than 1 h), but care must be taken not to overdry or underdry the sections. In a convection oven there is a considerable margin of error. If a moisture section is left in longer than necessary, no great harm is done, and the ovendry weight will not be affected significantly. However, if a moisture section is left in a microwave oven even slightly longer than necessary, considerable thermal degradation can occur. The indicated ovendry weight of the moisture section will be less than it should be, and the calculated moisture content will be too great. This danger can be decreased by using a microwave oven with variable power settings. Through experience, the operator can establish combinations of species, size, and initial moisture content of moisture section, ovendrying time, and oven power setting that give accurate ovendry weights.

Weighing Ovendry Moisture Sections

Ovendried moisture sections are weighed by the same procedures as freshly cut moisture sections. However, the sections must be weighed immediately after removing from the oven to prevent moisture adsorption.

Calculating Moisture Content of Moisture Sections

Moisture content of the moisture sections is calculated by dividing the weight of the removed water by the ovendry weight of the sections and multiplying the quotient by 100. Since the weight of the water equals the original weight of the section minus its ovendry weight, the formula for this calculation is

$$\text{Moisture content in percent} = \frac{\text{Original weight} - \text{Ovendry weight}}{\text{Ovendry weight}} \times 100 \qquad (1)$$

Example: Calculate the average moisture content of two moisture sections (fig. 6-1) when

Green weight of moisture section a_1 is 98.55 g

Ovendry weight of moisture section a_1 is 59.20 g

Green weight of moisture section a_2 is 86.92 g

Ovendry weight of moisture section a_2 is 55.02 g

Wanted: The average moisture content of moisture sections a_1 and a_2, Two methods of calculating average moisture content in percent can be used.

Method 1:

Moisture content of section a_1

$$= \frac{98.55 - 59.20}{59.20} \times 100 = 66.6 \text{ percent}$$

Moisture content of section a_2

$$= \frac{86.92 - 55.02}{55.02} \times 100 = 58.0 \text{ percent}$$

The average moisture content of moisture sections a_1 and a_2 is

$$\frac{66.5 + 58.0}{2} = 62.2 \text{ percent}$$

Method 2:

If the sections are weighed together, the combined green weight of sections a_1 and a_2 is 185.47 g, and their combined ovendry weight is 114.22 g. Then

Average moisture content

$$= \frac{185.47 - 114.22}{114.22} \times 100 = 62.4 \text{ percent}$$

Although the average moisture content of moisture sections a_1 and a_2 calculated by method 2 results in a slightly higher value than that obtained by method 1, the calculated ovendry weight of the kiln sample using either method will be the same when corrected to the nearest 0.01 lb.

It is sometimes convenient when making calculations to use a shortcut method of calculating moisture content by the formula

Moisture content

$$= \left(\frac{\text{Original weight}}{\text{Ovendry weight}} - 1\right) \times 100$$

Substituting the weights for moisture section a_1 in this formula

Moisture content in percent of section a_1

$$= \left(\frac{98.55}{59.20} - 1\right) \times 100 = (1.6647 - 1) \times 100$$

$$= 66.5 \text{ percent}$$

Calculating Ovendry Weight of Kiln Samples

The moisture content of a kiln sample at the time of cutting and weighing is assumed to be the same as the average of the moisture content values of the two moisture sections cut from each end of the sample. Knowing this value and the weight of the sample at the time the sections were cut, the ovendry weight of the sample can be calculated by using the following formula:

Ovendry weight of kiln sample

$$= \frac{\text{Original weight of kiln sample}}{100 + \text{MC of sample in percent}} \times 100 \qquad (2)$$

where MC is moisture content

Example: Calculate the ovendry weight of kiln sample A-1 (fig. 6-1), which had an original weight of 4.46 lb, using the average moisture content calculated for moisture sections a_1 and a_2, 62.2 percent.

$$\text{Ovendry weight of kiln sample} = \frac{4.46}{100 + 62.2} \times 100$$

$$= 0.02749 \times 100$$

$$= 2.75 \text{ lb}$$

A shortcut version of equation (2) that is useful with calculators is

Ovendry weight of kiln sample

$$= \frac{\text{Original weight of kiln sample}}{1 + \text{Moisture content in decimal form}}$$

Substituting the weights for kiln sample A-l,

Ovendry weight of kiln sample

$$= \frac{4.46}{1 + 0.622} = 2.75 \text{ lb}$$

Placing Samples in Kiln Charges

After kiln samples are cut, end coated, and weighed, they are placed in sample pockets as described in chapter 5 and illustrated in figure 6-2. Sample pockets are usually placed at several locations along the length of the kiln in the sides nearest the walls. Since the kiln samples are representative of the lumber being dried, they should at all times be exposed to the same drying conditions or they will give a false estimate of the moisture content of the kiln charge. For example, if samples are cut and weighed several days before the lumber is loaded into the kiln, the samples should be inserted in the loads or packages during the time the lumber is outside the kiln.

If a mixed kiln charge is being dried, the samples representing each type of material should be placed in the truckloads or packages containing that lumber. For example, if 4/4 and 6/4 pine lumber are being dried in the same charge, the 4/4 samples should be with the 4/4 lumber and the 6/4 samples with the 6/4 lumber.

Some operators of poorly lighted kilns place small colored-glass reflectors or reflective tape on the edges of the samples or the edges of boards above and below the sample pocket. These reflectors can be located with a flashlight. To guard against replacing samples in the wrong pocket after weighing, a number or letter corresponding to the sample can be written on the edge of the board immediately above or below the pocket.

Using Kiln Samples During Drying

As drying progresses, the drying conditions in the kiln are changed on the basis of the moisture content of the samples at various times during the run. How frequently the samples must be weighed will depend on the rate of moisture loss; the more rapid the loss, the more frequently samples must be weighed. The samples must be returned to their pockets immediately after weighing.

Calculating Current Moisture Content of Samples

Two weights are required to calculate the current moisture content of a sample: the current weight and the calculated ovendry (OD) weight. The formula used is as follows:

$$\text{Current moisture content} = \frac{\text{Current weight} - \text{Calculated OD weight}}{\text{Calculated OD weight}} \times 100 \qquad (3)$$

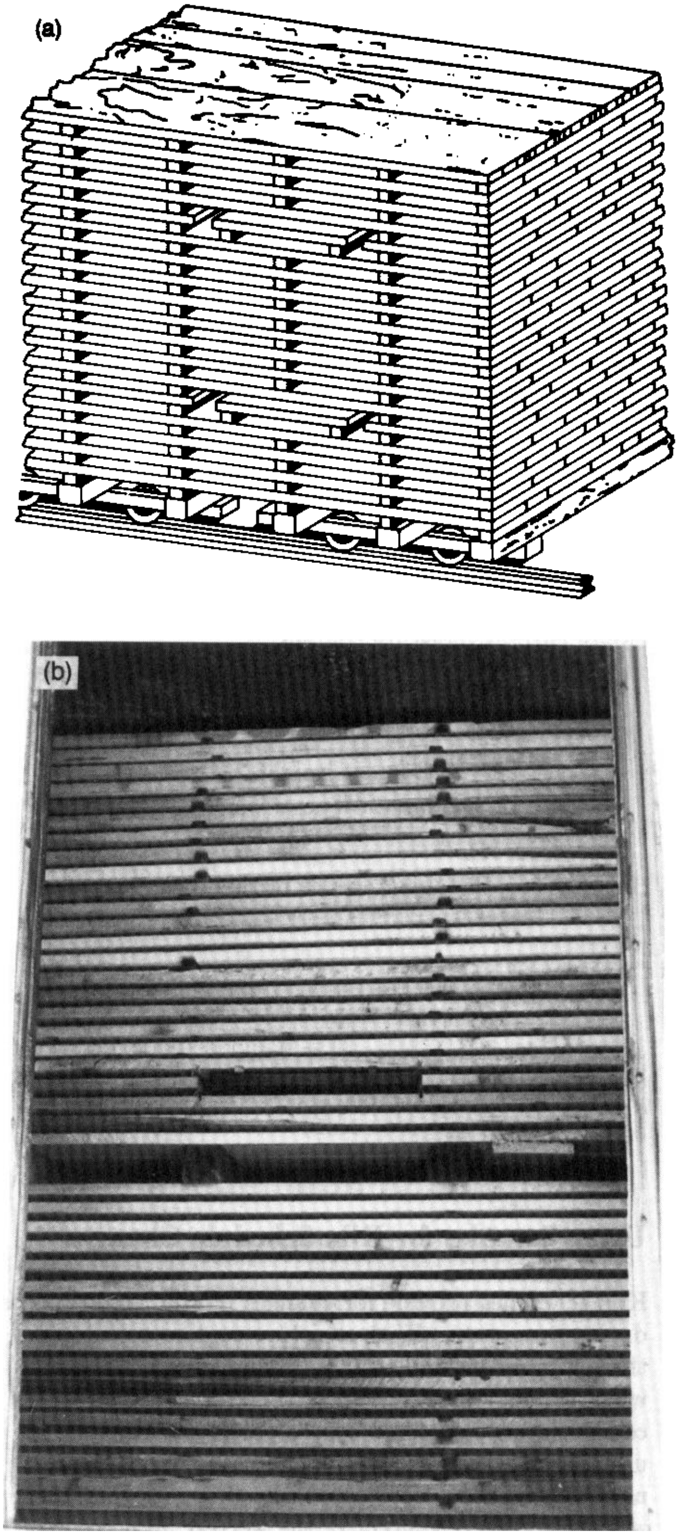


Figure 6-2—(a) Schematic showing placement of kiln samples in sample pockets built in the side of a load of lumber. The pockets should be deep enough so that the kiln samples do not project beyond the edge of the load. (b) Photograph showing kiln sample in place. (ML88 5624, MC88 9028)

Thus, if the calculated ovendry weight of the sample is 2.75 lb and its current weight 4.14 lb, then

$$\begin{aligned}\text{Current moisture content} &= \frac{4.14 - 2.75}{2.75} \times 100\\ &= 0.5054 \times 100\\ &= 50.5 \text{ percent}\end{aligned}$$

After another day of drying, this sample may weigh 3.85 lb. The current moisture content of the sample will then be

$$\begin{aligned}\frac{3.85 - 2.75}{2.75} \times 100 &= 0.400 \times 100\\ &= 40.0 \text{ percent}\end{aligned}$$

The following shortcut formula can also be used to calculate current moisture content:

$$\text{Current moisture content} = \left(\frac{\text{Current weight}}{\text{Calculated ovendry weight}} - 1\right) \times 100$$

Substituting the above values in this formula,

$$\begin{aligned}\left(\frac{3.85}{2.75} - 1\right) \times 100 &= (1.400 - 1) \times 100\\ &= 0.400 \times 100\\ &= 40.0 \text{ percent}\end{aligned}$$

Using Samples for Kiln Schedule Changes

Kiln schedules provide for changes in kiln conditions as drying progresses. With moisture content schedules, the temperature and relative humidity are changed when the moisture content of the kiln samples reaches certain levels as defined by the particular schedule in use. If the schedules recommended in chapter 7 are used, drying conditions should be changed when the average moisture content of the wettest 50 percent of the kiln samples equals a given moisture content in the schedule. Sometimes, a kiln operator may change drying conditions according to the wettest one-third of the samples or the average moisture content of a smaller group that may be distinctly wetter or more difficult to dry than the others. These are called the controlling samples. The moisture content of the driest sample determines when equalizing should be started (ch. 7).

Using Automatic Systems

When automatic control systems are used, the use of kiln samples and moisture sections is changed somewhat. When electronic probes are used, there is no need to cut kiln samples or moisture sections. The principles of selecting sample boards still apply, however, because the probes will be inserted in sample boards. Variation in drying time between sample boards also needs to be known. When miniature load cells are used, kiln samples and moisture sections are still necessary. However, since the weights of the sample boards are taken automatically and continuously, there is no need to enter the kiln to get kiln samples. Computer interface and control do not require manual calculation of current moisture content.

The use of electronic probes that estimate moisture content from electrical resistance is growing. Such probes offer automatic control, but they currently have some limitations. The change in electrical resistance with moisture contents above 30 percent is small, so that the probes are limited in accuracy above this level of moisture content. Currently, charges in kilns that use these control systems are dried to 30 percent moisture content using home other control principle, and probes are able to control from 30 percent to final moisture content.

Intermediate Moisture Content Tests

If the moisture content of the moisture sections does not truly represent that of the kiln sample, the calculated ovendry weight of the kiln sample will be wrong. This may mislead the operator into changing kiln conditions at the wrong time, with such serious consequences as prolonged drying time, excessive drying defects, and nonuniformly dried lumber. For example, if water pockets are present in the moisture sections but not in the sample, the calculated ovendry weight of the sample will be too low and its current moisture content too high. This will lead the kiln operator to believe that the moisture content is higher than it really is, and scheduled kiln condition changes will be delayed. The end result is an unnecessary extension of drying time. Conversely, if water pockets are present in the sample but not in the moisture sections, the calculated ovendry weight of the sample will be too high and its current moisture content too low. This will lead the kiln operator to believe that the moisture content is lower than it really is, and scheduled kiln condition changes will be made too soon. The result is an acceleration of the kiln schedule that could cause drying defects. These potential problems can be avoided by making intermediate moisture content estimates.

When to Make Intermediate Tests

When the calculated moisture content of one or a few kiln samples is much higher than that of the other samples, or if their rate of drying appears to be much slower than the average rate, a moisture check should be made on those samples for a better estimate of their calculated ovendry weight. The best time for making an intermediate estimate is when the average moisture content of the samples is about 20 to 25 percent. Intermediate estimates can be made on all the samples in the charge if the operator wants an even better estimate of moisture content.

How to Make Intermediate Tests

Trim a section about 5 in long from one end of the kiln sample. Then, cut a 1-in-wide moisture section from the newly exposed end of the sample, weigh it immediately, and ovendry. Coat the freshly cut end of the shortened sample and weigh it immediately. The new weight of the sample is the new "original" weight used in equation (2). After weighing the sample, place it in its pocket in the kiln charge. As soon as the moisture section has been dried, weigh it and calculate its moisture content with equation (1). Substitute the new moisture content value, together with the new original weight of the sample in equation (2), to obtain a new calculated ovendry weight. Use the new calculated ovendry weight in equation (3) to obtain the current moisture content of the sample in all subsequent weighings.

A moisture content check may be desirable near the end of the kiln run to obtain a better estimate of when to start equalizing.

Intermediate Shell and Core Moisture Tests

Moisture content gradients are discussed in chapter 1. Sometimes, it is useful for the kiln operator to know the moisture contents of the shell (the outer part of the board) and the core (the inner part of the board). For example, in a species that is susceptible to drying defects, such as oak, it is quite important to delay raising the temperature in the kiln to the high temperatures of the last few steps in the kiln schedule until the core moisture content is 25 percent or below. Otherwise, honeycomb is likely to develop (ch. 8). However, when the core is at 25 percent moisture content, the average moisture content for the whole piece will be something less than 25 percent and thus will not always be a reliable indicator of the core moisture content. Therefore, shell and core moisture content estimates are sometimes useful. A typical moisture section, 1 in along the grain, is cut and then further cuts are made into the shell and core portions, as shown in figure 6-3. The shell and core are weighed separately and then ovendried so that the moisture content can be calculated according to equation (1).

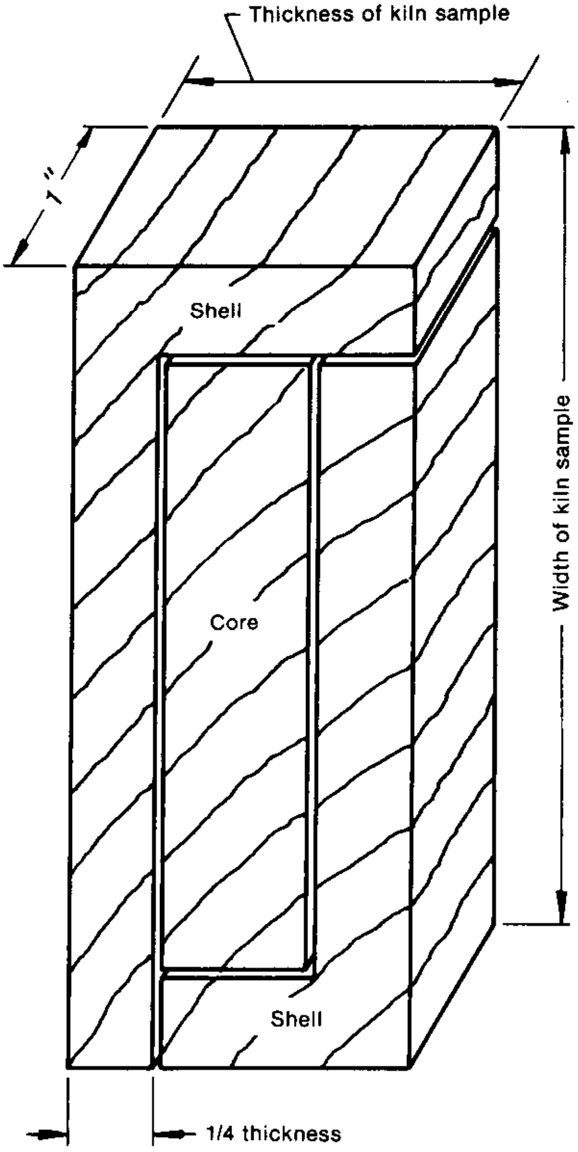


Figure 6.-3—Method of cutting section for measuring shell and core moisture content. (ML88 5586)

Final Moisture Content And Stress Tests

After the lumber has been dried to the desired final moisture content, the drying stresses relieved by a conditioning treatment (ch. 7), and the charge removed from the kiln, a final moisture content check on the sample boards is often desirable. The average moisture content as well as shell and core estimates can be made in the same way as already described.

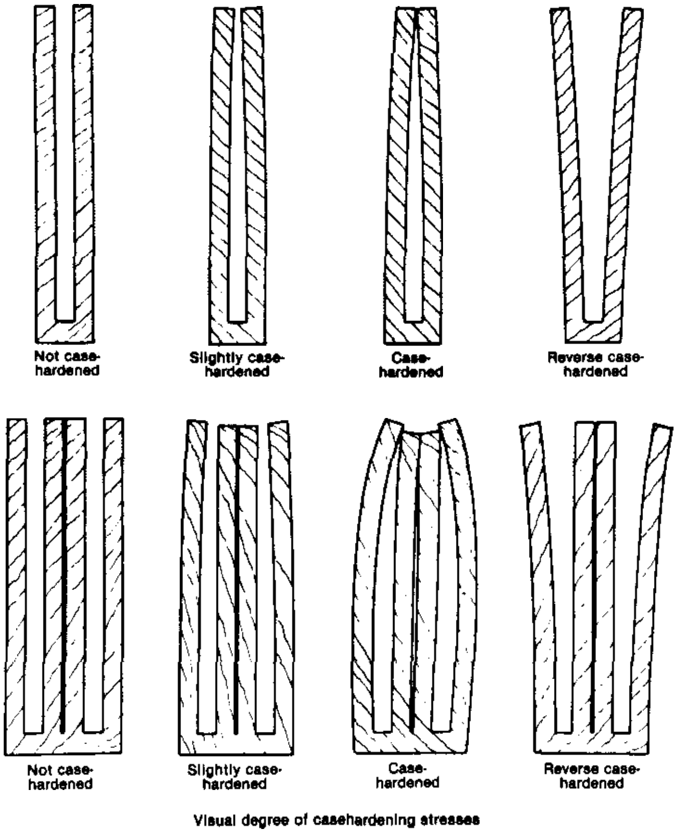


Figure 6-4—Method of cutting stress sections for casehardening tests. Lumber that is less than 1-1/2 in thick is cut into three prongs, and the middle prong is removed; lumber that is 1-1/2 in thick or thicker is cut into six prongs, and the second and fifth prongs are removed. (ML88 5585)

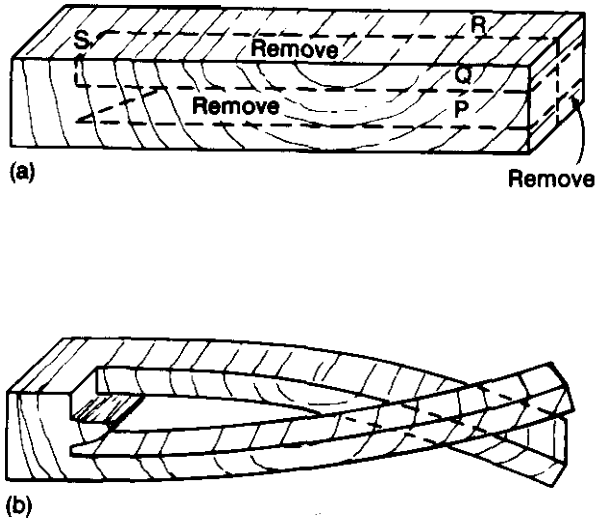


Figure 6-5—(a) Method of cutting stress sections for severe casehardening tests. (b) Prongs are offset so that they can cross and indicate severity of casehardening. (ML88 5584)

Drying stresses are discussed in chapter 1, the relief of drying stresses (conditioning) is discussed in chapter 7, and the consequences of unrelieved stresses are discussed in chapter 8. Here, we describe how to prepare and interpret stress sections. There are two basic ways to prepare stress sections. Both methods work on the principle that the stresses, that is, tension in the core and compression in the shell, will become unbalanced when a saw cut is made. Figure 6-4 shows one way to cut stress sections and illustrates the reaction of sections that are casehardened (sections with residual drying strews). When the sections have stress, the two outer prongs pinch in because the tension stress in the core is released by the saw cut. Thus, the inner faces of the prongs shorten because of the release of stresses.

In situations where drying stresses are severe, the prongs as cut in figure 6-4 will touch and in fact snap together tightly. Because they touch, it is difficult to judge the severity of the stresses. The second method of making the casehardening test visually distinguishes between severe and moderate drying stresses. The stress section is sawed to allow diagonally opposite prongs to bypass each other by an amount related to the severity of drying stresses (fig. 6-5b). The sawing diagram for preparing these sections is shown in figure 6-5a. After cutting the section from the sample board, saw on lines P and Q but do not remove the section loosened by these cuts. Saw along line R, which is approximately midway in the section's width. Saw diagonally along S and its diagonally opposite counterpart. Remove the diagonally opposite prongs and the loose center section to allow free movement for the remaining diagonally opposite prongs. If the drying stresses are severe, the prongs will cross, as shown in figure 6-6.

Unfortunately, residual drying stresses and moisture gradients sometimes interact and can cause confusion. If the core of a cut stress section is not at the same equilibrium moisture content as the air where it is cut, the moisture content of the core will change, and the inner face will either shrink and react as if casehardened, or swell and react as if reverse casehardened (fig. 6-4). Most commonly, the moisture content of the core is high enough so that the core shrinks when exposed to the surrounding air. Then, the inner face created by the saw cut loses moisture and shrinks. The result is that the prongs pinch in as if casehardened. The time required for prong movement is a good indication of whether residual drying stresses or moisture gradients cause prong movement, or if the cause is a combination of these. Residual drying stresses cause prong movement immediately, whereas a change caused by moisture content requires at least several hours to complete. If immediate prong movement is observed,

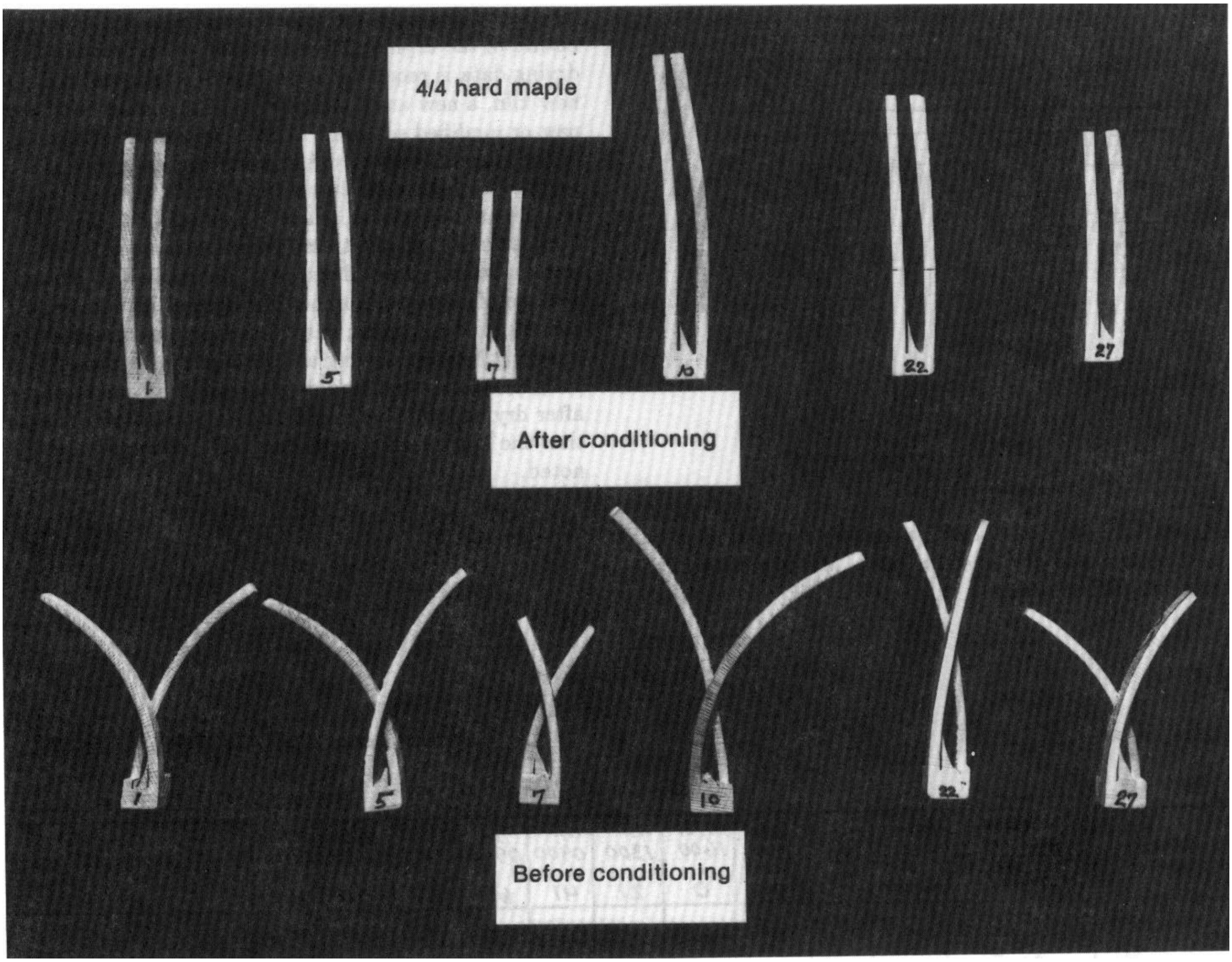


Figure 6-6—Stress sections showing crossing of prongs when sections are cut by the procedure shown in figure 6-5. (MC88 9034)

followed by additional prong movement, both factors are the cause. In either case, prong movement points to a condition that should be corrected to avoid warp upon resawing or machining (ch. 8). Either additional stress relief or equalization or both procedures are required.

Occasionally, the transverse casehardening test will show no stress, but the lumber will bow when resawed. Bowing is caused by longitudinal stress resulting from either longitudinal tension set in the surface zones or longitudinal shrinkage differentials caused by reaction wood (tension wood in hardwoods). These stresses are most likely to be unrelieved when conditioning temperature or equilibrium moisture content is too low or when conditioning time is too short. The longitudinal stress sticks in figure 6-7 show whether such stresses are present. If longitudinal stresses are a problem, conditioning should be at 180°F or higher. The lumber must have been equalized, and the recording instrument must be in calibration. If longitudinal stresses are still a problem, the wet-bulb setting can be raised 1 °F over the recommended value. Also, the conditioning period can be extended about 4 h per inch of thickness. If tension wood stresses are very severe, they may not yield to any conditioning treatment.

Recording Drying Data

Good recordkeeping of the details of kiln runs can be useful to the kiln operator in several ways: (1) for modifying drying schedules on subsequent charges to obtain faster drying without sacrificing quality, (2) for developing time schedules for certain types of lumber that are dried frequently, (3) for determining the effect of seasonal weather conditions on kiln performance and drying time, and (4) for checking kiln performance for causes of nonuniform drying or drying defects.

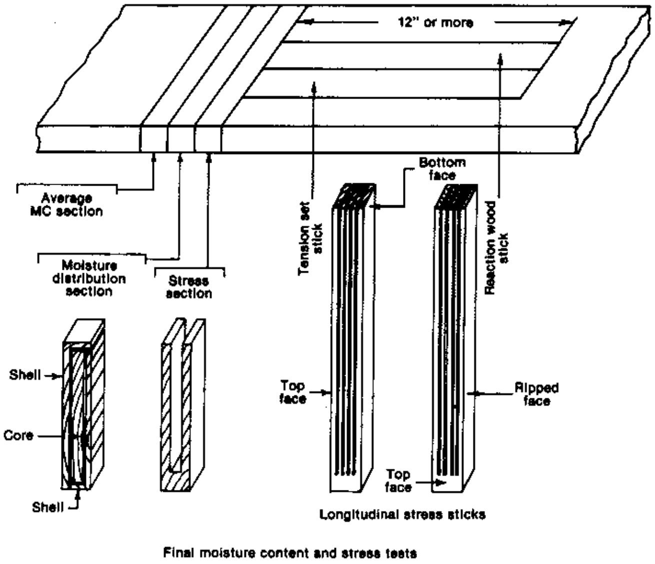
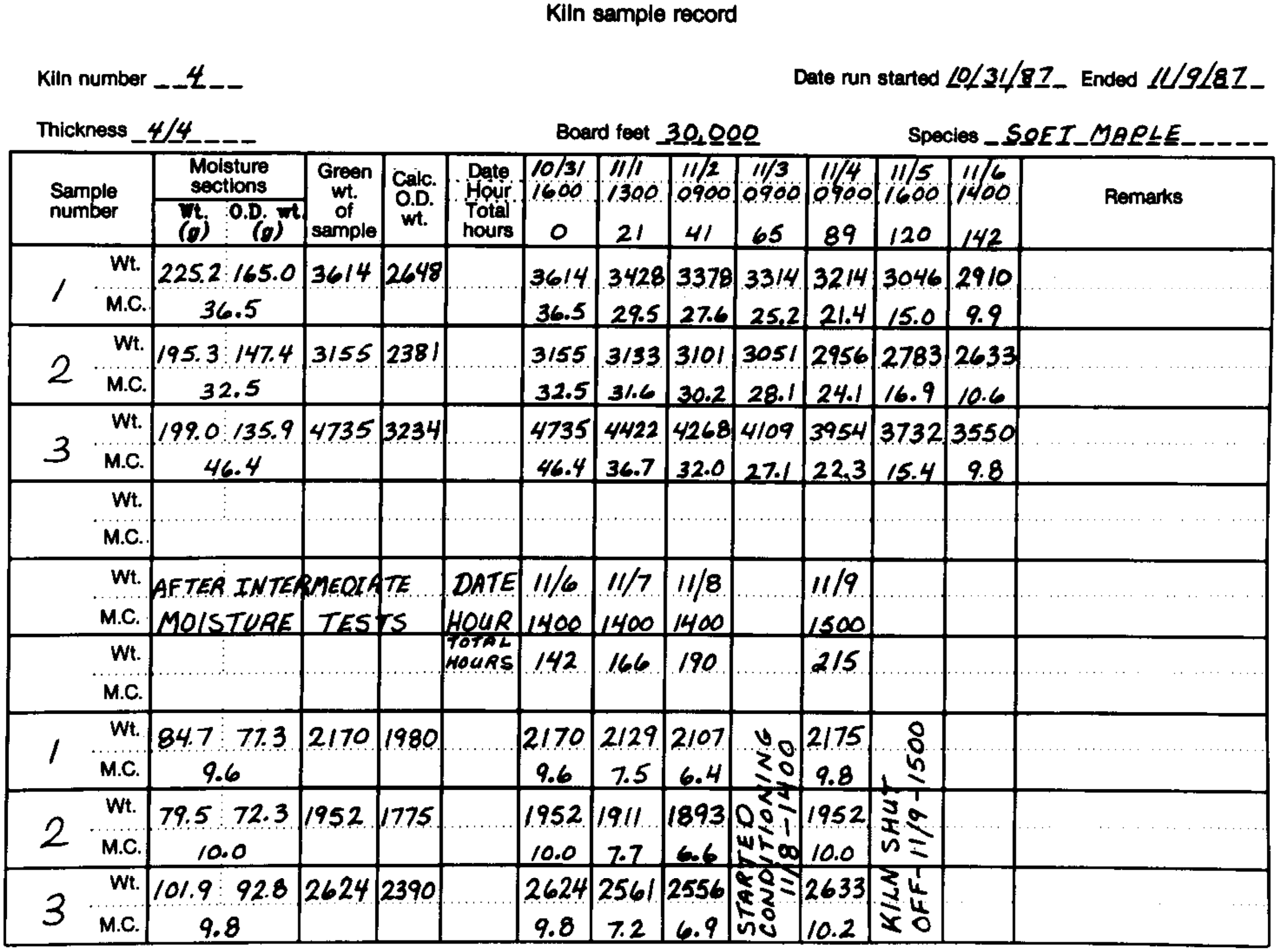


Figure 6-7—Method of cutting sections for final moisture content and drying stress tests. MC is moisture content. (ML88 5583)

The kinds of data to be recorded will vary with the nature of the drying. More than the usual amount of drying data is required in the case of a test run in a new kiln, a new and unfamiliar type of lumber, and a new or modified schedule. Also, good documentation of the kiln run may be useful when precise drying is required or high-value lumber is dried. The data can include lumber species, grade, origin (of both the lumber (sawmill) and the trees (geographical location) it was cut from), grain (flatsawn or quartersawn), percentage of sapwood, number of rings per inch, moisture content, and thickness; date of sawing; intermediate handling between sawing and drying; drying data (initial), schedule, time, and defects; handling and storage after drying; and shipping date. Any other information that the kiln operator considers relevant should also be noted.



Kiln sample record

Kiln number 4

Date run started 10/31/87 Ended 11/9/87

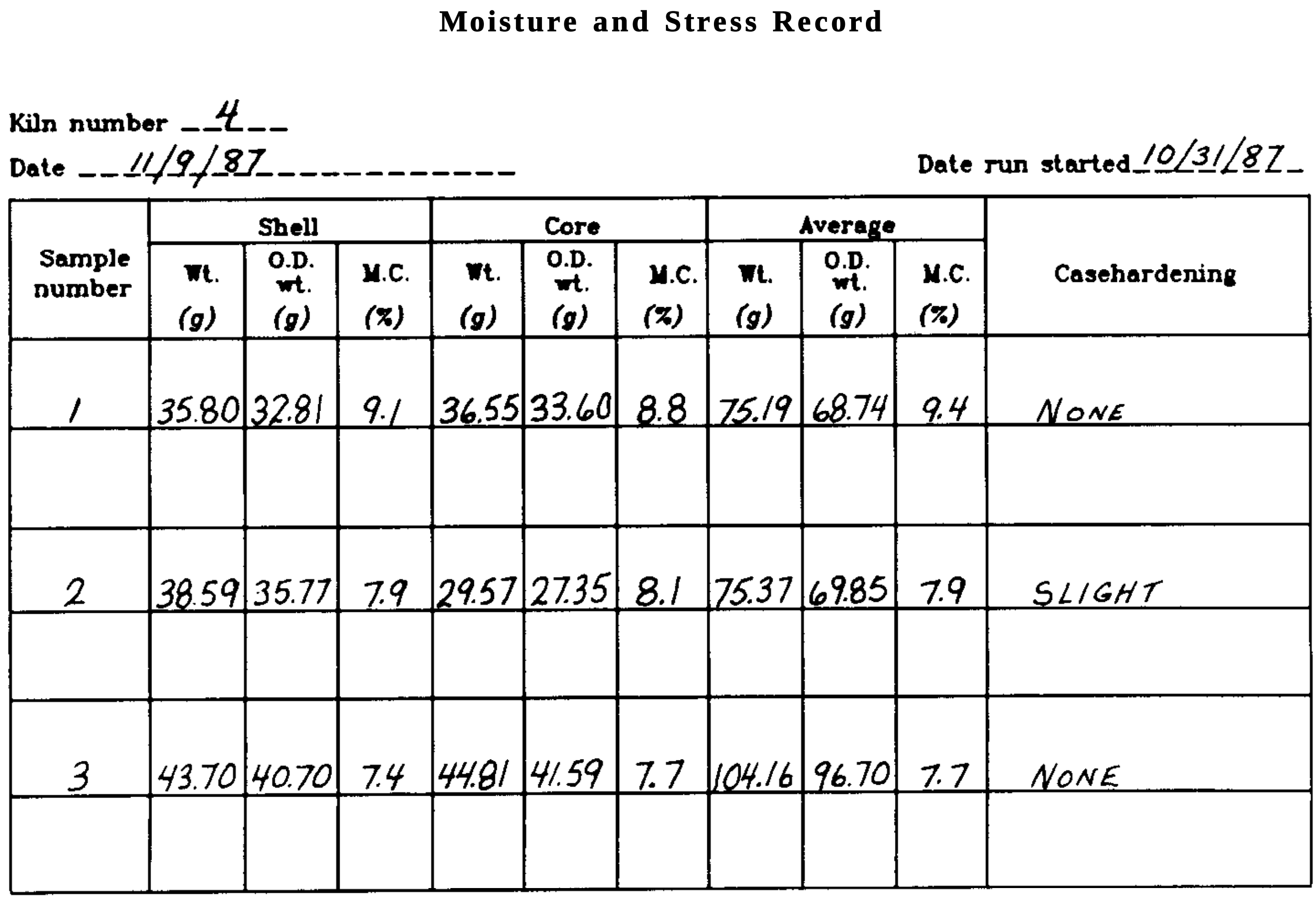
Thickness 4/4

Board feet 30,000

Species SOFT MAPLE

Sample number		Moisture sections		Green wt. of sample	Calc. O.D. wt.	Date Hour Total hours	10/31 1600 0	11/1 1300 21	11/2 0900 41	11/3 0900 65	11/4 0900 89	11/5 1600 120	11/6 1400 142	Remarks
		Wt. (g)	O.D. wt. (g)											
1	Wt.	225.2	165.0	3614	2648		3614	3428	3378	3314	3214	3046	2910	
	M.C.	36.5					36.5	29.5	27.6	25.2	21.4	15.0	9.9	
2	Wt.	195.3	147.4	3155	2381		3155	3133	3101	3051	2956	2783	2633	
	M.C.	32.5					32.5	31.6	30.2	28.1	24.1	16.9	10.6	
3	Wt.	199.0	135.9	4735	3234		4735	4422	4268	4109	3954	3732	3550	
	M.C.	46.4					46.4	36.7	32.0	27.1	22.3	15.4	9.8	
	Wt.													
	M.C.													
	Wt.	AFTER INTERMEDIATE				DATE	11/6	11/7	11/8		11/9			
	M.C.	MOISTURE	TESTS			HOUR	1400	1400	1400		1500			
	Wt.					TOTAL HOURS	142	166	190		215			
	M.C.													
1	Wt.	84.7	77.3	2170	1980		2170	2129	2107	STARTED CONDITIONING 11/8—1400	2175	KILN SHUT OFF—11/9—1500		
	M.C.	9.6					9.6	7.5	6.4		9.8			
2	Wt.	79.5	72.3	1952	1775		1952	1911	1893		1952			
	M.C.	10.0					10.0	7.7	6.6		10.0			
3	Wt.	101.9	92.8	2624	2390		2624	2561	2556		2633			
	M.C.	9.8					9.8	7.2	6.9		10.2			

Figure 6-8—Form used for recording kiln sample data in a dry kiln run of 4/4 air-dried soft maple. Data for 3 of 10 kiln samples are shown. (ML88 5582)



Moisture and Stress Record

Kiln number 4

Date 11/9/87

Date run started 10/31/87

Sample number	Shell Wt. (g)	Shell O.D. wt. (g)	Shell M.C. (%)	Core Wt. (g)	Core O.D. wt. (g)	Core M.C. (%)	Average Wt. (g)	Average O.D. wt. (g)	Average M.C. (%)	Casehardening
1	35.80	32.81	9.1	36.55	33.60	8.8	75.19	68.74	9.4	NONE
2	38.59	35.77	7.9	29.57	27.35	8.1	75.37	69.85	7.9	SLIGHT
3	43.70	40.70	7.4	44.81	41.59	7.7	104.16	96.70	7.7	NONE

Figure 6-9—Form for recording final moisture content and drying stress data for three kiln samples. (ML87 5321)

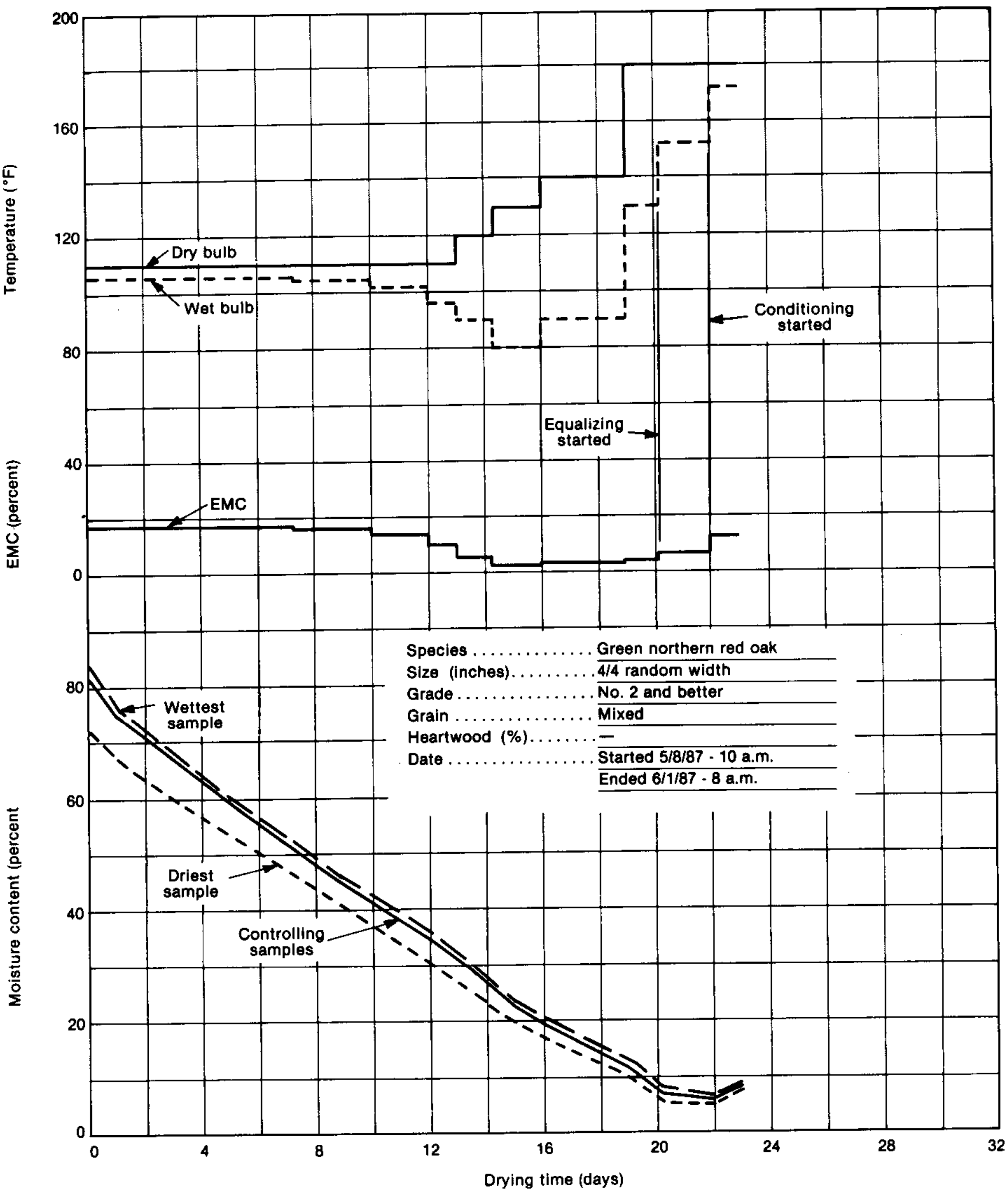
Forms for Recording Data

Kiln sample data should be recorded on suitable forms, such as ones supplied by kiln manufacturers. Many kiln operators develop their own forms to fit their specific needs. Two forms are shown in figures 6-8 and 6-9. Drying data obtained for each sample during the kiln run can be entered on a kiln sample record form (fig. 6-8). Other data such as kiln number, lumber volume, species, thickness, and starting and ending dates for the run can be entered as required in a heading. The form in figure 6-8 is for only three sample boards. This form also shows data recorded for intermediate moisture content estimates and the moisture regained during the conditioning treatment. The weight of the end coating used on the kiln samples can also be recorded, if required.

Data for the final moisture and drying stress tests can be recorded on a form like the one shown in figure 6-9. The degree of casehardening present in the lumber is noted on this form. Supplemental moisture data obtained with a moisture meter should also be recorded.

Graphs of Drying Data

Graphs of drying data show at a glance the time required to reach certain moisture contents. A plot of the moisture contents of several kiln samples is shown in the lower portion of figure 6-10 for 4/4 northern red oak. The curve illustrates the steady loss of moisture over the entire drying period. Curves plotted from data obtained from each sample are useful for checking kiln performance and the reliability of the moisture contents of the kiln samples. For example, if the moisture loss data from some samples in several charges in the same zones in a kiln consistently indicate a slower or faster drying rate than that of the other samples in the charges, this is evidence of a cold or hot zone or different air circulation in that location. The source of trouble can usually be found and corrected. On the other hand, if it is known or if an investigation shows that the cause is not associated with a cold or hot zone or different air circulation, the calculated ovendry weight of the kiln sample may be inaccurate and an intermediate moisture content estimate is needed.



Species .... Green northern red oak
Size (inches).......... 4/4 random width
Grade .... No. 2 and better
Grain .... Mixed
Heartwood (%)........ —
Date .... Started 5/8/87 - 10 a.m.
Ended 6/1/87 - 8 a.m.

Figure 6-10—Graph showing kiln-drying schedule and moisture content at various times during drying of 4/4 northern red oak. EMC is equilibrium moisture content. (ML88 5581)

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Chapter 7
Kiln Schedules

Chapter 7 was revised by William T. Simpson, Supervisory Research Forest Products Technologist, and R. Sidney Boone, Research Forest Products Technologist.

A kiln schedule is a carefully worked-out compromise between the need to dry lumber as fast as possible and, at the same time, to avoid severe drying conditions that will cause drying defects (ch. 8). It is a series of dry- and wet-bulb temperatures that establish the temperature and relative humidity in the kiln and are applied at various stages of the drying process. Temperatures are chosen to strike this compromise of a satisfactory drying rate and avoidance of objectionable drying defects. The stresses that develop during drying (ch. 1) constitute the limiting factor that determines the kiln schedule. The schedules must be developed so that the drying stresses do not exceed the strength of the wood at any given temperature and moisture content. Otherwise, the wood will crack either on the surface or internally, or be crushed by forces that collapse the wood cells. Wood generally becomes stronger as moisture content decreases, and, to a lesser extent, it becomes weaker as temperature increases. The net result is that as wood dries, it becomes stronger because of the decreasing moisture content and can tolerate higher drying temperatures and lower relative humidities without cracking. This is a fortunate circumstance because as wood dries, its drying rate decreases at any given temperature, and the ability to raise the drying temperature helps maintain a reasonably fast drying rate. Thus, rapid drying is achieved in kilns by the use of temperatures as high as possible and relative humidities as low as possible. For hardwoods, relative humidity can generally be reduced substantially before temperature can be raised substantially.

Drying stresses are related to the difference between the moisture content of the interior and surface of the lumber. The extent of this difference is related to the kiln temperature, relative humidity, and airflow as well as the characteristics of the species. The larger the difference in moisture content, the greater the drying stresses. If the drying stresses become too great, they can exceed the strength of the wood and cause surface and internal cracks. Many kiln schedules are based on average moisture content of the wood because it indicates the difference in moisture content between the interior and surface of the wood.

Kiln schedules can be classified as general or special. General schedules are intended for drying lumber intended for almost any product and will do a satisfactory job. Special schedules are those developed to attain certain drying objectives; for example, to reduce drying time, dry chemically treated lumber, or maintain maximum strength of the lumber for special uses. Because of the many variables in the character of wood, type and condition of kiln, quality of drying required, and cost considerations, no schedule presented in this chapter can be considered ideal. The schedules are pre sented as guides for kiln operators in developing schedules best suited for their own particular operation. In general, the schedules presented are conservative and can often be accelerated with care; this chapter also outlines procedures for systematically accelerating a schedule.

Commercial kilns use different methods for drying hardwoods and softwoods. In general, hardwood lumber is slower drying and more susceptible to defects than softwood lumber. Also, most end uses of kiln-dried hardwood lumber require uniformity of moisture content and permit few drying defects. Softwoods, on the other hand, generally dry faster and more uniformly than hardwoods, and are less susceptible to drying defects. Also, most structural lumber is made from softwoods, and the standards for such lumber are lower in regard to drying defects and tolerance of moisture content. The net result is that hardwoods are generally kiln dried by moisture content schedules; that is, dry- and wet-bulb temperatures are changed when the lumber reaches certain moisture contents. Softwoods, on the other hand, are generally kiln dried by time schedules—whether the wood is intended for structural lumber or for appearance uses, such as furniture or millwork. In time schedules, dry- and wet-bulb temperatures are changed after certain periods with no estimate of moisture content as a guide. Moisture content schedules can often be changed to time schedules after lumber of the same species, thickness, and source is repeatedly dried in the same kiln.

Satisfactory time schedules have been worked out for drying softwood lumber of a uniform character in the same type of kiln. An operator inexperienced in drying softwoods may want to consider a moisture content schedule as a safer way to get started and then switch over to a time schedule later. Even though moisture content schedules are rarely used for softwood lumber, they are included in this manual for the occasions when they might be useful.

The schedules listed in this chapter are designed for use in kilns where the air velocity is approximately 400 ft/min. The general schedules are conservative enough to produce lumber with a minimum of drying defects in a reasonably short time. The operator should not make the schedules more conservative unless there is some specific reason for doing so, such as abnormal lumber or poor kiln performance. With properly maintained kilns, the general schedules can usually be modified to shorten drying time.

The schedules presented in this manual are also presented in the report by Boone et al. (1988) referenced at the end of this chapter. In this report, the kiln schedules are completely written out rather than coded, and thus the report serves as a quick reference source for schedules.

Hardwood Schedules

General Hardwood Schedules

Pilot testing and considerable commercial experience have demonstrated that the general schedules developed by the Forest Products Laboratory for steam-heated kilns, which are presented in this chapter, are satisfactory for drying 2-in and thinner hardwood lumber. They form the base from which an operator can develop the most economical schedule for a specific type of kiln. Related information on application and modification of the schedules is also presented together with suggestions for drying thick hardwoods.

Moisture Content Basis

Both drying rate and susceptibility to drying defects are related to the moisture content of lumber, so kiln schedules are usually based on moisture content. The successful control of drying defects as well as the maintenance of the fastest possible drying rate in hardwood lumber depends on the proper selection and control of temperature and relative humidity in the kiln.

At the start of drying, a fairly low temperature is required to maintain maximum strength in the fibers near the surface to help prevent surface checks (ch. 8). The relative humidity should be kept high early in drying to minimize the surface checking caused by the tension stresses that develop in the outer shell of lumber (ch. 1). Even at these mild initial kiln conditions, the lumber will lose moisture rapidly. Therefore, each combination of species and thickness (and in some cases, end product) has been classified into a schedule code of "T" number for temperature and "C" number for wet-bulb depression settings. To maintain a fast drying rate, relative humidity must be lowered gradually as soon as the moisture content and stress condition of the wood will permit. Wood becomes stronger as moisture content decreases and can withstand higher drying stresses. As a general rule, relative humidity can be safely lowered gradually after the green wood has lost about one-third of its moisture content. The temperature generally cannot be raised, even gradually, until the average moisture content reaches about 30 percent. These first temperature changes must be gradual because at about this moisture content the stresses begin to reverse; that is, the core of the lumber goes into tension (ch. 1), and the danger of internal honeycomb becomes a concern. When the moisture content at midthickness is below 25 to 30 percent moisture content (which means the average moisture content for l-in-thick lumber is about 20 percent), it is generally safe to make a large increase in dry-bulb temperature in order to maintain a fast drying rate. In thicker lumber of some dense species, it is necessary to bring average moisture content down to 15 percent to get midthickness moisture content down to 25 to 30 percent. If the temperature is raised too soon while the core is still wet and weak, the danger of honeycomb is great in some species such as oak. An ample number of kiln samples should be used to make good estimates of these critical moisture contents. The recommended operating procedure is to take the average moisture content of the wetter half of the kiln samples—called the controlling samples-as the factor that determines when to change drying conditions (ch. 6).

Material Considerations

The general schedules are for hardwoods that are to be dried from the green condition. They can be modified to apply to previously air-dried lumber. The schedules are for the more difficult to dry types of lumber in a species-for example, flatsawn heartwood. Because of the difference in the moisture content of sapwood and heartwood in many species, most of the kiln samples should be taken from the wettest heartwood and their moisture content used in applying the kiln schedule. Modifications are suggested later in this chapter for lumber that is all or predominately sapwood.

Recommended Schedules for Steam-Heated Kilns

Schedules for dry-bulb temperatures and wet-bulb depressions are given in tables 7-1 and 7-2. Together, the dry-bulb temperature and the wet-bulb depression determine the relative humidity and the wood equilibrium moisture content (EMC) (ch. 1, table 1-6).

Table 7-1 lists 14 temperature schedules ranging from a very mild schedule, T1, to a severe schedule, T14. In all cases, initial temperatures are maintained until the average moisture content of the controlling samples reaches 30 percent.

Table 7-2 lists the wet-bulb depression schedules for six moisture content classes. These classes are related to the green moisture content of the species (table 7-3). Another moisture content class, H, will be discussed later. There are eight numbered wet-bulb depression schedules; number 1 is the mildest and number 8, the most severe. The wet-bulb temperature to be set on the recorder-controller is obtained by subtracting the wet-bulb depression from the dry-bulb temperature.

Table 7-4 is an index of recommended schedules for 4/4 to 8/4 hardwood lumber and other products. While the same schedule is listed for 4/4, 5/4, and 6/4 lumber, these thicknesses obviously will have different drying times and should be dried separately. For drying 6/4 lumber of refractory species such as oak, the 8/4 schedule may be desirable.

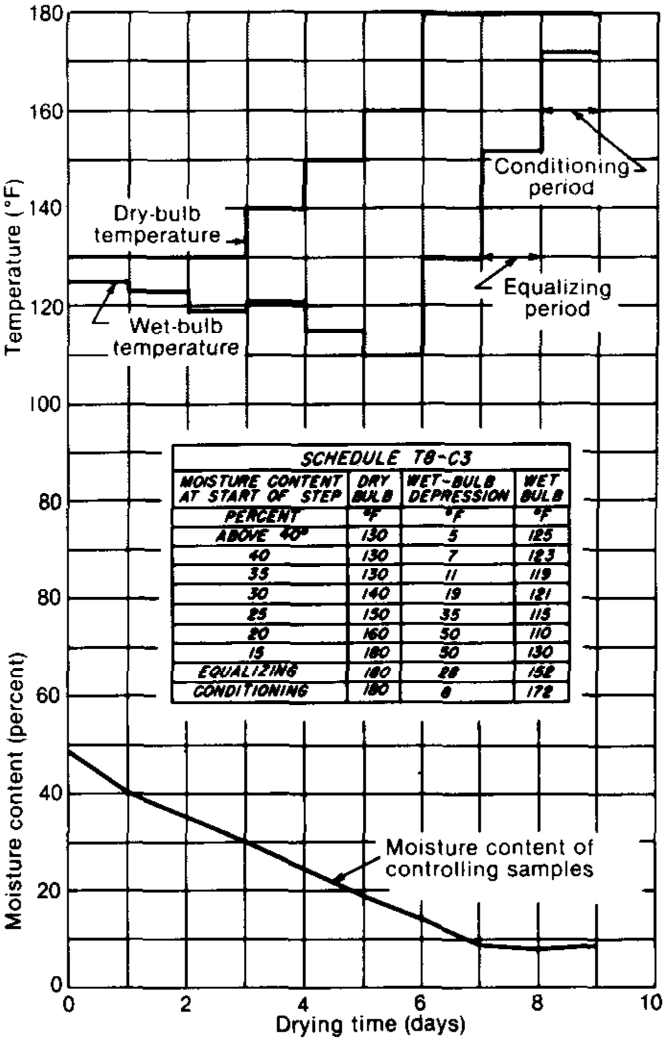
There are 672 possible schedules in tables 7-1 and 7-2. There is no demonstrated need for so many schedules, nor have they all been tested. They merely represent a systematic way to develop the whole range of degrees of severity in kiln schedules. The combination of experience and judgment then allows one to estimate an appropriate schedule.

Kiln-drying hardwoods thicker than 8/4 from the green condition is often impractical because of the long kiln time. A common practice is to either air dry the lumber before kiln drying or use a predryer before kiln drying. Table 7-5 is an index of suggested schedules for 10/4 and thicker hardwood lumber. These schedules are not as well established as the schedules for thinner lumber and should be used with caution.

Assembly of a Drying Schedule

A form such as the one in table 7-6 can be used to assemble a drying schedule as follows:

1. From table 7-4, find the schedule code number for the lumber to be dried. In table 7-6 the code numbers are T8-C3 for 4/4 sugar maple. Place the code numbers at the top of the form.
2. Since the first change in drying conditions involves the wet-bulb depression, write the wet-bulb depression step numbers 1 through 6 in column 2.
3. In column 3, write the moisture content values corresponding to these steps from the appropriate moisture content class of table 7-2. In this example, the class is C, so the values are >40, 40, 35, 30, 25, and 20.
4. In column 5, write the wet-bulb depression values corresponding to the steps from the appropriate wet-bulb depression schedule number from table 7-2. In this example, the number is 3, so the wet-bulb depression values are 5, 7, 11, 19, 35, and 50.
5. In column 1, write the temperature step numbers. Since dry-bulb temperature changes are not made until the average moisture content of the controlling samples reaches 30 percent, repeat temperature step number 1 as often as necessary. In this example, it is repeated three times. The moisture content at the start of temperature step 5 is 15 percent (table 7-1). Therefore, in filling out the schedule form it is necessary to repeat wet-bulb depression step 6, as shown in table 7-6. Experienced kiln operators usually omit columns 1 and 2.



SCHEDULE T8-C3			
MOISTURE CONTENT AT START OF STEP	DRY BULB	WET-BULB DEPRESSION	WET BULB
PERCENT	°F	°F	°F
ABOVE 40°	130	5	125
40	130	7	123
35	130	11	119
30	140	19	121
25	150	35	115
20	160	50	110
15	180	50	130
EQUALIZING	180	28	152
CONDITIONING	180	8	172

Figure 7-1—Kiln schedule and drying curve for 4/4 sugar maple. (ML88 5608)

6. In column 4, write the dry-bulb temperature that corresponds to the temperature step number in table 7-1. If step 1 is repeated, the initial dry-bulb temperature must be repeated, as shown in table 7-6.
7. Subtract the wet-bulb depression from the dry-bulb temperature in each step to obtain the corresponding wet-bulb temperature. These values are entered in column 6.

Columns for relative humidity and EMC, which are helpful in understanding drying, can be added at the right of the table if desired. These values can be obtained from table 1-6 in chapter 1. The T8-C3 schedule for 4/4 sugar maple and a drying curve obtained in a kiln run are illustrated in figure 7-1.

Uniformity of moisture content and relief of drying stresses are achieved by equalizing and conditioning treatments near the end of drying, as described later in this chapter.

Examples of Assembled Schedules

Some schedules for hardwoods, assembled from tables 7-1 and 7-2, are illustrated in table 7-7. A study of these will be helpful when assembling schedules for other species.

The schedules listed in tables 7-1 and 7-2 may be conservative for some types of dry kilns and for some drying requirements. With experience, an operator should be alert to the possibility of modifying schedules to reduce drying time. Schedule modifications are discussed later in this chapter.

Use of Schedules for Air-Dried or Predried Lumber

The general schedules for green hardwoods are also recommended for kiln drying lumber that has previously been air dried or dried in a predryer. Most kiln samples should be prepared from the wettest and slowest drying boards, but should include at least one sample from the driest and fastest drying boards (ch. 6).

For 4/4, 5/4, and 6/4 (except oak) lumber that has been dried to 20 to 30 percent moisture content, the following procedure applies:

1. Bring the dry-bulb temperature up to the value prescribed by the schedule for the average moisture content of the controlling kiln samples, keeping the vents closed and the steam spray turned off.
2. After the kiln has reached the dry-bulb temperature, set the wet-bulb temperature.
   a. If the air-dried or predried lumber has not been wetted on the surface or exposed to a long period of high humidity just before entering the kiln, set the wet-bulb temperature as specified by the schedule.
   b. If there has been surface wetting or moisture regain, set the wet-bulb controller for a 10 °F wet-bulb depression and turn on the steam spray. Let the kiln run 12 to 18 h at this wet-bulb setting, and then change to the wet-bulb setting specified by the schedule.

For 6/4 and 8/4 oak that has been dried to 20 to 30 percent moisture content, the following procedure applies:

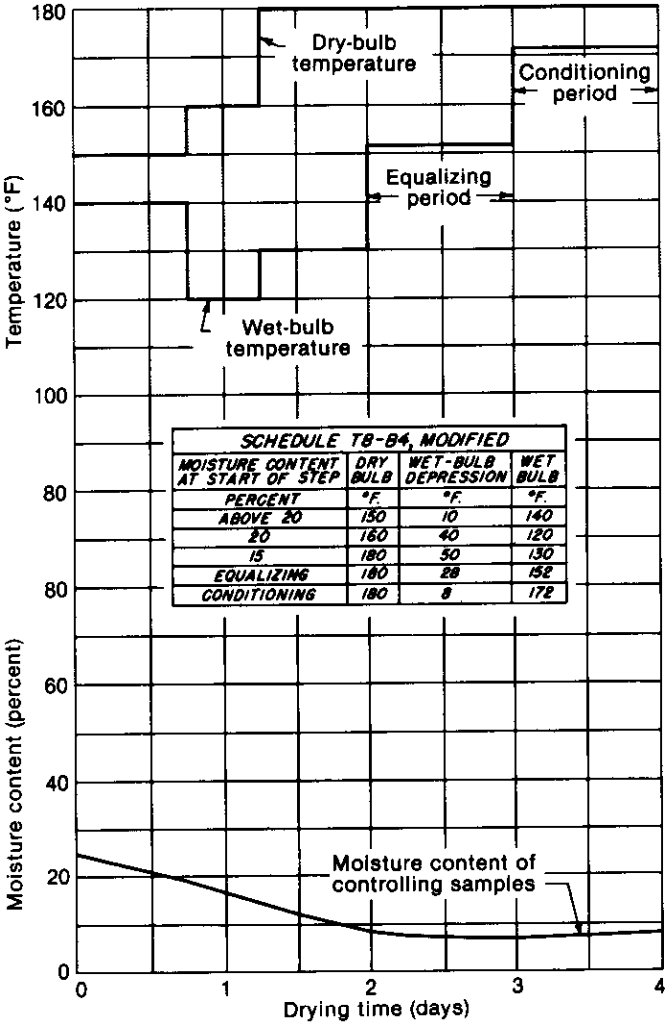
1. Bring the dry-bulb temperature up to the value prescribed by the schedule for the average moisture content of the controlling kiln samples, keeping the vents closed. Use steam spray (manually) only as needed to keep the wet-bulb depression from exceeding 12 °F.
2. After the kiln has reached the dry-bulb temperature, set the wet-bulb temperature.
   a. If there has been no surface moisture regain, set the wet-bulb temperature at the level specified by the schedule.
   b. If there has been surface moisture regain, set the wet-bulb controller for an 8 °F wet-bulb depression and turn on the steam spray. Let the kiln run for 18 to 24 h at this setting. Then set a 12 °F depression for 18 to 24 h before changing to the conditions specified in the schedule.

If the moisture content of lumber going into the kiln is much above about 30 percent, the procedure for lumber that has been only partially air dried or predried is slightly different. For 4/4, 5/4, and 6/4 (except oak) lumber, the following procedure applies:

1. Bring the dry-bulb temperature up to the value prescribed by the schedule for the average moisture content of the controlling kiln samples. Keep the vents closed and use steam spray only as needed to keep the wet-bulb depression from exceeding 10 °F. Do not allow the depression to become less than 5 °F or moisture may condense on the lumber.
2. After reaching the prescribed dry-bulb temperature, run each of the first three wet-bulb depression steps of the whole schedule a minimum of 12 h, but still observe the 5 °F minimum wet-bulb depression. Then change to the conditions prescribed for the moisture content of the controlling samples.

For partially dried 6/4 and 8/4 oak, the following procedure applies:

1. Bring the dry-bulb temperature up to the value prescribed by the schedule for the average moisture content of the controlling kiln samples. Keep the vents closed and use steam spray only as needed to keep the wet-bulb depression from exceeding 8 °F. Do not allow the depression to become less than 5 °F.
2. After the prescribed dry-bulb temperature has been reached, run each of the first three wet-bulb depression steps of the schedule a minimum of 18 h while still observing the 5 °F minimum wet-bulb depression. When the kiln conditions coincide with those prescribed by the schedule for the average moisture content of the controlling samples, change to the moisture content basis of operation.



SCHEDULE T8-B4, MODIFIED			
MOISTURE CONTENT AT START OF STEP	DRY BULB	WET-BULB DEPRESSION	WET BULB
PERCENT	°F.	°F.	°F.
ABOVE 20	150	10	140
20	160	40	120
15	180	50	130
EQUALIZING	180	28	152
CONDITIONING	180	8	172

Figure 7-2—Kiln schedule and drying curve for air-dried 4/4 black cherry that has regained surface moisture before entering the kiln. (ML88 5607)

The kiln-drying conditions for 4/4 air-dried black cherry that has regained surface moisture before entering the kiln are shown in figure 7-2.

Air-dried lumber should not be subjected to high humidity at the start of kiln drying. This may cause surface checks to open during subsequent drying and thereafter remain open. It may also increase warping.

Modifications to General Hardwood Schedules

Once a kiln operator has dried a certain species and item by one of the general kiln schedules without causing defects or excessive degrade, modification of the schedule should be considered to reduce drying time. Perhaps the lumber can stand a more severe schedule without developing serious defects, or the dried product does not need to be free of defects. The operator should try to develop the fastest drying schedules consistent with acceptable amounts and types of defects. Schedules should be modified in a systematic way, for which good records will be helpful. It must be recognized, however, that schedule modification satisfactory for lumber from one source and dried in one kiln may not be satisfactory for lumber from another source and dried in a different kiln.

Kiln schedule modifications required by factors of kiln operation or performance are dealt with in chapter 9. Drying charges of mixed species are also discussed in chapter 9.

The first move in systematic schedule modification is to shift from one wet-bulb depression schedule to another, the second is to shift temperature schedules, and the third is to modify certain steps within the schedule.

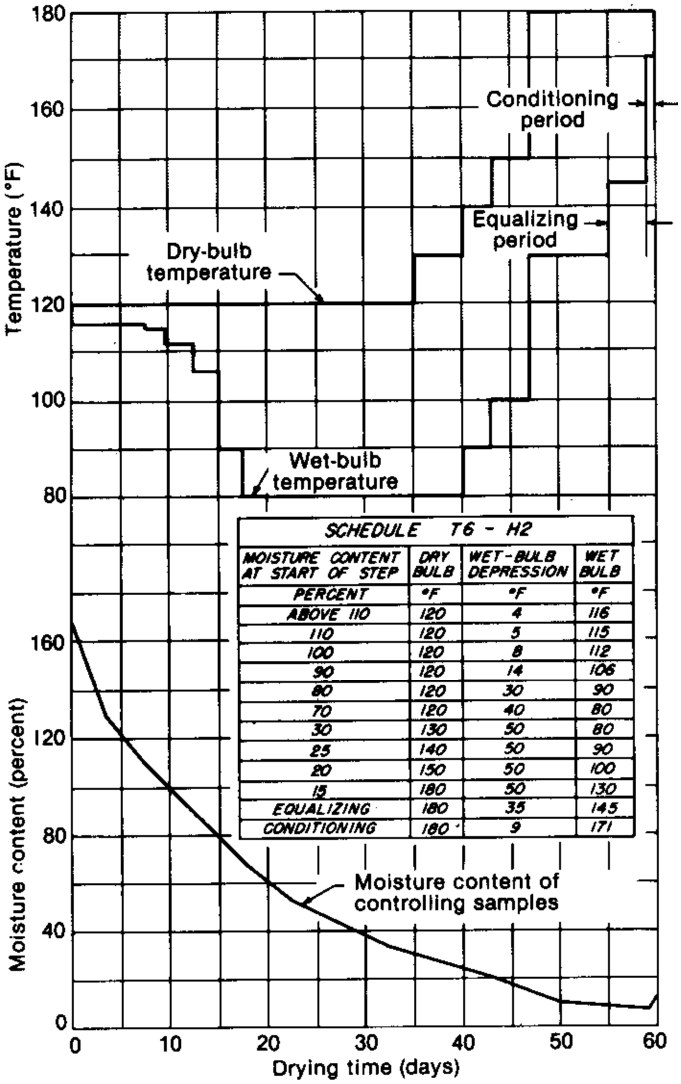
Shifting Wet-Bulb Depression Schedules

The moisture content classes (table 7-3) are set up so that a species of wood can be classified in accordance with the green moisture content of its heartwood. The moisture content limits of the classes were chosen on a conservative basis. Thus, the first modification that a kiln operator should consider is to shift to a higher moisture class, particularly if the green moisture content is near the upper end of the values in the class. For example, 4/4 northern red oak at 95 percent moisture content has been successfully dried in pilot tests on the E2 instead of the D2 schedule, with a saving of 4 or 5 days in drying time. By going to the E2 schedule, the first increase in wet-bulb depression is made at 60 percent moisture content rather than at 50 percent. This modification is especially useful when the lumber to be dried is mostly sapwood.

The next modification that should be considered is to shift to the next higher wet-bulb depression schedule number. This modification results in an increased wet-bulb depression at each moisture content level. It may cause minor surface and end checks that are generally of little concern for many uses. A drastic change in wet-bulb depression may cause severe surface and end checks.

Using H-Type Wet-Bulb Depression Schedules

A special moisture content class, designated as H, has been devised to permit more use of the principles that the first change in wet-bulb depression can be made when one-third of the green moisture content is gone and that additional increases in wet-bulb depression can be made soon after. This is particularly useful in drying species with a green moisture content of greater than 140 percent, but may also be applied with some advantage to lumber with a green moisture content of 100 percent or more. The H schedules are given in table 7-8. The wet-bulb depression schedule numbers are the same as those in table 7-2.



SCHEDULE T6 - H2			
MOISTURE CONTENT AT START OF STEP	DRY BULB	WET-BULB DEPRESSION	WET BULB
PERCENT	°F	°F	°F
ABOVE 110	120	4	116
110	120	5	115
100	120	8	112
90	120	14	106
80	120	30	90
70	120	40	80
30	130	50	80
25	140	50	90
20	150	50	100
15	180	50	130
EQUALIZING	180	35	145
CONDITIONING	180	9	171

Figure 7-3—Kiln conditions and drying curve for 1-1/2-in-thick water tupelo heartwood, based on H schedule T6-H2. (ML88 5606)

To set up a specific H schedule, find the moisture content for the first change in wet-bulb depression by taking two-thirds of the average green moisture content of the controlling samples. If, for example, their average green moisture content is 168 percent, the first change point is 112 percent. For convenience, this is rounded to 110. Subsequent changes in wet-bulb depression are made after each 10 percent loss in moisture. An H schedule developed for 6/4 water tupelo heartwood is shown in figure 7-3. In view of the long drying time in this particular case, preliminary air drying or predrying should be considered. However, H schedules are applicable to other, faster drying species.

Shifting Temperature Schedules

Temperature is critical in preventing collapse and honeycomb, two defects that may not appear until later in the drying process. Until the kiln operator has gained experience in drying a particular species and thickness, the recommended temperature schedule number should be followed. The general temperature schedules will safely dry most lumber used in commercial drying. If the lumber being dried is almost all sapwood or is relatively free of natural characteristics that contribute to drying defects, increasing the temperature (T) number by 1 or 2 to obtain a 10 °F greater initial temperature generally is permissible. For example, 9/4 all-sapwood sugar maple free of pathological heartwood and mineral streak has been dried on a T7 temperature schedule instead of the recommended T5 schedule. The milder T5 schedule would be used for drying a charge of sugar maple that had a considerable amount of heartwood or mineral streak.

Changes Within the Schedule

The only significant change that can be made within a wet-bulb depression schedule is a more rapid reduction of wet-bulb temperature during the intermediate stages of drying. The logical approach is to increase the wet-bulb depression in steps 3 and 4 of table 7-2. This modification should be approached with caution, and several charges should be dried before making further modification. If any objectionable amount of checking occurs, ease back the wet-bulb depression to the previously satisfactory schedule.

Three types of temperature changes within the T schedules (table 7-1) can be considered. One is to use a temperature in the initial stage of drying that is between that of steps 1 and 2 of the recommended schedule. For some slow-drying species, such as 4/4 red oak, using an initial temperature of 115 °F instead of 110 °F until the lumber reaches 30 percent moisture content may be satisfactory if experience has shown no surface checking at 110 °F. Another type of change is to increase the dry-bulb temperature during the intermediate stages of drying. This is the most dangerous change because of the possibility of honeycomb in some species and should be approached with caution. A third type of change is to increase the temperature during the last stages of drying. After the average moisture content of the controlling samples has reached 15 to 20 percent, temperatures of 200 °F or greater can be used without damaging the wood. Research and experience are beginning to show that many hardwood species that have been dried to below 15 to 20 percent can be safely dried the rest of the way at temperatures as high as 230 °F.

Special Hardwood Schedules

Although the general hardwood schedules, with minor modifications, will do a good job of drying most species for most end uses, special purpose schedules are advantageous in some cases. Some examples follow.

Maximum Strength Schedules

Exposure of wood to temperatures above 150 °F can cause some permanent reduction in strength. At kiln temperatures of 200 °F or less, only long exposure would cause excessive strength reduction. Thus, the general drying schedules and proper operating procedues do not significantly reduce the strength of the lumber; lumber strength is sufficient for most end uses. However, when the wood is to be used for products requiring high strength per unit weight, such as aircraft, ladders, and sporting goods, somewhat lower temperatures should be used in drying. Table 7-9 lists temperature schedule code numbers for various softwood and hardwood species, and table 7-10 lists the actual maximum drying temperatures at various moisture contents recommended for these schedules. For example, from table 7-9, 1-in-thick Sitka spruce has a temperature schedule number of 2. Then, from table 7-10, the maximum drying temperature at 40 percent moisture content is 145 °F. Any general schedule used should thus be modified to stay below these maximum temperatures. Wet-bulb depressions should remain the same as listed in the general schedules.

Alternative Schedules for Some Species

Some species have peculiar drying characteristics or there is some other reason for a special drying schedule. Some of the more useful schedules are mentioned in the following paragraphs; these and other special schedules are described in table 7-11.

Hickory.—Upper grades of hickory are sometimes used for high-quality specialty products, such as tool handle stock, and require a slightly more conservative schedule than that listed in table 7-4.

Swamp and water tupelo.—The heartwood and sapwood of swamp and water tupelo have quite different drying characteristics. When the heartwood and sapwood can be separated, it is advantageous to dry them separately by different schedules.

Aspen.—Aspen trees sometimes develop a darkened area of wet-pocket wood in the center of the tree. This wood is slow drying and susceptible to collapse; it is usually present in the lower grade boards sawn from the center of the log. The upper grades of lumber sawn from the outside of larger logs can ***still*** be dried by the recommended general schedule.

Sugar maple.—Some end uses of sugar maple put a premium on the whitest color possible for sapwood, and the special schedule in table 7-11 will accomplish this. Also sugar maple sometimes has mineral streaks that are impermeable and subject to collapse and honeycomb during drying.

Red oak.—The red oaks are subject to a bacterial infection that invades the living tree and subsequently causes the lumber to be more susceptible to drying defects. There is little if any visual difference between bacterially infected and noninfected lumber. Often, however, infected oak has a characteristic rancid odor. With care, bacterially infected oak can be dried with a minimum of surface checks and honeycomb by using schedules listed in table 7-11.

Red and white oak—In sawing lumber from logs, the saw usually leaves small tears and fractures in the surface fibers of a board. These tears are points of weakness where drying stresses can cause surface checks to occur. If these boards are lightly surfaced, the tears are removed and the boards are less likely to surface check. As a result. the kiln schedule can be accelerated.

Time Schedules

Hardwood time schedules have been developed for some of the western hardwoods and are listed in table 7-12.

High-Temperature Schedules

High-temperature kiln drying is usually defined as the use of dry-bulb temperatures above 212 °F, usually in the range of 230 to 250 °F. Research and limited experience have shown that many of the low-density hardwoods can be dried at high temperatures while still maintaining quality. Schedules for these species are shown in table 7-13.

Schedules for Imported Species

The same principles that govern the selection of schedules for domestic species also apply to imported species. The schedules recommended in table 7-14 were gathered largely from the world literature on lumber drying. Table 7-14 is arranged by common name, and the scientific names can be found in chapter 1, table 1-2.

Schedule for Presurfaced Northern Red Oak

Presurfacing of lumber before kiln drying can result in reduced degrade from warping and practically eliminate surface checking. The technique, when combined with an accelerated schedule, can lead to 16 to 30 percent savings in drying time for 4/4 red oak. Other benefits of presurfacing include increased volume per kiln load and reduction of planer jams in the rough mill. Successful use of this technique depends on uniform air velocity of about 400 ft/min, well-baffled loads, accurate temperature and humidity control, adequate moisture content sampling, and a knowledgeable kiln operator. The cost to initiate and use the system is minimal.

The procedure is simple and only requires that the rough lumber be surfaced on two sides prior to stacking for drying. A double surfacer can be placed near the lumber grading station and ahead of the automatic stacker. Conveyors can feed the lumber and take it away from the planer. An alternative to using a knife planer in the line is to install an abrasive planer using 24- or 36-grit belts.

Whichever way the planing is done, the machine should be set to remove equal amounts from each side of the boards. For example, lumber sawed 1-1/8 in thick in the rough can be planed to 1-1/32 in by taking 3/64 in from each face; if the boards are sawn to reasonably uniform thickness, 80 percent of the pieces will have clean faces for their full length.

No change is required in the stacking operation, assuming the usual good practices are followed, including uniform sticker thickness and spacing, good vertical alignment, box piling, and support for ends of boards. One or two extra courses can generally be stacked in a unit package of surfaced lumber compared to a package of rough lumber of the same height. No change is required in kiln loading procedures when using surfaced lumber, again assuming good pile support, good alignment, and proper baffling are already practiced.

One major reason for presurfacing lumber before drying is to be able to accelerate the drying and thereby reduce costs. Existing schedules can be used, and it is possible to save about 10 percent in drying time as compared with drying rough lumber. Part of this saving is due to reducing or eliminating the thickness variation between boards and to the fact that the lumber is slightly thinner than rough stock.

Research work on oak drying has shown that because surfacing reduces the potential for checking and splitting, higher temperatures can be used earlier in the kiln run. McMillen (1969) developed a schedule for accelerated drying of presurfaced 1-in-thick northern red oak (table 7-13). Tests of this schedule on various loads of red oak in a variety of kilns have shown that 16 to 30 percent drying time can be saved in commercial kilns, if the schedule is followed as designed. In terms of kiln days, this means 4/4 oak can be safely dried green from the saw to 7 percent moisture content in 18 days instead of 21 to 28 days.

Successful use of this schedule depends on the following:

1. The kiln equipment must be in good repair—accurate calibration of the recorder-controller; good adjustment of vents, automatic valves, and traps; and proper operation of fan and baffle system.
2. The kiln load must be well stacked and baffled so the air velocity through the load is at least 400 ft/min.
3. Drying must be controlled with well-selected kiln samples. A minimum of six samples are recommended; eight are preferred for better knowledge of moisture content distribution.
4. The kiln operator must be confident that the drying information is accurate and must make schedule changes promptly.

There are two disadvantages to presurfacing lumber prior to drying: (1) since hardwood lumber is graded in the rough form, surfacing the boards may change the grade and make any dispute about the original grade difficult to settle and (2) if a planer is not readily available for presurfacing, the added cost of the machine may not be justifiable. This could especially be true if the rough lumber was very accurately sawn.

Softwood Schedules

Softwood Moisture Content Schedules

The softwood moisture content schedules presented in this chapter can be used with the kiln sample procedure of chapter 6 to dry softwood lumber with a minimum of drying defects. These schedules are described for the sake of the few instances where they might be used and for the sake of maintaining knowledge about them. Because softwoods are generally easy to dry, industry practice has gone to almost exclusive use of time schedules. Time schedules will be discussed in the next section.

Moisture Content Basis

As in the drying of hardwoods, there is a relationship between the moisture content of the lumber and the drying conditions the lumber can withstand. Although the stress patterns that develop in softwood lumber during drying differ from those in hardwood lumber, the surface zones do become stressed in tension (so that surface checking is a danger) during the early stages of drying and ultimately become stressed in compression. However, stress reversal generally does not occur until the lumber reaches a moisture content somewhere between 20 and 15 percent-a little lower than in hardwoods. Therefore, wet-bulb depressions should not be drastically increased until the lumber reaches this moisure content level. Gradual changes in wet-bulb depression can be made early in drying, however, in accordance with the moisture content of the lumber. The temperature and moisture content relationships that cause collapse and honeycombing in hardwoods affect softwoods similarly.

Material Considerations

The difference between sapwood and heartwood moisture content is considerable in many softwoods (ch. 1, table 1-5). Generally, the heartwood is more susceptible to drying defects, so most of the schedules are based on the moisture of the heartwood. In some situations, however, the heartwood dries to a safe moisture content level before the sapwood is dry enough to stand a drastic increase in wet-bulb depression. In these cases, the schedules are based on the moisture content of the sapwood or of a mixture of sapwood and heartwood.

Wetwood or sinker stock can be a problem when drying some softwood species such as redwood, hemlock, sugar pine, eastern and western white pine, and the true firs. This is wood that contains so much water and so little air in the cell cavities that it sometimes sinks in water. Wetwood dries slowly and is subject to collapse if too high a temperature is used during the initial stages of drying. If practical, it is desirable to sort the green softwoods of species prone to wetwood into different weight or moisture content classes and dry each separately.

The softwood moisture content schedules are intended for drying green lumber, but they can be applied to partially air-dried lumber as well.

Moisture Content Schedules

The softwood moisture content schedules are given in tables 7-15 and 7-16. These schedules are similar *to* the general schedules for hardwoods, except for a few important differences. Wet-bulb depressions of 40 °F or more are avoided until the controlling moisture content reaches 15 percent. Changes in wet-bulb depression between 15 and 35 °F are made gradually, 5 °F at a time. For drying lower grades, final wet-bulb depressions generally do not exceed 20 °F. The main features of moisture content schedules of this type were discussed in the Hardwood Schedules section in this chapter. In the moisture content method of operation, the initial temperature is maintained until the controlling kiln samples have an average moisture content of 30 percent.

Table 7-17 is an index of recommended schedules for 4/4, 6/4, and 8/4 softwood lumber, of both upper and lower grades. The schedules for lower grade lumber generally call for lower final temperatures and smaller final wet-bulb depressions to reduce loosening of knots and to hold planer splitting to a minimum.

Table 7-18 is an index of suggested schedules for 10/4 and thicker softwoods. The drying time may be too long for ordinary commercial operations, but the schedules are suitable for special cases where thick lumber of upper grades is to be dried.

Instructions for assembling a softwood moisture content schedule are the same as those given for hardwoods.

Kiln Drying Air-Dried Lumber

Since preliminary air drying is uncommon for softwoods that are to be kiln dried (except for redwood, incense cedar, and western redcedar), recommended schedules for kiln drying air-dried lumber have not been developed. The following steps are suggested for the assembly of such a schedule.

1. Determine the moisture content of representative samples of slow- and fast-drying boards (ch. 6) and use the average moisture content of the wettest half of the samples as the controlling moisture content.
2. Use the temperature step of the recommended schedule corresponding to that moisture content (table 7-15).
3. If the controlling moisture content is above 40 percent, dry the lumber as green.
4. If the controlling moisture content is 40 percent or less, change the wet-bulb depression as follows:
    a. Use a depression of 10 to 15 °F for the initial 8 to 16 h.
    b. After this period, if the controlling moisture content is between 15 and 25 percent, change the wet-bulb depression to 20 °F.
    c. Use a wet-bulb depression of 30 °F or more after the lumber reaches 15 percent moisture content.

Modifying Softwood Moisture Content Schedules

The principles described for hardwood schedule modification generally can be applied to softwoods.

Commercial Softwood Time Schedules

Most western and southern softwood mills use time schedules to dry both upper and lower grade lumber. The drying conditions are changed at convenient intervals, such as every 12 or 24 h or multiples thereof. A wide range of schedules has been developed at individual mills or by individual researchers, and these schedules are often modified. The schedules given here represent schedules that should serve as a satisfactory starting point for kiln operators. They are intended as a guide from which an operator can develop the best schedule for the particular drying requirements and type of kiln at the mill. Time schedules are dependent on the rate of air circulation and kiln performance because these affect drying rate. The conventional-temperature schedules in this chapter are based on the performance of single-track or double-track kilns that are equipped with booster coils and for a minimum air velocity of 400 ft/min. The high- temperature schedules are intended for kilns with 800 to 1,000 ft/min air velocity.

Conventional-Temperature Kiln Schedules

The recommended schedules aye indexed in table 7-19, and the schedules themselves are written out in table 7-20. Because the schedules were developed from a wide diversity of actual schedules, the times given in the last step are for guidance only. The actual time required for individual kiln charges may vary from the times given. If at the end of a kiln run the moisture content level and the degree of moisture content uniformity do not meet requirements, modify the schedule or the equalizing time, or both, on subsequent charges. The length of time of the last step in the schedule is often modified to attain the desired target final moisture content. The most common procedure used to adjust drying time for variations in initial moisture content is to use the same initial and intermediate drying steps and then to lengthen or shorten the final step to reach the desired final moisture content. In winter when lumber is sometimes quite wet when placed in the kiln, the initial step is prolonged or is preceded by a milder step.

Lumber from trees that have been dead for some time, such as insect-killed trees, is likely to be lower in moisture content and therefore require less drying time than lumber from trees that were alive at the time of harvesting. Lumber from dead trees may be more susceptible to surface checking.

High-Temperature Kiln Schedules

The usual range of temperatures for high-temperature drying of softwoods is from 230 to 250 °F, although the current trend is for even higher temperatures. High-temperature drying of some softwood species has become common in the last 15 to 20 years. Although tests have shown that significant strength loss occurs in some western species, southern pine apparently is much less affected than other species and shows little or no strength loss. The effect of strength loss should be considered when selecting a kiln schedule for a product where loss of bending or tension strength is important.

Since the mid-1970's the majority of new kilns built for drying southern pine dimension lumber have been high-temperature kilns, and most of these have been direct-fired rather than steam-heated kilns. Wet-bulb control is not as precise in direct-fired kilns, and conditioning is generally not possible because steam spray is lacking. However, direct-fired kilns are usually less costly to build than steam-heated kilns and generally perform satisfactorily for southern pine lumber.

The species index of schedules is given in table 7-21, and the actual schedules are written out in tables 7-22 and 7-23.

Softwood Schedules for Special Purposes

Some softwood lumber and items require or benefit from special precautions or schedules, and the following sections discuss some of these special needs.

Brown-Stain Control

Brown stain is a discoloration of wood that can occur during kiln drying as a result of a change in the color of substances normally present in some softwoods. It can be a significant problem in drying sugar pine, eastern and western white pine, ponderosa pine, sinker hemlock heartwood, and the southern pines. Brown stain is most prevalent during hot and humid months. It occurs in logs that have been stored in water or on sprinkled log decks for long periods. The storage time between when lumber is sawed and dried should be kept to a minimum, especially if the lumber is solid piled.

Brown stain can be severe when high dry- and wet-bulb temperatures are used at the start of the schedule. If it is a problem, the initial dry-bulb temperature should be dropped so as not to exceed 120 °F. Use as large a wet-bulb depression as the lumber will tolerate without excessive surface and end checking. A suggested schedule based on moisture content for eastern and western white pine and sugar pine is given in table 7-24, and schedules based on time are provided in table 7-25. (See following section if setting the pitch is necessary.)

Setting Pitch and Retaining Cedar Oil

Kiln schedules can be modified either to retain oil in wood, as in drying eastern redcedar used for cedar chests, or to set pitch that might exude later from pine and cause paint and finishing problems by bleeding through. High temperature in the presence of moisture and steam causes volatile oils and resins to vaporize. Therefore, when drying eastern redcedar, avoid high temperatures and do not condition the lumber unless it is absolutely necessary because it will be resawed or surfaced unequally.

On the other hand, to set pitch it is desirable to drive off the volatile turpentine and other solvents normally present. This can be done most easily at the start of drying by using a high temperature. However, if brown stain is a problem, the best compromise is to use the anti-brown-stain schedule at the start of drying and finish with a dry-bulb temperature of at least 160 °F. A temperature of 160 °F is usually satisfactory for 4/4 lumber, but the final temperature for thicker lumber should be at least 170 °F.

Lumber Treated With Waterborne Preservatives or Fire Retardants

Some softwood species, particularly southern pine and Douglas-fir lumber and plywood, are often treated with fire retardants and preservatives. Preliminary drying is required before either treatment; the lumber can be predried in the same way as lumber that is not treated. During treatment, however, the lumber or timbers reabsorb considerable water, and they are often redried after treatment. The chemicals used in treatment usually accelerate the strength-reducing effects of prolonged exposure of moist wood to high temperatures. Research is in progress to help set maximum recommended drying temperatures for treated wood products where strength is critical, but until those temperatures are better defined the usual recommendation is to not exceed 190 °F for wood treated with waterborne preservatives and 160 °F for wood treated with fire retardants (Winandy 1988). Table 7-26 shows several satisfactory schedules for treated Douglas-fir plywood.

Maximum Strength Schedules

Maximum drying temperatures for maintaining maximum strength were discussed earlier in this chapter. The maximum temperatures for softwoods for each moisture level are shown in table 7-10, and the species code numbers for finding these temperatures are shown in table 7-9.

Bevel Siding, Venetian Blinds, and Other Resawed Products

Softwood lumber that is to be resawed into bevel siding, venetian blinds, or other products should be properly equalized and conditioned (see section on equalizing and conditioning treatments) to obtain a uniform moisture content over the cross section and to relieve drying stresses. Otherwise, the resawed halves of the boards will quite likely cup (ch. 8). Before equalizing, use the final wet-bulb depression given in the schedules to achieve a low average moisture content as soon as possible.

Bundled Short-Length Items

Most drying of bundled short-length items takes place from the end-grain surfaces. Because some of these items do not end or surface check readily, kiln schedules for them can be rather severe. Other items, however, still require low dry-bulb temperatures to avoid collapse.

Because western redcedar shingles produced from wet stock that is logged in low areas may collapse, the shingles are dried with an initial dry-bulb temperature of about 95 °F. This temperature is gradually increased over a 10- to 14-day period to 150 °F or higher. Shingles produced from stock at a relatively low moisture content can be started at 150 °F or higher and finished at 180 °F. In both cases, wet-bulb temperature is not controlled, and the vents are kept open.

Incense cedar pencil stock is usually dried from a green to partially dry condition in the form of 3-in planks or squares and then cut into thin slats and graded. These slats are treated with a small amount of wax, bundled, and treated with a water-soluble dye. Because the treatment generally is a full-cell process in which all cell cavities become filled with liquid, the slats may collapse under severe drying conditions. Use low temperatures and high relative humidities at the start of drying and gradually make them more severe as drying progresses. Drying times are quite long, usually 23 to 30 days.

Pine squares, which are 4/4, 5/4, and 6/4 in cross section and 24 to 36 in long, are dried in bundles about 5 in square. Use a constant kiln temperature of 140 °F dry bulb and 110 °F wet bulb. Drying time is 13 to 14 days. Similar drying conditions can be used on other short items made of easily dried softwoods.

Large Timbers and Poles

It is not customary to kiln dry large timbers or poles of many species because of the long drying times required. Such wood is usually air-dried or used green. One notable exception is southern pine. Because of its relative ease of drying and extensive use, successful high-temperature schedules have been developed for southern pine; several schedules are given in table 7-27 for crossarms and poles. Timbers with cross sections of 4 to 5 in are often used for decking and as such require proper drying with a minimum of surface checks. Schedules for such timbers are given in table 7-28. Even more so than with other schedules presented in this chapter, these specialized schedules represent a starting point for the kiln operator to build on. In many cases, the objective of kiln drying large timbers is only to dry the outer shell of the timber to either control surface checking or remove water so that the outer shell can be treated with a waterborne preservative.

Tank Stock

Lumber for tank stock can be dried by the schedules used for the upper grades of the same thickness. Since the stock is used in contact with water or aqueous solutions, it should not be dried lower than 15 to 20 percent moisture content. Therefore, equalization (see Equalizing and Conditioning Treatments section) should be done at an equilibrium moisture content (EMC) of about 12 percent.

Knotty Pine Lumber

Knotty pine lumber is often used for decorative purposes and thus has higher appearance requirements than other low-grade pine lumber. The moisture content or time schedules given for lower grade lumber are generally satisfactory for preventing excessive checking or loosening of knots during the first stages of drying. Drying time, however, should be prolonged to reach a final moisture content of 7 to 8 percent. Somewhat lower relative humidities may be needed to reach this final moisture content without prolonging drying. The pitch should be set with a final temperature of at least 160 °F. Conditioning to relieve stresses is also desirable.

Dehumidification Kiln Schedules

Dehumidification kilns began gaining use in the United States in the late 1970's and have grown in popularity since then. Because of their relative newness, a wide range of schedules is not available for recommendation. The moisture content schedules recommended in this chapter should be satisfactory for most purposes. The major difference between schedules for steam-heated and dehumidification kilns is temperature limitation. Dehumidification kilns cannot attain the common 180 °F final temperature of most conventional schedules. Early dehumidification kilns were limited to a maximum temperature of 120 °F, which resulted in prolonged drying times below the fiber saturation point. Newer models can operate up to 160 °F and can approach the drying times of steam-heated kilns.

The schedules for steam-heated kilns can be converted for use with a dehumidification kiln, as shown in table 7-29. The schedule T4-C2 for 4/4 white oak is converted to accommodate a maximum dry-bulb temperature of 120 °F. To make the conversion, substitute 120 °F for those dry-bulb temperatures above 120 °F and then maintain an EMC in the dehumidification schedule step about the same as in the conventional schedule step. A similar conversion can be made for a dehumidification kiln with a 160 °F maximum temperature, although the converted schedule will differ only in the last step of the schedule. Note that some dehumidification kiln manufacturers recommend that their equipment not be operated at dry-bulb temperatures above 160 °F and wet-bulb temperatures above approximately 110 to 120 °F.

An ideal application of dehumidification kilns is their use in minimizing surface checking in the early stages of drying refractory species. Low dry-bulb temperatures and high relative humidities are sometimes difficult to maintain in steam-heated kilns, particularly in hot weather. Often, the use of steam spray to increase relative humidity only raises the dry-bulb temperature without reducing the wet-bulb depression. In a tightly built dehumidification kiln, it is possible to maintain dry-bulb temperatures of 90 °F or less while still maintaining a relative humidity of 80 percent or more. These conditions are quite successful in preventing surface checking. A general purpose, low-temperature schedule is suggested in table 7-30. Variations of this schedule that apply the general principle of low initial dry-bulb temperature and high humidity followed by a gradual increase of dry-bulb temperature and decrease of relative humidity should also be successfull.

Sterilizing, Equalizing, and Conditioning Treatments

Sterilizing Treatments

A sterilizing treatment can be used in the dry kiln to stop the growth of excessive mold on the surface of wood under certain conditions (ch. 8). The dry kiln can also be used to sterilize wood that has been infected with stain or decay fungi or attacked by wood-destroying insects.

Mold

Mold can develop on green lumber in a kiln operating at temperatures up to 120 °F. Although the mold generally does not penetrate the wood enough to cause serious stain during kiln drying, it can fill up the air spaces in a load of lumber and seriously interfere with air circulation. Not only does this slow drying as a whole, but the lumber under the mold may honeycomb later in drying when the temperature is raised under the false belief that moisture content is low enough to safely raise the temperature.

To sterilize for mold, the kiln charge (green lumber only) should be steamed at or near 100 percent relative humidity at a dry-bulb temperature of 130 °F or higher for 1 h after all parts of the kiln have reached that temperature. After steaming, the normal drying schedule should begin. Infrequently, two sterilizing treatments may be required about a day apart to stop the development of mold. If the growth is not heavy enough to block air circulation, sterilization is not necessary.

Fungal Stain and Decay

The temperatures normally used at the start of kiln drying are usually high enough to stop the growth of stain or decay organisms that may have infected green wood during storage or air drying. A temperature of 110 °F stops the growth of these organisms but does not kill them. Tests show that a temperature of 150 °F or higher for at least 24 h should kill all stain and decay fungi. As long as the wood is kept below 20 percent moisture content, new stain and decay will not start.

Insects

Both softwoods and hardwoods are attacked by a number of wood-boring insects, whether the wood is green or dry. Imported lumber or air-dried lumber that has been stored for a long time should be examined for evidence of insects. If they are found, a sterilizing treatment should be given.

Lyctus (powder-post) beetles and their eggs and larvae are killed by heating the lumber according to the schedule given in table 7-31. The schedule conditions include allowances for heating the lumber to the center, for cold spots in the kiln, and for additional time as a safety factor. To sterilize, use an EMC that is within 2 percent above or below the moisture content of the wood. If the wood has less than 8 percent moisture content, a temperature above 140 °F and a relative humidity somewhat below 60 percent should give satisfactory results, using the times given in table 7-31 for the 130 °F temperature. Exact data on temperatures and times required to kill other insects are not available, but the higher temperature schedule of table 7-31 may be adequate.

Normal kiln drying or temperature sterilization will not prevent future infestation by insects.

Equalizing and Conditioning Treatments

Equalizing and conditioning have been mentioned several times in this manual, and the purpose of this section is to discuss them in detail. Frequently, the moisture content of lumber varies considerably among boards in a kiln charge. This can be because of natural variability in drying rate or initial moisture content, heartwood and sapwood, or wet pockets in the lumber, or variability in drying conditions in various parts of the kiln. Variation in final moisture content can cause serious problems in the subsequent processing and use of the lumber. The purpose of equalizing is to reduce this variation in moisture content.

The drying stresses discussed in chapter 1 often remain in boards even after drying is complete. These residual drying stresses (often called casehardening although there is no actual hardening of the surface) can cause problems of warp and saw blade pinching in manufacture and use (ch. 8) and should be removed from the lumber for many end uses. The purpose of conditioning is to relieve the residual compressive drying stresses in the shell by plasticization with high temperature and high relative humidity. Conditioning has another beneficial effect of producing more uniform moisture content throughout the thickness of the boards. Effective equalizing is necessary before satisfactory conditioning can be accomplished because the effectiveness of conditioning depends on moisture content.

Conditioning is not really necessary for softwood dimension lumber that will be kiln dried to an average moisture content of 15 percent or a maximum of 19 percent; furthermore, it is not effective at such a high moisture content. Equalizing may be necessary or desirable for such lumber. On the other hand, equalizing and conditioning are usually necessary for hardwood or softwood lumber that will be dried to below 11 percent moisture content and used in end products with stricter requirements.

Equalizing and conditioning treatments also depend on the type of kiln schedule. Equalizing depends on knowledge of the variability of moisture content between boards. The only way to get this information is through tests. When a moisture-content-based schedule is used with kiln samples, the samples will serve as the basis for equalizing and can also be used to prepare stress sections (ch. 6). When a time-based schedule is used without kiln samples, it is more difficult to devise effective equalizing and conditioning treatments. One way to devise an equalizing treatment is to use an electric moisture meter during the last stages of drying to estimate variability. If this is done, care must be taken to ensure that the correct temperature is applied to the meter reading. The other way to devise an equalizing treatment to follow a time-based schedule is to develop, by experience, a time-temperature schedule that equalizes relative humidity. This will later minimize rejects in processing lumber with surface fuzziness in planing caused by high moisture content or with planer splits caused by low moisture content. Similarly, the options for developing conditioning treatments to follow a time-based schedule are to cut stress sections or to ascertain the need and develop the procedures for conditioning through trial and error.

The following procedures are based on the use of kiln samples for equalization and stress sections for conditioning. The basic principles can be applied to develop procedures for time-based equalizing and conditioning. The procedures given will be satisfactory for lumber that is dried to final average moisture content of from 5 to 11 percent. Table 7-32 contains basic information on the moisture content of the kiln samples and the kiln EMC conditions for these treatments. Wet-bulb depression values required to obtain desired EMC conditions are given in chapter 1, table 1-6.

Equalizing Treatment

The procedure for equalizing a kiln charge of lumber, using table 7-32, is as follows:

1. Start equalizing when the driest kiln sample in the charge has reached an average moisture content 2 percent below the desired final average moisture content. For example, if the desired final average moisture content is 8 percent, start equalizing when the driest kiln sample reaches 6 percent.
2. As soon as the driest sample reaches the moisture content value stated in step 1, establish an equalizing EMC in the kiln equal to that value. In the example given in step 1, the equalizing EMC would be 6 percent. During equalizing, use as high a dry-bulb temperature as the drying schedule permits.
3. Continue equalizing until the wettest sample reaches the desired final average moisture content. In the example given in step 1, the wettest sample would be dried to 8 percent.

If the equalizing treatment is to be followed by a conditioning treatment, it may at times be necessary to lower the temperature to obtain the desired conditioning EMC condition. If so, begin by lowering the temperature 10 °F 12 to 24 h prior to the start of conditioning. Also, lower the wet-bulb temperature to maintain the desired equalizing EMC.

Conditioning Treatment

The conditioning treatment, whether or not preceded by an equalizing treatment, should not be started until the average moisture content of the wettest sample reaches the desired final average moisture content.

The procedure for conditioning is as follows:

1. The conditioning temperature is the same as the final step of the drying schedule or the highest temperature at which the conditioning EMC can be controlled. For softwoods, set the wet-bulb temperature so the conditioning EMC will be 3 percent above the desired final average moisture content. For hardwoods, the conditioning EMC is 4 percent above the desired final average moisture content. The wet-bulb depression that will give the desired conditioning EMC is given in chapter 1, table 1-6. If, at the dewed conditioning temperature, a wet-bulb depression value is not shown for the desired EMC, choose the wet-bulb depression value for the nearest higher EMC given for that temperature. Set the desired wet-bulb temperature for the proper depression but do not raise the dry-bulb temperature above the equalizing temperature until after the proper wet-bulb temperature is attained.

   Example: Assume a hardwood species with a desired final moisture content of 8 percent and a conditioning temperature of 170 °F. The conditioning EMC from table 7-32 is 12 percent. At 170 °F, an 8 °F wet-bulb depression will give an EMC of 12.4 percent (table 1-6). If the lumber is a softwood, the conditioning EMC would be 11 percent and the wet-bulb depression 10 °F.
2. Continue conditioning until satisfactory stress relief is attained.

The time required for conditioning varies considerably with species and lumber thickness, the type of kiln used, and kiln performance. At a conditioning temperature of 160 to 180 °F, hardwoods generally require 16 to 24 h for 4/4 lumber and up to 48 h for 8/4 lumber. Some 4/4 softwood species can be conditioned in as short as 4 h. If conditioning temperatures are lower than 160. to 180 °F, conditioning time will be prolonged.

The most exact way to determine when conditioning is complete is the casehardening test described in chapter 6. Conditioning time should not be continued any longer than necessary because of excessive steam consumption and excessive moisture pickup, particularly in low-density species.

If tests for average moisture content are made immediately after the conditioning treatment, **the moisture** content obtained will be about 1 to 1-1/2 percent above the desired value because of the surface moisture regain. After cooling, the average moisture content should be close to that desired.

Kiln-Drying Time

The approximate time required to kiln dry softwood lumber can be estimated from some of the time schedules given earlier in the chapter. Table 7-33 lists approximate drying times for 1-in-thick softwood and hardwood species. The times listed are for kiln drying at conventional temperatures where the final schedule temperature is approximately 180 °F. Lumber thicker than 1 inch will take longer to dry than the times given in table 7-33. The increase in drying time is more than proportional to the increase in thickness. For example, if thickness is doubled, the drying time will be increased by a factor of about 3 to 3.5.

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Table 7-1—Moisture content schedules for hardwoods

Dry-bulb temperature step no.	Moisture content at start of step (percent)	Dry-bulb temperatures (°F) for various temperature schedules													
		T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14
1	>30	100	100	110	110	120	120	130	130	140	140	150	160	170	180
2	30	105	110	120	120	130	130	140	140	150	150	160	170	180	190
3	25	105	120	130	130	140	140	150	150	160	160	160	170	180	190
4	20	115	130	140	140	150	150	160	160	160	170	170	180	190	200
5	15	120	150	160	180	160	180	160	180	160	180	180	180	190	200

Table 7-2—General wet-bulb depression schedules for hardwoods

Wet-bulb depression step no.	Moisture content (percent) at start of step for various moisture content classes						Wet-bulb depressions (°F) for various wet-bulb depression schedules							
	A	B	C	D	E	F	1	2	3	4	5	6	7	8
1	>30	>35	>40	>50	>60	>70	3	4	5	7	10	15	20	25
2	30	35	40	50	60	70	4	5	7	10	14	20	30	35
3	25	30	35	40	50	60	6	8	11	15	20	30	40	50
4	20	25	30	35	40	50	10	14	19	25	35	50	50	50
5	15	20	25	30	35	40	25	30	35	40	50	50	50	50
6	10	15	20	25	30	35	50	50	50	50	50	50	50	50

Table 7-3—Moisture content classes for various green moisture content values

Green moisture content (percent)	Moisture content class
up to 40	A
40 to 60	B
60 to 80	C
80 to 100	D
100 to 120	E
Above 120	F

Table 7-4—Code number index of schedules[1] recommended for kiln drying domestic hardwood 4/4 to 8/4 lumber and other products

	Lumber schedules				Schedules for other products		
	4/4, 5/4, and 6/4		6/4				
Species	Dry-bulb temperature	Wet-bulb depression	Dry-bulb temperature	Wet-bulb depression	Name	Dry-bulb temperature	Wet-bulb depression
Alder, red	T10	D4	T8	D3			
For darker color	T11	D3	—	—			
For lighter color	T5	D5	—	—			
Apple	T6	C3	T3	C2			
Ash, black	T8	D4	T5	D3			
Ash, green, Oregon. white	T8	B4	T5	B3			
Aspen	T12	E7	T10	E6			
Basswood							
Standard	T12	E7	T10	E6			
Light color	T9	E7	T7	E6			
Beech	T8	C2	T5	C1	1-in squares	T8	C3
					2-in squares	T5	C2
Birch, paper	T10	C4	T8	C3	1-in squares	T10	C6
					2-in squares	T8	C4
Birch, yellow	T8	C4	T5	C3	1-in squares	T8	C5
					2-in squares	T5	C4
Blackgum	T12	E5	T11	D3			
Boxelder	T8	D4	T6	C3			
Buckeye, yellow	T10	F4	T8	F3			
Butternut	T10	E4	T8	E3			
Cherry, black	T8	B4	T5	B3			
Chestnut	T10	E4	T8	E3			
Cottonwood, normal	T10	F5	T8	F4			
Cottonwood, wet streak	T8	D5	T6	C4			
Dogwood	T6	C3	T3	C2	Shuttles	T3	B2
Elm, American and slippery	T6	D4	T5	D3			
Elm, rock	T6	B3	T3	B2			
Hackberry	T8	C4	T6	C3			
					White handles		
					Small	T1	D2
					Large	T1	C2
Hickory	T8	D3	T6	D1	Pink handles		
					Small	T8	D1
					Large	T8	C1
Holly	T6	D4	T4	C3			
Hophornbeam (ironwood)	T6	B3	T3	B1			
Laurel, California (Oregon Myrtle)	T6	A4	T5	A3			
Locust, black	T6	A3	T3	A1			
Madrone	T4	B2	T3	B1			
Magnolia	T10	D4	T8	D3			
Maple, bigleaf, red, silver	T8	D4	T6	C3			
					Bowling pins (end coated)	T3	A3
Maple, sugar (hard)	T8	C3	T5	C2	1-in squares	T8	C4
					2-in squares	T5	C3
Oak, California black[2]	T3	B1	T3	B1			
Oak, red (upland)[2]	T4	D2	T3	D1			
Oak. red (southern lowland)[2]	T2	C1	(3)	(3)			
Oak, white (upland)[2]	T4	C2	T3	C1			
Oak, white (lowland)[2]	T2	C1	(3)	(3)			
Osage-orange	T6	A2	T3	A1			
Pecan	T8	D3	T6	D1			
Persimmon	T6	C3	T3	C2	Golf club heads	T3	C2
					Shuttles	T3	B2
Sassafras	T8	D4	—	—			
Sweetgum (sap gum)	T12	F5	T11	D4	1-in squares	T12	F6
					2-in squares	T11	D5

Table 7-4—Code number index of schedules[1] recommended for kiln drying domestic hardwood 4/4 to 8/4 lumber and other products-concluded

	Lumber schedules				Schedules for other products		
	4/4, 5/4, and 6/4		8/4				
Species	Dry-bulb tempera-ture	Wet-bulb depression	Dry-bulb tempera-ture	Wet-bulb depression	Name	Dry-bulb tempera-ture	Wet-bulb depression
Sweetgum (red gum)	T8	C4	T5	C3			
Sycamore	T6	D2	T3	D1			
Tanoak	T3	B1	T3	B1			
Tupelo, black	T12	E5	T11	D3			
Tupelo, swamp	T10	E3	T8	D2			
Tupelo, water	T6	H2	—	—			
Walnut, black	T6	D4	T3	D3	Gunstock blanks	T3	D4
Willow, black	T10	F4	T8	F3			
Yellow-wofar	T11	D4	T10	D3			

[1] Schedules are given in tables 7-1 and 7-2.

[2] All 6/4 oak species should be dried by the 8/4 schedule.

[3] See table 7-11.

Table 7-5—Code number index of schedules suggested for kiln drying thick domestic hardwoods[1]

	Schedules for various thicknesses of lumber[2]					
	10/4 lumber		12/4 lumber		16/4 lumber	
Species	Dry-bulb tempera-ture	Wet-bulb depression	Dry-bulb tempera-ture	Wet-bulb depression	Dry-bulb tempera-ture	Wet-bulb depression
Alder, red	T6	C3	T6	C3	—	—
Ash, white	T5	B3	T3	B2	T3	A1
Aspen	T8	E5	T8	D5	T7	C4
Birch, yellow	T5	B3	T3	B2	T3	A1
Blackgum	T11	D3	T9	C2	T7	C2
Boxelder	T5	C2				
Cherry	T5	B2	T3	B2	T3	A1
Cottonwood	T6	E3	T5	D2	—	—
Cottonwood, wet streak	T4	D3	T3	C2	—	—
Elm, American	T5	D2	T3	C2	—	—
Elm, rock	T3	B2	T3	B1	T3	A1
Hackberry	T6	C3	T5	C2	T3	B1
Maple, bigleaf, red, silver	T5	C2	T3	B2	—	—
Maple, sugar (hard)	T3	B2	T3	A1[3]	T3	A1[3]
Oak, red	T3	C1	T3	C1	—	—
Oak, white	T3	B1	T3	B1	—	—
Sweetgum (sap gum)	T11	D3	T9	C3	—	—
Sweetgum (red gum)	T5	C2	T5	B2	—	—
Sycamore	T3	D1	T3	C1	T3	B1
Tupelo, black	T11	D3	T9	C2	T7	C2
Walnut. black	T3	D3	T3	C2	—	—
Yellow-poplar	T9	C3	T7	C2	T5	C2

[1] A good end coating should be applied to all stock in most cases.

[2] For squares, use a web-bulb depression number one unit higher than the one suggested for lumber. Thus, for 3- by 3-in birch, use T3-B3.

[3] After passing 30 percent moisture content, gradually shift to wet-bulb depression schedule B2.

Tabled 7-6—Method of assembly of kiln-drying schedule for green 4/4 sugar maple[1]

Dry-bulb temperature step no.	Wet-bulb depression step no.	Moisture content at start of step (percent)	Dry-bulb temperature (°F)	Wet-bulb depression (°F)	Wet-bulb temperature (°F)	Relative humidity (percent)	Equilibrium moisture content (percent)
1	1	>40	130	5	125	86	16.0
1	2	40	130	7	123	81	14.0
1	3	35	130	11	119	71	11.5
2	4	30	140	19	121	56	8.4
3	5	25	150	35	115	35	5.1
4	6	20	160	50	110	24	3.2
5	6	15	180	50	130	26	3.3

[1] Schedule Code no. T8-C3

Table 7-7—Examples of general schedules for kiln drying lumber of certain hardwood Species[1]

Moisture content at start of step (percent)	4/4, 5/4, 6/4 lumber schedules			8/4 lumber schedules		
	Dry-bulb temperature	Wet-bulb depression	Wet-bulb temperature	Dry-bulb temperature	Wet-bulb depression	Wet-bulb temperature
			OAK, RED (UPLAND)			
	SCHEDULE T4-D2			SCHEDULE T3-D1		
	110	4	106	110	3	107
	110	5	105	110	4	106
	110	8	102	110	6	104
	110	14	96	110	10	100
	120	30	90	120	25	95
	130	40	90	130	40	90
	140	50	90	140	50	90
	180	50	130	160	50	110
			OAK, WHITE			
	SCHEDULE T4-C2			SCHEDULE T3-C1		
	110	4	106	110	3	107
	110	5	105	110	4	106
	110	8	102	110	6	104
	120	14	106	120	10	110
	130	30	100	130	25	105
	140	50	(2)	140	50	(2)
	180	50	(2)	160	50	(2)
			MAPLE, HARD			
	SCHEDULE T8-C3			SCHEDULE T5-C2		
>40	130	5	125	120	4	116
40	130	7	123	120	5	115
35	130	11	119	120	8	112
30	140	19	121	130	14	116
25	150	35	115	140	30	110
20	160	50	110	150	50	100
15	180	50	130	160	50	110
			ASH, WHITE; CHERRY			
	SCHEDULE T8-B4			SCHEDULE T5-83		
>35	130	7	123	120	5	115
35	130	10	120	120	7	113
30	140	15	125	130	11	119
25	150	25	125	140	19	121
20	160	40	120	150	35	115
15	180	50	(2)	160	50	(2)
			BLACKGUM			
	SCHEDULE T12-E5			SCHEDULE T11-D3		
>60	160	10	150	150	5	145
60	160	14	146	150	5	145
50	160	20	140	150	7	143
40	160	35	125	150	11	139
35	160	50	110	150	19	131
30	170	50	120	160	35	125
25	170	50	120	160	50	110
20	180	50	130	170	50	120
15	180	50	130	180	50	130

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[1] All temperature values are in degrees Fahrenheit.

[2] Close control of wet-bulb temperature not necessary.

Table 7-8—H-type wet-bulb depression schedules for hardwoods

Wet-bulb depression step no.	Moisture content at start of step (percent)	Wet-bulb depressions (°F) for various wet-bulb depression schedules							
		1	2	3	4	5	6	7	8
1	Green (G)	3	4	5	7	10	15	20	25
2	2/3 G	4	5	7	10	14	20	30	35
3	2/3 G-10	6	8	11	15	20	30	40	50
4	2/3 G-20	10	14	19	25	35	50	50	50
5	2/3 G-30	25	30	35	40	50	50	50	50
6	2/3 G-40	50	50	50	50	50	50	50	50

Table 7-9—Temperature schedule code numbers for maximum strength retention

Species	Schedule numbers according to species thickness				
	1 in	1-1/2 in	2 in	3 in	>3 in
	SOFTWOODS				
Baldcypress	4	4	5	6	7
Douglas-fir	3	4	5	6	7
Fir,					
noble	2	3	4	6	7
red	3	4	5	6	7
Hemlock, western	4	5	6	6	7
Pine,					
northern white	4	5	6	7	8
ponderosa	4	5	6	6	7
red	2	3	4	6	7
sugar	3	4	5	6	7
western white	4	5	6	7	8
Spruce					
red	2	3	4	5	6
Sitka	2	3	4	5	6
white	2	3	4	5	6
White-cedar, Port-Orford					
	HARDWOODS				
Ash, commercial white	5	5	—	—	—
Birch, yellow	5	5	—	—	—
Cherry, black	5	5	—	—	—
African mahogany	5	5	—	—	—
Mahogany, true	5	5	—	—	—
Maple,					
silver	3	3	—	—	—
sugar	3	3	—	—	—
Oak,					
commercial red	8	8	—	—	—
commercial while	8	8	—	—	—
Sweetgum	6	6	—	—	—
Yellow-poplar	3	4	5	6	7
Walnut, black	4	4	—	—	—

Table 7-10—Maximum drying temperatures for maximum strength retention

Moisture content (percent)	Maximum drying temperature (°F) for various schedules[1]							
	1	2	3	4	5	6	7	8
≥45	140	135	130	125	120	115	110	105
[2]40	145	140	135	130	125	120	115	110
30	150	145	140	135	130	125	120	115
25	155	150	145	140	135	130	125	120
20	160	155	150	145	140	135	130	125
15	165	160	155	150	145	140	135	130
to final	170	165	160	155	150	145	140	135

[1] Temperature schedule code numbers described in table 7-9.

[2] When the initial moisture content of the stock exceeds 40 percent, the initial temperature should be maintained until the moisture content reaches 40 percent, at which time the temperature may be increased 5°F.

Table 7-11—Special schedules for certain hardwood species

Moisture content at start of step (percent)	Temperatures (°F) for various thicknesses of lumber					
	4/4		6/4		8/4	
	Dry bulb	Wet bulb	Dry bulb	Wet bulb	Dry bulb	Wet bulb
HICKORY-UPPER GRADES FOR SPECIAL PURPOSES						
>50	130	125	120	115	120	117
50	130	123	120	113	120	116
40	130	114	125	114	120	113
35	130	114	130	97	125	114
30	150	112	140	104	130	97
25	150	100	140	104	140	90
20	180	130	180	130	150	100
15	180	130	180	130	180	130
TUPELO, SWAMP—HEARTWOOD						
>60	140	135	140	135	—	—
60	140	133	140	133	—	—
50	140	129	140	129	—	—
40	140	121	140	121	—	—
35	140	105	140	105	—	—
30	150	100	150	100	—	—
25	160	110	160	110	—	—
20	170	120	170	120	—	—
15	180	130	180	130	—	—
TUPELO, SWAMP—SAPWOOD						
>60	160	150	160	150	—	—
60	160	146	160	150	—	—
50	160	146	160	140	—	—
40	160	146	160	125	—	—
35	160	110	160	125	—	—
30	170	120	170	120	—	—
25	170	120	170	120	—	—
20	180	130	180	130	—	—
15	180	130	180	130	—	—
TUPELO, WATER—HEARTWOOD						
>70	130	123	120	[1]116	—	—
70	130	120	120	[2]90	—	—
60	130	115	120	90	—	—
50	130	105	120	90	—	—
40	130	[2]90	120	90	—	—
35	130	90	120	90	—	—
30	140	90	130	90	—	—
25	150	100	140	90	—	—
20	160	110	150	100	—	—
15	180	130	180	130	—	—

Table 7-11—Special schedules for certain hardwood species-continued

Moisture content at start of step (percent)	Temperatures (°F) for various thicknesses of lumber					
	4/4		6/4		8/4	
	Dry bulb	Wet bulb	Dry bulb	Wet bulb	Dry bulb	Wet bulb
TUPELO, WATER—SAPWOOD						
>70	160	150	140	133	—	—
70	160	150	140	130	—	—
60	160	146	140	125	—	—
50	160	146	140	115	—	—
40	160	146	140	100	—	—
35	160	110	140	90	—	—
30	170	120	150	100	—	—
25	170	120	160	110	—	—
20	180	130	170	120	—	—
15	180	130	180	130	—	—
ASPEN—LOW COLLAPSE						
>70	110	100	110	100	140	133
70	110	100	110	100	140	130
60	115	100	115	100	140	125
50	120	100	120	100	140	120
40	130	105	130	105	140	110
30	150	110	150	110	[3]150	100
25	150	110	150	110	170	120
20	[3]180	135	[3]180	135	170	120
[4]12	180	130	180	130	180	130
[5]8	180	130	180	130	200	140
SUGAR MAPLE, WHITE COLOR—INITIAL MOISTURE CONTENT BELOW 50 PERCENT						
[6]>28	105	95	—	—	—	—
28	108	95	—	—	—	—
24	108	90	—	—	—	—
20	108	90	—	—	—	—
16	115	90	—	—	—	—
13	125	90	—	—	—	—
10	160	105	—	—	—	—
(Condition)	170	154	—	—	—	—
SUGAR MAPLE, WHITE COLOR—INITIAL MOISTURE CONTENT ABOVE 50 PERCENT						
[6]>40	105	95	—	—	—	—
40	108	95	—	—	—	—
35	108	90	—	—	—	—
30	108	90	—	—	—	—
26	108	90	—	—	—	—
20	115	90	—	—	—	—
16	125	90	—	—	—	—
12	160	105	—	—	—	—
(Condition)	170	154	—	—	—	—

Table 7-11—Special schedules for certain hardwood species—continued

Moisture content at start of step (percent)	Temperatures (°F) for various thicknesses of lumber					
	4/4		6/4		8/4	
	Dry bulb	Wet bulb	Dry bulb	Wet bulb	Dry bulb	Wet bulb
UPLAND RED OAK—PRESURFACED						
[7]>53	115	111	—	—	—	—
53	115	110	—	—	—	—
43	115	107	—	—	—	—
37	115	101	—	—	—	—
[8]35	120	90	—	—	—	—
30	125	90	—	—	—	—
27	130	90	—	—	—	—
21	140	90	—	—	—	—
17	180	130	—	—	—	—
UPLAND WHITE OAK—PRESURFACED						
[7]>42	115	111	—	—	—	
42	115	110	—	—	—	
37	115	107	—	—	—	
33	115	101	—	—	—	
[8]35	120	90	—	—	—	
30	125	90	—	—	—	
27	130	90	—	—	—	
21	140	90	—	—	—	
17	180	130	—	—	—	
RED OAK, 4/4 AND 5/4—BACTERIA INFECTED						
>55	105	102	—	—	—	—
55	105	100	—	—	—	—
45	105	96	—	—	—	—
35	105	92	—	—	—	—
30	105	90	—	—	—	—
27	110	93	—	—	—	—
25	120	100	—	—	—	—
20	130	100	—	—	—	—
15	150	110	—	—	—	—
12	180	130	—	—	—	—
RED OAK, 6/4—BACTERIA INFECTED						
>50	—	—	100	97	—	—
50	—	—	100	95	—	—
45	—	—	100	93	—	—
40	—	—	100	90	—	—
35	—	—	105	92	—	—
30	—	—	110	95	—	—
25	—	—	120	100	—	—
20	—	—	130	100	—	—
16	—	—	150	110	—	—
12	—	—	180	130	—	—

Table 7-11—Special schedules for certain hardwood species—continued

Moisture content at start of step (percent)	Temperatures (°F) for various thicknesses of lumber					
	4/4		6/4		8/4	
	Dry bulb	Wet bulb	Dry bulb	Wet bulb	Dry bulb	Wet bulb
RED OAK, 8/4—BACTERIALLY INFECTED, AIR DRIED OR PREDRIED (DRYING HISTORY UNKNOWN)						
>20	—	—	—	—	110	100
20	—	—	—	—	125	110
18	—	—	—	—	140	110
14	—	—	—	—	160	110
10	—	—	—	—	180	130
RED OAK, 8/4—BACTERIALLY INFECTED, DRIED FROM GREEN IN PREDRYER, THEN KILN DRIED						
>80	—	—	—	—	90	87
80	—	—	—	—	96	93
75	—	—	—	—	100	96
65	—	—	—	—	100	95
44	—	—	—	—	105	95
32	—	—	—	—	115	100
30	—	—	—	—	120	100
26	—	—	—	—	125	100
21	—	—	—	—	150	110
18	—	—	—	—	160	110
16	—	—	—	—	170	120
12	—	—	—	—	180	130
SOUTHERN LOWLAND RED AND WHITE OAK, 6/4 AND 8/4—AIR DRIED OR PREDRIED TO 25 PERCENT MOISTURE CONTENT						
>30	—	—	105	97	105	97
25	—	—	110	99	110	99
20	—	—	120	105	120	105
15	—	—	130	100	130	100
11	—	—	160	110	160	110
(Equalize)	—	—	173	130	173	130
(Condition)	—	—	180	170	180	170
MAPLE—MINIMUM HONEYCOMB IN 6/4 AND 8/4 MINERAL STREAK						
[8-10]>40	—	—	110	106	—	—
40	—	—	110	105	—	—
35	—	—	110	102	—	—
30	—	—	120	106	—	—
25	—	—	125	95	—	—
20	—	—	130	90	—	—
[11]30	—	—	140	95	—	—
25	—	—	150	100	—	—
20	—	—	160	110	—	—
15	—	—	180	130	—	—
NORTHERN RED OAK—PRESURFACED 1-INCH						
>53	115	111	—	—	—	—
53	115	110	—	—	—	—
43	115	107	—	—	—	—
37	115	101	—	—	—	—
35	120	90	—	—	—	—

Table 7-11—Special schedules for certain hardwood species—concluded

Moisture content at start of step (percent)	Temperatures (°F) for various thicknesses of lumber					
	4/4		6/4		8/4	
	Dry bulb	Wet bulb	Dry bulb	Wet bulb	Dry bulb	Wet bulb
30	125	90	—	—	—	—
27	130	90	—	—	—	—
21	140	90	—	—	—	—
17	180	130	—	—	—	—

[1] See figure 7-3 for changes between 110 and 70 percent moisture content on the H2 schedule.

[2] It may not be possible to achieve 90 °F wet-bulb temperature in hot weather.

[3] Operate with vents closed; no steam spray until equalizing.

[4] For 8/4, continue until wettest sample is 8 percent.

[5] For 8/4, time on this step is about 5 days

[6] The 4/4 schedule also applies to 5/4.

[7] Average moisture content of all samples controls.

[8] Average moisture content of wettest half of samples controls.

[9] This schedule should also be used for mineral-streaked yellow birch.

[10] Kiln samples should be 2 ft longer than normal so that three or four intermediate moisture content tests can be made. For green stock, start with normal kiln sample proceduire. For air-dried stock, cut both an average section and a "darkest zone" section at the start. Cut out the darkest, wettest appearing portion of the latter section with a bandsaw. Weight and ovendry this portion separately to determine when temperature of 140 °F and higher can be used. After the final drying condition has run 1 day, revert to the full-size kiln sample method to start equalizing and conditioning.

[11] Begin control on darkest zone of wettest sample.

Table 7-12—Time schedules for domestic hardwood lumber species

step no.	Time (h)	Temperature (°F) Dry bulb	Wet bulb
	ALDER, RED—4/4, 5/4, 6/4		
1	0 to 12	150	145
2	12 to 24	150	140
3	24 to 48	155	140
4	48 to 72	165	140
5	72 to 120	180	140
6	(or until dry)	180	140
	ALDER, RED—8/4		
1	0 to 48	130	120
2	48 to 72	135	120
3	72 to 96	140	125
4	96 to 120	145	125
5	120 to 144	150	125
6	144 to 168	155	125
7	168 to 192	160	130
8	192 to 216	165	135
9	(or until dry)	165	135
	ALDER, RED—10/4, 12/4		
1	0 to 12	130	125
2	12 to 36	135	130
3	36 to 84	140	135
4	84 to 132	145	135
5	132 to 180	150	135
6	180 to 228	155	135
7	228 to 276	160	135
8	276 to 324	170	135
9	(or until dry)	170	135
	ASH, OREGON—4/4, 5/4, 6/4		
1	0 to 12	150	145
2	12 to 48	150	140
3	48 to 84	155	140
4	84 to 132	165	140
5	132 to 156	180	140
6	(or until dry)	180	140
	ASH, OREGON—8/4, 10/4, 12/4		
1	0 to 12	130	125
2	12 to 36	135	130
3	36 to 84	140	135
4	84 to 132	145	135
5	132 to 180	150	135
6	180 to 228	155	135
7	228 to 276	160	135
8	276 to 324	170	135
9	(or until dry)	170	135
	LAUREL, CALIFORNIA OR OREGON MYRTLE—4/4, 5/4, 6/4		
1	0 to 24	130	123
2	24 to 28	135	125
3	48 to 72	140	125
4	72 to 96	150	135
5	96 to 120	155	135
6	120 to 144	160	135
7	144 to 168	180	140
8	(or until dry)	180	140
	MAPLE, BIG LEAF—4/4. 5/4, 6/4		
1	0 to 48	130	120
2	48 to 72	135	120
3	72 to 96	140	125
4	96 to 120	145	125
5	120 to 144	150	125
6	144 to 168	155	125
7	168 to 192	160	130
8	192 to 216	165	135
9	(or until dry)	165	135
	MAPLE, OREGON—8/4		
1	0 to 12	130	125
2	12 to 36	135	130
3	36 to 84	140	135
4	84 to 132	145	135
5	132 to 180	150	135
6	180 to 228	155	135
7	228 to 276	160	135
8	276 to 324	170	135
9	(or until dry)	170	135
	OAK, CALIFORNIA SLACK AND OREGON WHITE, AND TANOAK—4/4, LOWER GRADES		
1	0 to 216	110	106
2	216 to 312	110	104
3	312 to 384	115	104
4	384 to 432	120	104
5	432 to 492	180	105
6	(or until dry)	180	105
	OAK, CALIFORNIA BLACK AND OREGON WHITE—6/4, LOWER GRADES		
1	0 to 360	110	106
2	360 to 504	110	104
3	504 to 576	110	100
4	576 to 672	115	100
5	672 to 816	120	100
6	816 to 980	180	145
7	(or until dry)	180	145

Table 7-13—High-temperature kiln schedules for domestic hardwood lumber species

Temperature step no.	Moisture content (percent)	Time (h)	Temperature (°F)	
			Dry bulb	Wet bulb
ALDER, RED—4/4, 5/4				
1	—	0-3	215	210
2	—	3-9	210	210
3	—	9-21	230	205
4	—	21-36	230	200
5	—	36-39	230	195
6	—	39-51	215	210
7	—	51-59	Cool lumber in kiln	
ASPEN AND BALSAM POPLAR—2 BY 4 DIMENSION				
1	—	0-2	180	180
2	—	2-59	250	180
3	—	59-61	Kiln off, no fans	
4	—	61-79	204	196
5	—	79-94	250	180
BASSWOOD, BLACKGUM, RED MAPLE, SWEETGUM SAPWOOD, AND YELLOW-POPLAR—4/4, 5/4				
1	Green to 7%	20-26	230	180
2	(Cool to below 212 °F)			
3	(Equalize)	11-16	203	160
4	(Condition)	10-12	192	180
ASPEN—4/4, 5/4,6/4, 7/4, AND 2-IN DIMENSION				
1	(Warmup)	3	201	201
2	(Green to dry)	—	220	201
3	(Condition)	—	205	201
RED ALDER, BASSWOOD, BLACKGUM, RED MAPLE, AND YELLOW-POPLAR—7/4 FLITCHES				
1	Green to 10%	20-26	235	180
2	(Cool to below 212 °F)			
3	(Equalize)	24-48	200	188

Table 7-14—Code number index of schedules recommended for kiln drying Imported species

Species (common name)	4/4, 5/4, and 6/4 lumber schedules		8/4 lumber schedules		Species (common name)	4/4, 5/4, and 6/4 lumber schedules		8/4 lumber schedules	
	Dry bulb temperature	Wet-bulb depression[1]	Dry bulb temperature	Wet-bulb depression[1]		Dry-bulb temperature	Wet-bulb depression[1]	Dry-bulb temperature	Wet-bulb depression[1]
Afrormosia	T10	D5S	T8	D4S	Keruing	T3	D2	T3	D1
Albarco	T3	D2	T3	D1	Lauan, red and white	T6	D4	T3	D3
Andiroba	T3	C2	T3	C1	Lignumvitae	T2	C2	T2	C1
Angelique	T2	B2	—	—	Limba	T10	D5S	T8	D4S
Apitong	T3	D2	T3	D1	Mahogany, African	T6	D4	T3	D3
Avodire	T6	D2	T3	D1	Mahogany, true	T6	D4	T3	D3
Balata	T1	B1	—	—	Manni	T3	C2	T3	C1
Balsa	T10	D4S	T8	D3S	Merbau	T3	C2	T3	C1
Banak	T3	C2	T3	C1	Mersawa	T6	D2	T3	D1
Benge	T3	C2	T3	C1	Mora	T2	C2	T2	C1
Bubinga	T2	C2	T2	C1	Obeche	T14	C5S	T12	C5S
Caribbean pine	T10	D4S	T8	D3S	Ocote pine	T10	D4S	T8	D3S
Cativo	T3	C2	T3	C1	Okoume	T6	D2	T3	D1
Ceiba	T10	D5S	T8	D4S	Opepe	T6	D2	T3	D1
Cocobolo	T2	C2	T2	C1	Parana pine	T3	D2	T3	D1
Courbaril	T3	C2	T3	C1	Pau Marfim	T6	C3	T5	C2
Cuangare	T5	C3	—	—	Peroba de campos	T3	D2	T3	D1
Cypress, Mexican	T10	D5S	T8	D4S	Peroba rosa	T6	D2	T3	D1
Degame	T2	C2	T2	C1	Primavera	T6	F3	—	—
Determa	T6	D2	T3	D1	Purpleheart	T6	D2	T3	D1
Ebony, East Indian	T3	C2	T3	C1	Ramin	T3	C2	T2	C1
Ebony, African	T6	D2	T3	D1	Roble (Quercus)	T2	C2	T2	C1
Gmelina	T13	C4S	T11	D3S	Roble (Tabebuia)	T6	D2	T3	D1
Goncalo alves	T3	C2	—	—	Rosewood, Indian	T6	D2	T3	D1
Greenheart	T2	C2	T2	C1	Rosewood, Brazilian	T3	C2	T3	C1
Hura	T6	D2	T3	D1	Rubberwood	T6	D2	—	—
Ilomba	T3	C2	T3	C1	Sande	T5	C3	—	—
Imbuia	T6	D2	T3	D1	Santa Maria	T2	D4	T2	D3
Ipe	T3	C1	—	—	Sapele	T2	D4	T2	D3
Iroko	T6	D2	T3	D1	Sepetir	T8	B3	T5	B1
Jarrah	T3	C2	T3	C1	Spanish cedar	T10	D4S	T8	D3S
Jelutong	T10	D4S	T8	D3S	Sucupira (Bowdichia)	T5	B2	—	—
Kapur	T10	D4S	T8	D3S	Sucupira (Diplotropis)	T7	B3	—	—
Karri	T3	C2	T3	C1	Teak	T10	D4S	T8	D3S
Kempas	T6	D2	T3	D1	Wallaba	T2	C2	T2	C1

[1] The letter S denotes softwood schedule code number from table 7-15.

Table 7-15—Moisture content schedules for softwoods

Dry-bulb temperature step no.	Moisture content at start of step (percent)	Dry-bulb temperatures (°F) for various temperature schedules													
		T1	T2	T3	T4	T5	T6	T7	T8	T9	T10	T11	T12	T13	T14
1	>30	100	100	110	110	120	120	130	130	140	140	150	160	170	180
2	30	105	110	120	120	130	130	140	140	150	150	160	170	180	190
3	25	105	120	130	130	140	140	150	150	160	160	160	170	180	190
4	20	115	130	140	140	150	150	160	160	160	170	170	180	190	200
5	15	120	150	160	180	160	180	160	180	160	180	180	180	190	200

Table7-16—Moisture content wet-bulb depression schedules for softwoods

Wet-bulb depression step no.	Moisture content (percent) at start of step for various moisture content classes						Wet-bulb depressions (°F) for various wet-bulb depression schedules							
	A	B	C	D	E	F	1	2	3	4	5	6	7	8
1	>30	>35	>40	>50	>60	>70	3	4	5	7	10	15	20	25
2	30	35	40	50	60	70	4	5	7	10	14	20	25	30
3	25	30	35	40	50	60	6	8	11	15	20	25	30	35
4	20	25	30	35	40	50	10	14	15	20	25	30	35	35
5	(1)	20	25	30	35	40	15	20	20	25	30	35	35	35
6	—	(1)	20	25	30	35	20	25	25	30	35	35	35	35
7	—	—	(1)	20	25	30	25	30	30	35	35	35	35	35
8	—	—	—	(1)	20	25	30	35	35	35	35	35	35	35
9	—	—	—	—	(1)	20	35	35	35	35	35	35	35	35
10	15	15	15	15	15	15	50	50	50	50	50	50	50	50

[1] Go directly to step 10..

Table 7-17—Code number index of moisture content schedules[1] recommended for kiln drying 4/4, 6/4, and 8/4 softwood lumber

Species	Schedules for lower grades[2]			Schedules for upper grades[2]		
	4/4	6/4	8/4	4/4	6/4	8/4
Baldcypress	—	—	—	T12-E3	—	T11-D2
Cedar						
Alaska	—	—	—	T12-A3	—	T11-A2
Atlantic white	—	—	—	T12-A4	—	T11-A3
Eastern redcedar	—	—	—	T5-A4	—	T5-A3
Incense	—	—	—	T11-B5	—	T10-B4
Northern white	—	—	—	T12-B4	—	T11-B3
Port-Orford	—	—	—	T11-B4	—	T10-B3
western redcedar						
Light	T9-A6	—	—	T10-B5	—	T10-B3
Heavy	—	—	—	T5-F4	—	T5-F3
Douglas-fir						
coast region	T7-A4	—	[3]T7-A4	T11-A4	—	T10-A3
Inland region	[4]T9-A4	—	[4]T9-A4	—	—	—
Fir						
Balsam	—	—	—	T12-E5	—	T10-E4
California red	—	—	—	T12-E5	—	T10-E4
Grand	—	—	—	T12-E5	—	T10-E4
Noble	—	—	—	T12-A5	T11-A4	T10-A3
Pacific silver	—	—	—	T12-B5	—	T10-B3
Subalpine	—	—	—	T12-B5	—	T12-B
White	T9-D6	—	T9-D5	T12-E5	T11-E5	T10-E4
Hemlock						
Eastern	—	—	—	T12-C4	—	T11-C3
Western	[3]T11-E5	—	T11-E5	T12-C5	T11-C5	T11-C4
Larch	[4]T7-C5	—	[3]T7-C5	T9-B4	T7-C4	T7-C3
Pine						
Eastern white						
Regular	T9-C5	—	T9-C4	T11-C5	—	T10-C4
Jack	T9-C4	—	T9-C3	—	—	—
Lodgepole	T5-C5	—	—	T10-C4	—	T9-C3
Ponderosa						
Heartwood	T9-A6	T7-A6	T5-A5	—	—	—
Sapwood	T11-C7	—	—	T9-C6	T7-C5	T7-C5
Antibrown-stain	—	—	—	T7-E6	—	T7-E5
Red	—	—	—	T12-B4	—	T11-B3
Southern yellow	T12-C5	—	—	T13-C6	T12-C5	T12-C5
sugar						
Light	T9-E7	T7-E6	—	T5-E6	T5-E6	T5-E5
Heavy	—	—	—	T5-F6	T5-F6	T5-F5
Western white						
Regular	T9-C6	—	[4]T7-C6	T9-C5	T7-C5	T7-C4
water core	T9-E6	—	—	—	—	—
Redwood						
Light	—	—	—	T5-D6	—	T5-D4
Heavy	—	—	—	T4-F5	T3-F5	T3-F4
Spruce						
Eastern (black, red, white)	—	—	—	T11-B4	—	T10-B3
Englemann	T7-B6	T5-B5	[3]T5-B5	T9-E5	—	T7-E4
Sitka	T7-A5	—	—	T12-B5	T12-B4	T11-B3
Tamarack	—	—	—	T11-B3	—	T10-B3

[1] Schedules are given in tables 7-20 and 7-21.

[2] Lower grades include commons, dimension, and box; upper grades include clears, selects, shop, and factory; also tight-knotted paneling.

[3] Maximum wet-bulb depression 25 °F.

[4] Maximum wet-bulb depression 20 °F.

Table 7-18—Code number index of moisture content schedules[1] suggested for kiln drying thick softwood lumber[2]

Species	Index for various lumber thicknesses 10/4	12/4	16/4
Baldcypress	T8-A4	T8-A4	—
Cedar			
Atlantic white	T7-A3	T7-A3	—
Incense	T5-F3	T5-F3	—
Northern white	T7-A3	T7-A3	—
Western redcedar (light)	T7-A2	T7-A2	—
Douglas-fir, coast region	T5-A1	T5-A1	T5-A1
Fir			
Balsam	T8-A4	T8-A4	—
California red	T8-A3	T8-A3	—
Grand	T8-A4	T8-A3	—
Noble	T5-A2	T5-A2	—
White	T8-A4	T8-A4	—
Hemlock			
Eastern	T8-A3	T8-A2	—
Western	T8-A4	T8-A3	—
Larch, western	T7-A3	T7-A2	—
Pine			
Eastern white	T10-C4	T8-C3	T5-C2
Ponderosa	T7-A4	T7-A4	—
Red	T7-A3	T7-A3	—
Southern	T10-C4	T10-C4	—
Western white	T7-C4	T5-C3	—
Redwood (light)	T5-C4	T5-C3	—
Spruce			
Eastern (black, red, white)	T5-A2	T5-A2	—
Engelmann	T7-A4	T7-A3	—
Sitka	T5-B2	T5-B2	—
Tamarack	T7-A3	T7-A3	—

[1] Schedules are given in table 7-20 and 7-21.

[2] Upper grades, including clears, selects, and factory lumber.

Table 7-19—Index of time schedules1 for kiln drying softwood species at conventional temperatures

Common name (botanical name)	Schedules for lower grades[2]			Schedules for upper grades[3]				Comments[4]
	4/4,5/4	6/4	8/4	4/4,5/4	6/4	8/4	12/4, 16/4	
Cedar								Light to medium sorts only. Prone to collapse. For heavy sort, air dry to 20 percent moisture content and kiln dry with table HC, starting with step 4.
Alaska yellow *(Chamaecyparis nootkatensis)*	EC	HC	HC	EC	HC	HC		
Incense *(Libocedrus decurrens)*	HC[a]	HC	GC	HC[a]	HC	GC	LC	[a]Use 12 h for each setting. Decrease dry- and wet-bulb settings by 10°F for first 46 h.
Port-Orford *(Chamaecyparis lawsoniana)*	HC	—	FC	HC	LC	LC		
Western juniper *(Juniperus occidentalis)*	HC	HC	—	HC	HC	—	—	
Western redcedar *(Thuja plicata)*	HC	HC	GC	HC	HC	LC	—	
Douglas-fir *(Pseudotsuga menziesii)*	IC[b]	IC[c]	IC[c]	JC[d]	JC[d]	JC[d]	FC	Upper grades, including laminated stock, dimension, 4/4 common. Clears and shop require conditioning in most cases. Ladder stock requires lower temperature to prevent strength reduction. [b]Omit step 1 and reduce step 3 to 12 h. [c]Reduce step 3 to 12 h. [d]Omit step 1 for vertical grain.
Fir, true	IC	IC	IC[e]	JC[f]	JC[g]	JC[g]	FC	True fir and hemlock can be dried together, but problems with percent overdry and wets are likely. [e]96 to 108 h all widths. [f]96 h flat grain; start with step 2 for vertical grain, 60 h. [g]10 to 14 days for sinker heartwood.
Alpine *(Abies lasiocarpa)*								
Balsam (A. *balsamera)*								
California red (A. *magnifica)*								
Grand *(A. grandis)*								
Noble (A. *nob/is)*								
Pacific silver *(A. amabilis)*								
White *(A. concolor)*								
Hemlock								Hemlock and true fir can be dried together, but problems with percent overdry and wets are likely. Prone to excessive warp and checking. [h]96 to 108 hall widths. [i]96 h flat grain; start with step 2 for vertical grain, 60 h. [j]14 days for sinker heartwood.
Mountain *(Tsuga mertensiana)*	IC	IC	IC	—	—	—	—	
Western *(T. heterophylla)*	IC	IC	IC[h]	JC[i]	JC[j]	JC[j]	FC	

Table 7-19—Index of time schedules[1] for kiln drying softwood species at conventional temperatures—concluded

Common name *(botanical name)*	Schedules for lower grades[2]			Schedules for upper grades[3]				Comments[4]
	4/4,5/4	6/4	8/4	4/4,5/4	6/4	8/4	**12/4, 16/4**	
Larch								
Alpine *(Larix lyalli)*	IC	IC	IC	—	—	—	—	
Western *(L. occidentalis)*	IC	IC	IC	JC	JC	JC	FC	
Pine								
Eastern white *(Pinus strobus)*	BBC	—	CCC	—	—	—	—	
Jack *(P. banksiana)*	IC[k]	IC[k]	IC[k]	IC[k]	—	—	—	[k] Omit first 12 h of schedule
Jeffrey *(P. jetfreyi)*	IC[k]	IC[k]	IC[k]	—	—	—	—	
Limber *(P. flexilis)*	IC[k]	IC[k]	IC[k]	IC[k]	JC	JC	—	
Lodgepole *(P. contorta)*	IC[k]	IC[k]	IC[k]	IC[k]	JC	JC	GC	
Ponderosa *(P. ponderosa)*	QC	RC	RC	SC	TC	UC	VC	
Southern	AC	—	BC	AC	—	BC	CC	3 by 5 timbers use table PC. 10/4 and 12/4 flitches use table OC.
Loblolly *(Pinus taeda)*								
Longleaf *(P. palustris)*								
Shortleaf *(P. echinata)*								
Slash *(P. elliottii)*								
Sugar (P. lambertiana)								
Heavy	WC	XC	XC	WC	XC	—	—	
Light.	YC	YC	ZC	YC	YC	XC	AAC	
Eastern white *(P. strobus)*	MC	—	NC	MC	—	NC	—	
Idaho white/western white *(P. monticola)*	KC	UC	UC	KC	UC	UC	—	
Redwood *(Sequoia sempervirens)*								[l] Air dry to 20 percent moisture content. then dry with table DC.
Light	GC	FC	(l)	GC	FC	(l)	—	
Heavy and medium	(m)	(m)	(m)	(m)	(m)	(m)	—	[m] Air dry to 20 percent moisture content, then dry with table GC. Prone to collapse.
Spruce								
Slack *(Picea mariana)*	IC[n]	IC[n]	IC[n]	IC	GC	GC	FC	[n] Reduce last 3 steps of schedule from 24 to 18 h each setting.
Engelmann *(P. engelmannii)*	IC[n]	IC[n]	IC	IC	GC	GC	FC	
Red *(P. rubens)*	IC[o]	IC[o]	IC	IC	IC	IC	—	
Sitka *(P. sitchensis)*	JC	JC	EC	EC	EC	HC	FC[o]	[o] Air dry to 20 percent moisture content, then dry with table IC
White *(P. glauca)*	IC[n]	IC[n]	IC	IC	GC	GC	FC	
Yew, Pacific *(Taxus brevifolia)*	HC	HC	FC	HC	HC	HC[o]	—	

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[1] See table 7-20 for description of schedules.

[2] Lower grades include commons, dimensions, box, and studs.

[3] Upper grades include clears, selects, shop, and factory.

[4] Comments are cross-referenced to column entries by superscript letters.

Table 7-20—Time schedules for kiln drying softwood lumber at conventional temperatures

step no.	Time (h)	Temperature (°F)	
		Dry-bulb	Wet-bulb
	SCHEDULE AC (SP[1]—4/4,5/4; STEAM)[2]		
1	0 to 24	140	130
2	24 to 48	160	130
3	48 to 72	185	125
4	72 to 96	185	120
	SCHEDUAL BC (SP—8/4; STEAM)[2]		
1	0 to 24	140	[3]130
2	24 to 48	160	130
3	48 to 72	185	125
4	72 to 96	185	120
5	96 to 120	185	115
	SCHEDULE CC (SP—12/4 DIMENSION; STEAM)[2]		
1	0 to 24	130	130
2	24 to 48	140	130
3	48 to 72	160	130
4	72 to 96	185	125
5	96 to 120	185	120
6	120 to 144	185	115
	SCHEDULE DC[2]		
1	0 to 12	150	145
2	12 to 24	150	140
3	24 to 48	155	140
4	48 to 72	165	140
5	72 to 120 (or until dry)	180	140
	SCHEDULE EC[2]		
	0 to 12	150	145
	12 to 48	150	140
	48 to 84	155	140
	84 to 132	165	140
	132 to 156 (or until dry)	180	140
	SCHEDULE FC[2]		
	0 to 12	130	125
	12 to 36	135	130
	36 to 84	140	135
	84 to 132	145	135
	132 to 180	150	135
	180 to 228	155	135
	228 to 276	160	135
	276 to 324 (or until dry)	170	135

step no.	Time (h)	Temperature (°F)	
		Dry-bulb	Wet-bulb
	SCHEDULE GC[2]		
1	0 to 48	130	120
2	48 to 72	135	120
3	72 to 96	140	125
4	96 to 120	145	125
5	120 to 144	150	125
6	144 to 168	155	125
7	168 to 192	160	130
8	192 to 216	165	135
9	216 to 240 (or until dry)	170	135
	SCHEDULE HC[2]		
1	0 to 24	130	123
2	24 to 48	135	125
3	48 to 72	140	125
4	72 to 96	150	135
5	96 to 120	155	135
6	120 to 144	160	135
7	144 to 168 (or until dry)	180	140
	SCHEDULE IC[2]		
1	0 to 12	180	170
2	12 to 36	180	165
3	36 to 60	180	155
4	60 to 84 (or until dry)	180	145
	SCHEDULE JC[2]		
1	0 to 12	170	164
2	12 to 24	170	160
3	24 to 48	175	160
4	48 to 72	180	160
5	72 to 96 (or until dry)	180	140
	SCHEDULE KC[2]		
1	0 to 24	130	115
2	24 to 48	140	120
3	48 to 72	160	135
4	72 to 96 (or until dry)	170	135

Table 7-20—Time schedules for kiln drying softwood lumber at conventional temperatures—continued

SCHEDULE LC[2]

Step no.	Time (h)	Temperature (°F) Dry-bulb	Temperature (°F) Wet-bulb
1	0 to 24	110	100
2	24 to 48	115	105
3	48 to 72	120	110
4	72 to 96	125	110
5	96 to 120	130	115
6	120 to 144	140	120
7	144 to 168	150	125
8	168 to 192	160	130
9	192 to 216 (or until dry)	170	135

SCHEDULE MC[2]

Step no.	Time (h)	Temperature (°F) Dry-bulb	Temperature (°F) Wet-bulb
1	0 to 24	140	130
2	24 to 48	145	130
3	48 to 72	150	130
4	72 to 96	155	130
5	96 to 120	160	130
6	120 to 144	170	135
7	144 to final	180	130

SCHEDULE NC[2]

Step no.	Time (h)	Temperature (°F) Dry-bulb	Temperature (°F) Wet-bulb
1	0 to 24	145	138
2	24 to 48	150	140
3	48 to 72	155	140
4	72 to 96	160	140
5	96 to 120	170	145
6	120 to 144	180	150
7	144 to final	180	145

SCHEDULE OC[2]

Step no.	Time (h)	Temperature (°F) Dry-bulb	Temperature (°F) Wet-bulb
1	0 to 72	140	133
2	72 to 84	140	130
3	84 to 96	140	125
4	96 to 104	150	130
5	104 to 116	160	135
6	116 to 128	170	140
7	128 to 130	180	130

SCHEDULE PC[2]

Step no.	Time (h)	Temperature (°F) Dry-bulb	Temperature (°F) Wet-bulb
1	0 to 72	130	126
2	72 to 96	130	125
3	96 to 120	135	125
4	120 to 132	140	132
5	132 to 144	150	138
6	144 to 156	155	140
7	156 to 168	160	130

SCHEDULE QC[2]

Step no.	Time (h)	Temperature (°F) Dry-bulb	Temperature (°F) Wet-bulb
	0 to 24	150	130
	24 to 48	150	120
	48 to 72 (or until dry)	170	130

SCHEDULE RC[2]

Step no.	Time (h)	Temperature (°F) Dry-bulb	Temperature (°F) Wet-bulb
	0 to 24	160	140
	24 to 36	165	140
	36 to 60 (or until dry)	170	140

SCHEDULE SC’

Step no.	Time (h)	Temperature (°F) Dry-bulb	Temperature (°F) Wet-bulb
1	0 to 24	130	115
2	24 to 48	140	115
3	48 to 72	150	120
4	72 to 84 (or until dry)	170	140

SCHEDULE TC[2]

Step no.	Time (h)	Temperature (°F) Dry-bulb	Temperature (°F) Wet-bulb
	to 24	130	115
	to 48	140	115
	to 72	145	115
	to 96	160	125
	to 136	170	140

SCHEDULE UC[2]

Step no.	Time (h)	Temperature (°F) Dry-bulb	Temperature (°F) Wet-bulb
1	0 to 16	120	105
2	16 to 24	125	105
3	24 to 36	130	105
4	36 to 48	135	115
5	48 to 60	145	120
6	60 to 72	150	125
7	72 to 96	160	130
8	96 to 108	165	135
9	108 to 120	170	140
10	120 to 144	170	135
11	144 to 156	180	140

SCHEDULE VC[2]

Step no.	Time (h)	Temperature (°F) Dry-bulb	Temperature (°F) Wet-bulb
1	0 to 24	115	108
2	24 to 48	120	110
3	48 to 72	125	115
4	72 to 96	130	120
5	96 to 216	140	130
6	216 to 264	145	130
7	264 to 336	150	135
8	336 to 408	155	140
9	408 to 504 (or until dry)	160	140

Table 7-20—Time schedules for kiln drying softwood lumber at conventional temperatures—concluded

Step no.	Time (h)	Temperature (°F)	
		Dry-bulb	Wet-bulb
	SCHEDULE WC’		
1	0 to 48	120	(Vents open)
2	48 to 72	125	(Vents open)
3	72 to 84	130	(Vents open)
4	84 to 96	135	(Vents open)
5	96 to 120	140	(Vents open)
6	120 to 132	150	100
7	132 to 144	155	105
8	144 to 168 (or until dry)	160	110
	SCHEDULE XC’		
1	0 to 24	105	(Vents open)
2	24 to 48	110	(Vents open)
3	48 to 72	115	(Vents open)
4	72 to 96	120	(Vents open)
5	96 to 120	125	100
6	120 to 144	130	100
7	144 to 168	135	105
8	168 to 192	140	105
9	192 to 216	145	105
10	216 to 240	150	108
11	240 to 264	155	108
12	264 to 288 (or until dry)	160	110
	SCHEDULE YC[4]		
1	0 to 24	120	(Vents open)
2	24 to 48	130	100
3	48 to 72	140	105
4	72 to 84	150	105
5	84 to 96 (or until dry)	170	120
	SCHEDULE ZC[4]		
1	0 to 12	115	(Vents open)
2	12 to 36	130	95
3	36 to 60	140	95
4	60 to 72	150	100
5	72 to 96 (or until dry)	160	115
	SCHEDULE AAC[4]		
1	0 to 168	105	(Vents open)
2	168 to 336	130	105
3	336 to 504	145	105
4	504 to 672	150	105
5	672 to 840	160	110
	SCHEDULE BBC		
1	0 to 24	115	[2]100
2	24 to 72	120	[2]100
3	72 to 96	125	[2]105
4	96 to 120	130	[2]110
5	120 to 144	140	[2]120
6	144 to 156 (or until dry)	140	[2]127
	SCHEDULE CCC		
1	0 to 12	110	[2]100
2	12 to 36	120	[2]110
3	36 to 60	120	[2]105
4	60 to 84	120	[2]100
5	84 to 108	130	[2]105
6	Equalize	140	130

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[1] SP, southern pine.

[2] Equalize and condition as necessary

[3] Spray off; vents working.

[4] No conditioning.

Table 7-21—Index of time schedules[1] for kiln drying softwood lumber at high temperature (>212 °F)

Common name (botanical name)	Lumber schedules			Schedules for other products	Comment
	4/4,5/4	6/4	8/4		
Ceder, northern white					
(Thuja occidentalis)	IH	—	—		
Douglas-fir	AH	AH	AH		Can be dried with western larch.
(Pseudotsuga menziesii)			OH		
Fir, true					
Balsam *(Abies balsamera)*	AH	AH	AH		
California red (A. magnifica)	AH	AH	AH		
Grand (A. *grandis)*	AH	AH	AH		
Noble *(A. procera)*	AH	AH	AH		
Pacific silver (A. *amabilis)*	AH	AH	AH		Can be dried with western hemlock.
			PH		
Subalpine *(A. lasiocarpa)*	AH	AH	AH		
QH					
White *(A. concolor)*	AH	AH	AH	4 by 6-in decking, FH	
				Studs, GH	
Hemlock					
Mountain *(Tsuga mertensiana)*	AH	AH	AH		
Western (T. heterophylla)	AH	AH	AH		Can be dried with Pacific silver fir.
			PH		
Larch, western					
(Lark occidentalis)	AH	AH	AH		Can be dried with Douglas-fir.
			OH		
Pine					
Jack *(Pinus banksiana)*	AH	AH	AH	Studs, MH	
Limber *(P. flexilis)*	AH	AH	AH		
Lodgepole *(P. contorta)*	AH	AH	AH	Studs, MH	
Ponderosa *(P. ponderosa)*	AH	AH	AH	Studs, HH	
Red (Norway) *(P. resinosa)*	JH	—	KH		
Southern	—	—	—	2 by 4, DH	Can be used with steam heat.
Loblolly *(P. taeda)*	BH, CH	—	—	2 by 10, DH	
Longleaf *(P. palustris)*	—	—	—	4 by 4, EH	
Shortleaf *(P. echinata)*	—	—	—		
Slash *(P. elliottii)*	—	—	—		
Spruce					
Black *(Picea mariana)*	AH	AH	AH		
	JH	—	KH		
Engelmann *(P. engelmannii)*	AH	AH	AH		
Red *(P. rubens)*	JH	—	KH		
White *(P. glauca)*	AH	AH	AH	Studs, MH	Can be dried with jack and lodgepole pine.
	JH	—	KH		Use NH with gas-fired kilns.

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[1] See table 7-22 for description of schedules.

Table 7-22—Time schedules for kiln drying softwood lumber at high temperatures

Step no.	Time (h)	Temperature (°F)	
		Dry-bulb	Wet-bulb
SCHEDULE AH[1]			
1	0 to 12	230	205
2	12 to 24	230	200
3	24 to 36 (or until dry)	230	195
SCHEDULE BH (C&BTR SYP–5/4; DIRECT FIRED)[1,2]			
1	0 to 16 (or until dry[3])	220	180
SCHEDULE CH (C&BTR SYP–1-IN RANDOM WIDTH; DIRECT FIRED)[1]			
1	0 to 15 (or until dry[4])	220	180
SCHEDULE DH (SYP–2 BY 4-2 BY 10; DIRECT FIRED)[1]			
1	0 to 24 (or until dry[5])	240	180
SCHEDULE EH (SYP–4 BY 4; DIRECT FIRED)[1]			
1	0 to 41 (or until dry[6])	220	165
SCHEDULE FH[1]			
1	0 to 8	220	210
2	8 to 24	220	205
3	24 to 60	220	200
4	60 to 96	225	200
5	96 until dry	235	200
SCHEDULE GH[1]			
1	0 to 6 or 2 h past period when temperatures leveled off	212	212
2	6 to 16	240	190
3	16 until dry (30-36 h)[7]	240	170
SCHEDULE HH[1]			
1	0 to 4	210	210
2	4 to 8	220	210
3	8 to 12	230	205
4	12 to 18	230	200
5	18 to 24	230	190
6	24 until dry	230	180
SCHEDULE MH (LODGEPOLE, JACK PINE, WHITE SPRUCE–STUDS)[1]			
1	0 to 6	180	160
2	6 to 12	180	160
3	12 to 26	220	185
4	26 to 35	220	180
5	35 to 46	220	160
SCHEDULE NH (WHITE SPRUCE–2-IN DIMENSION; GAS FIRED)[1]			
1	0 to 28	230	185
SCHEDULE OH (DOUGLAS-FIR, LARCH–2- BY 4-IN DIMENSION)[1]			
1	0 to 12	225	190
2	12 to 21	240	190
3	21 to 24	205	180
SCHEDULE PH (WESTERN HEMLOCK, AMABILIS FIR–2- BY 4-IN DIMENSION)[1]			
1	0 to 42	240	205
SCHEDULE QH (ALPINE FIR–2-IN DIMENSION)[1]			
1	0 to 54	235	180
2	54 to 58	(Steam)	—
3	58 to 62	235	180
4	62 to 66	(Steam)	—
5	66 to 90	235	180

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[1] Equalize and condition as necessary.

[2] C&BTR, common and Better grade; SYP, southern yellow pine.

[3] At 10 percent moisture content, final wet-bulb temperature will be approximately 145°F for direct-fired kilns and approximately 175°F for steam-heated kilns.

[4] At 10 percent moisture content, final wet-bulb temperature will be approximately 150°F for direct fired kilns.

[5] At 15 percent moisture content, final wet-bulb temperature will be approximately 155°F.

[6] At 20 percent moisture content, final wet-bulb temperature will be approximately 140°F.

[7] Pull charge when sapwood and corky heartwood are dry.

Table 7-23—Time schedules for kiln drying softwood lumber at high temperatures

step no.	Moisture content (percent)	Temperature (°F)	
		Dry-bulb	Wet-bulb
	SCHEDULE IH		
1	(Warmup—2 h)	—	212
2	Above 30	230	208
3	Below 30	230	192
4	(Conditioning)	190	180
	SCHEDULE JH		
1	(Warmup—2 h)	—	210
2	Above 35	235	200
3	35 to 20	240	190
4	Below 20	245	180
5	(Conditioning)	190	180
	SCHEDULE KH		
1	(Warmup—3 h)	—	210
2	(Hold for 1/2 h)	240	210
3	(Green to dry)	240	200
4	(Conditioning)	219	212

Table 7-24—Anti-brown-stain moisture content schedules for 4/4-6/4 eastern white pine, western white pine, and sugar pine

Moisture content at start of step (percent)	Dry-bulb temperature (°F)	Wet-bulb depression (°F)	Wet-bulb temperature (°F)
>100	120	15	(1)
100	120	15	105
85	120	20	100
60	130	25	105
45	130	30	100
30	140	35	105
25	150	35	115
20	160	35	125
15	180	28	152
(Conditioning—4 h)	152	12	140

[1] Spray value shut.

Table 7-25—Anti-brown-stain time schedules for eastern white pine, western white pine, and sugar pine

step no.	Time (h)	Dry-bulb temperature (°F)	Wet-bulb temperature (°F)
	4/4-5/4 LUMBER		
1	0 to 16	120	(1)
2	16 to 32	125	(1)
3	32 to 64	130	(1)
4	64 to 80	135	(1)
5	80 to 96	140	(1)
6	96 to 112	145	110
7	112 to 128	150	110
8	128 to 144	155	115
9	144 to 160	160	120
10	160 to 220	170	125
11	220 until dry	170	125
	7/4-8/4 LUMBER		
1	0 to 12	120	(1)
2	12 to 55	125	(1)
3	55 to 74	130	(1)
4	74 to 96	135	(1)
5	96 to 144	145	110
6	144 to 168	160	120
7	168 until dry	170	125

[1] Spray off, vents open.

Table 7-26—Recommended kiln schedules for Douglas-fir plywood treated with chromated copper arsenate preservative

Schedule’	Temperature (°F)		Drying time to approximately 14 percent(h)
	Dry-bulb	Wet-bulb	
	3/4-IN-THICK PLYWOOD		
1	165	160	49
2	185	180	41
	1/2-IN-THICK PLYWOOD		
1	165	160	27
2	185	180	24

[1] Two alternative schedules are given for each size of plywood.

[2] Initial wet-bulb temperature–the schedule calls for a 1 °F per h decrease in wet-bulb temperature as drying progresses.

Table 7-27—Suggested kiln schedules for large southern Pine timbers and poles

Time in each step (h)	Temperature (°F)		Comment
	Dry-bulb	Wet-bulb	
3 BY 6- AND 4 BY 8-IN TIMBERS			
48	140	125	The 180 °F final step is prolonged until the timbers reach 18 percent moisture content.
48	150	130	
48	160	135	
48	170	138	
48	180	140	
4-1/2-BY 5-1/2-IN CROSSARMS			
30	160	150	Final moisture content at a 1 -in depth is 17 to 22 percent.
24	170	150	
24	180	150	
24	190	150	
10 to 12	195	175	
3-1/2- BY 4-1/2-IN PARTIALLY AIR-DRIED CROSSARMS			
69	135	125	
24	145	125	
29	150	125	
15	165	132	
UP TO 6- BY 6-IN TIMBERS			
36	230	No control	Fan reversal every 3 h with 3-min venting at that time. Dry outer 2 in. to below fiber saturation point.
6- BY 6-IN AND GREATER TIMBERS AND POLES (SEVERE SCHEDULE)			
48	230	No control	Fan reversal every 3 h with 3-min venting at that time. Dry outer 2 in. to below fiber saturation point.
10-1/2-IN-DIAMETER POLES AND PILING (MILD SCHEDULE)			
24	134	120	
47	144	120	
47	153	120	
46	165	120	
8- TO 10-IN-DIAMETER POLES AND PILING (ACCELERATED SCHEDULE)			
114	170	120	Initial moisture content about 85 percent. Final moisture content 30 percent in outer 3 in.

Table 7-28—Time schedules for kiln drying 4- by 5-in roof decking

Step no.	Time (h)	Dry-bulb temperature (°F)	Wet-bulb temperature (°F)
		WHITE FIR	
1	0 to 24	150	140
2	24 to 48	155	140
3	48 to 72	160	145
4	72 to 96	165	150
5	96 to 192	170	155
		ENGELMANN SPRUCE	
1	0 to 144	165	145
2	144 to 168	177	120
		WESTERN REDCEDAR	
1	0 to 48	130	120
2	48 to 72	135	120
3	72 to 96	140	125
4	96 to 120	145	125
5	120 to 144	150	125
6	144 to 168	155	125
7	168 to 192	160	130
8	192 to 216	165	135
9	216 to 240	170	140

Table 7-29—Conversion of a schedule from a steam-heated kiln to dehumidification kiln

Moisture content at start of step (percent)	Temperature (°F)		Relative humidity (percent)	Equilibrium moisture content (percent)
	Dry-bulb	Wet-bulb		
		4/4 WHITE OAK–T4-C2 FOR STEAM-HEATED KILN		
>40	110	106	87	17.5
40	110	105	84	16.2
35	110	102	75	13.3
30	120	106	62	10.0
25	130	100	35	5.6
20	140	90	19	2.6
15	180	130	26	3.3
(Equalize)	173	130	30	4.1
(Condition)	180	170	79	11.1
		4/4 WHITE OAK–T4-C2 CONVERTED TO DEHUMIDIFICATION SCHEDULE WITH MAXIMUM TEMPERATURE OF 120 °F		
>40	110	106	87	17.5
40	110	105	84	16.2
35	110	102	75	13.3
30	120	106	62	10.0
25	120	91	35	5.6
20	120	80	17	3.3
15	120	80	17	3.3
(Equalize[1])	120	84	22	4.2
(Condition[2])	120	108	67	11.0

Table 7-30—General low-temperature schedule for kiln drying refractory species

Moisture content at start of step (percent)	Temperature (°F)		Relative humidity (percent)	Equilibrium moisture content (percent)
	Dry-bulb	Wet-bulb		
>50	90	86	85	17.3
50	90	84	78	14.7
45	95	88	75	13.9
40	95	85	66	11.6
35	100	88	62	10.6
30	100	85	54	9.2
25	105	88	50	8.7
20	110	87	40	6.8
15	120	90	31	5.4

Table 7-31—Schedule for killing Lyctus (powder-post) beetles and their eggs

Temperature (°F)		Relative humidity (percent)	Equilibrium moisture content (percent)	Thickness of lumber (in)	Kiln reaches set conditions (h)
Dry-bulb temperature	Wet-bulb depression				
				1	3
140	7	82	13.8	2	5
				3	7
				1	10
130	16	60	9.4	2	12
				3	14
				1	46
125	15	61	9.7	2	48
				3	50

Table 7-32—Kiln sample moisture content and equilibrium moisture content values for equalizing and conditioning a charge of lumber

Desired final average) moisture content (percent)	Equalizing moisture content values (percent)			Conditioning equilibrium moisture content values (percent)	
	Moisture content of driest sample at start	Equilibrium moisture content conditions in kiln	Moisture content of wettest sample at end	Softwoods	Hardwoods
5	3	3	5	8	9
6	4	4	6	9	10
7	5	5	7	10	11
8	6	6	8	11	12
9	7	7	9	12	13
10	8	8	10	13	14
11	9	9	11	14	15

Table 7-33—Approximate kiln-drying periods for 1-in lumber[1]

Species	Time (days) required to kiln dry 1-in lumber: 20 to 6 percent moisture content	Time (days) required to kiln dry 1-in lumber: Green to 6 percent moisture content
SOFTWOODS		
Baldcypress	4-8	10-20
Cedar		
Alaska	—	4-6
Atlantic white	—	8-10
Eastern redcedar	2-3	6-8
Incense	—	3-6
Northern white	—	8-10
Port-Orford	—	4-8
Western redcedar	—	10-15
Douglas-fir		
Coast type	—	2-4
Intermediate type	—	4-7
Rocky Mountain type	—	4-7
Fir		
Balsam	—	3-5
California red	—	3-5
Grand	—	3-5
Noble	—	3-5
Pacific silver	—	3-5
Subalpine	—	3-5
White	—	3-5
Hemlock		
Eastern	—	3-5
Western	—	3-5
Larch, western	—	3-5
Pine		
Eastern white	2-3	4-6
Lodgepole	—	3-5
Ponderosa	—	3-6
Red	—	6-8
Southern yellow		
Loblolly	—	3-5
Longleaf	—	3-5
Shortleaf	—	3-5
Sugar		
Light	—	3-4
Heavy	—	5-10
Western white	—	3-5
Redwood		
Light	3-5	10-14
Heavy	5-7	20-24
Spruce		
Eastern, black, red, white	—	4-6
Engelmann	—	3-5
Sitka	—	4-7
Tamarack	—	3-5
HARDWOODS		
Alder, red	3-5	6-10
Apple	4-7	10-15
Ash		
Black	5-7	10-14
White	4-7	11-15
Aspen	3-5	6-10
Basswood, American	3-5	6-10
Beech, American	5-8	12-15
Birch		
Paper	—	3-5
Yellow	5-8	11-15
Buckeye, yellow	5-8	12-16
Butternut	5-8	10-15
Cherry black	5-7	10-14
Chestnut, American	4-8	8-12
Chinkapin, golden	7-12	22-28
Cottonwood	4-8	8-12
Dogwood, flowering	5-8	12-16
Elm		
American	4-6	10-15
Rock	5-8	13-17
Hackberry	4-6	7-11
Hickory	4-12	7-15
Holly, American	5-8	12-16
Hophornbeam, eastern	5-8	12-16
Laurel, California	5-7	10-15
Locust, black	5-8	12-16
Madrone, Pacific	8-11	15-20
Magnolia	4-6	10-15
Mahogany	4-7	12-15
Maple		
Red, silver (soft)	4-6	7-13
Sugar (hard)	5-8	11-15
Oak		
California black	6-10	25-35
Live	—	30-40
Red	5-10	16-28
White	6-12	20-30
Osage-orange	5-8	12-16
Persimmon, common	5-8	12-16
Sweetgum		
Heartwood	8-12	15-25
Sapwood	5-7	10-15
Sycamore, American	4-7	6-12
Tanoak	7-12	24-30
Tupelo		
Black	4-6	6-10
Water	5-7	6-12
Walnut, black	5-8	10-16
Willow, black	5-8	12-16
Yellow-poplar	3-6	6-10

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[1] Because of the many factors affecting drying rate and the lack of specific data covering each case, wide variation from these values must be expected. These values represent only a general idea of average drying periods and should not be used as time schedules. Some of the drying times shown were obtained from commercial kiln operators.

Chapter 8
Drying Defects

Chapter 8 was revised by James C. Ward, Research Forest Products Technologist, and William T. Simpson, Supervisory Research Forest Products Technologist.

The success of a company and the livelihood of the dry kiln operator may depend on knowing the causes of defects in lumber and methods to prevent their occurrence. Since some defects are not observed in green lumber and are first noted after the drying operation, they are often called drying defects even though the defects may have started in the tree, log, or green lumber. Defects that develop in dry wood products during machining, gluing, and finishing operations may also be blamed on poor drying practices. A drying defect is any characteristic or blemish in a wood product that occurs during the drying process and reduces the product's intended value. Drying degrade is a more specific term that implies a drying defect that lowers the grade of lumber. Every year, drying degrade and other drying defects cost the softwood and hardwood lumber industries millions of dollars in lost value and lost volume caused by poor product performance. When unexpected defects appear in dried wood products, their cause is often blamed on the drying operation. The purpose of this chapter is to describe the various types of defects that can occur in dried wood products and to show how these defects are related to the kiln-drying operation.

Many features of wood affect its utility when it is processed into lumber and special products. These includes knots, ring shake, bark, mineral streaks, pitch pockets, compression and tension wood, juvenile wood, and spiral or interlocked grain, all of which form in the tree and directly influence the grade and value of each individual board. Ordinary processing of lumber may remove some of these natural features through trimming and thus improve the quality and value of the remaining piece.

Defects that reduce the grade and value of lumber often develop during logging, sawmilling, drying, finishing, and mechanical handling. A principal objective is to dry the wood economically with as little development of defects as possible. The degree of care to exercise in controlling the development of defects depends on the final use of the lumbar. It is important for the kiln operator to be familiar with the various defects that reduce the grade and value of dry wood products, to know when the defects can be reduced or eliminated with proper drying practices, and to recognize when corrective measures other than drying are required. When drying is used to control defects, it should be done in a manner consistent with the economy of the overall manufacturing system. Before adopting a drying procedure to control specific drying defects, the kiln operator should determine whether the procedure will induce other defects that may lower the value of the lumber.

Effect of Drying Temperatures

High temperatures reduce the strength of wood in two ways. First, there is an immediate and reversible effect. For example, wood is weakened when heated from 75 to 240 °F but regains strength if immediately cooled to 75 °F. The second effect occurs over time and is permanent. When wood is heated for long times at high temperatures, ‘it is permanently weakened; the loss of strength remains after the wood is cooled. Roth effects are greater at high moisture content than at low moisture content. The permanent effect is caused by a combination of time, temperature, and moisture content. Strength loss increases as any one of these factors increases.

The immediate,-reversible effect of high-temperature drying is important in the development of drying defects that result from breakage or crushing of wood cells. When the drying stresses described in chapter 1 become greater than the strength of the wood, this type of drying defect develops. This is why high temperatures early in drying are dangerous. The weakening effect of high temperatures coupled with high moisture content can cause the wood to fracture or be crushed.

High-temperature drying for long periods, particularly early in drying when the moisture content is high, may not result in breakage or crushing-type drying defects, but it can cause a permanent loss in strength or other mechanical properties that affect product performance in end use. Table 8-1 shows the effect of high-temperature drying (225 to 240 °F) compared to conventional-temperature drying (<180 °F) on stiffness (modulus of elasticity) and bending strength (modulus of rupture) of several species. In general, stiffness is not greatly reduced by high-temperature drying, hut bending strength may be reduced by as much as 20 percent.

For many uses of wood, some reduction in strength is not important. In some uses, it is quite important. For example, the 20 percent loss in bending strength noted in table 8-1 for Douglas-fir can be a concern in structural lumber. Wood for ladders, aircraft, and sporting goods requires high strength and toughness retention.

There is evidence that lumber treated with waterborne preservatives and fire retardants is particularly sensitive to strength reduction if drying temperatures are too high. Temperatures ranging from 140 to 160 °F have little effect on mechanical properties. The schedules in chapter 7 (tables 7-9 and 7-10) can be used where strength retention is a major concern.

Defect Categories

Most defects or problems that develop in wood products during and after drying can be classified under one of the following categories:

1. Rupture of wood tissue
2. warp
3. Uneven moisture content
4. Discoloration

Defects in any one of these categories are caused by an interaction of wood properties with processing factors. Wood shrinkage is mainly responsible for wood ruptures and distortion of shape. Cell structure and chemical extractives in wood contribute to defects associated with uneven moisture content, undesirable color, and undesirable surface texture. Drying temperature is the most important processing factor because it can be responsible for defects in each category.

Rupture of Wood Tissue

Many defects that occur during drying result. from the shrinkage of wood as it dries. In particular, the defects result from uneven shrinkage in the different directions of a board (radial, tangential, or longitudinal) or between different parts of a board, such as the shell and core. Rupture of wood tissue is one category of drying defects associated with shrinkage. Knowing where, when, and why ruptures occur will enable an operator to take action to keep these defects at a minimum. Kiln drying is frequently blamed for defects that have occurred during air drying, but most defects can occur during either process. In kiln drying, defects can be kept to a minimum by modifying drying conditions, and in air drying, by altering piling procedures.

Surface Checks

Surface checks are failures that usually occur in the wood rays on the flatsawn faces of boards (figs. 8-1 and 8-2). They occur because drying stresses exceed the tensile strength of the wood perpendicular to the grain, and they are caused by tension stresses that develop in the outer part, or shell, of boards as they dry (ch. 1). Surface checks can also occur in resin ducts and mineral streaks. They rarely appear on the edges of flatsawn boards 6/4 or lees in thickness but do appear on the edges of thicker flatsawn or quartersawn boards. Surface checks usually occur early in drying, but in some softwoods the danger persists beyond the initial stages of drying. They develop because the lum-

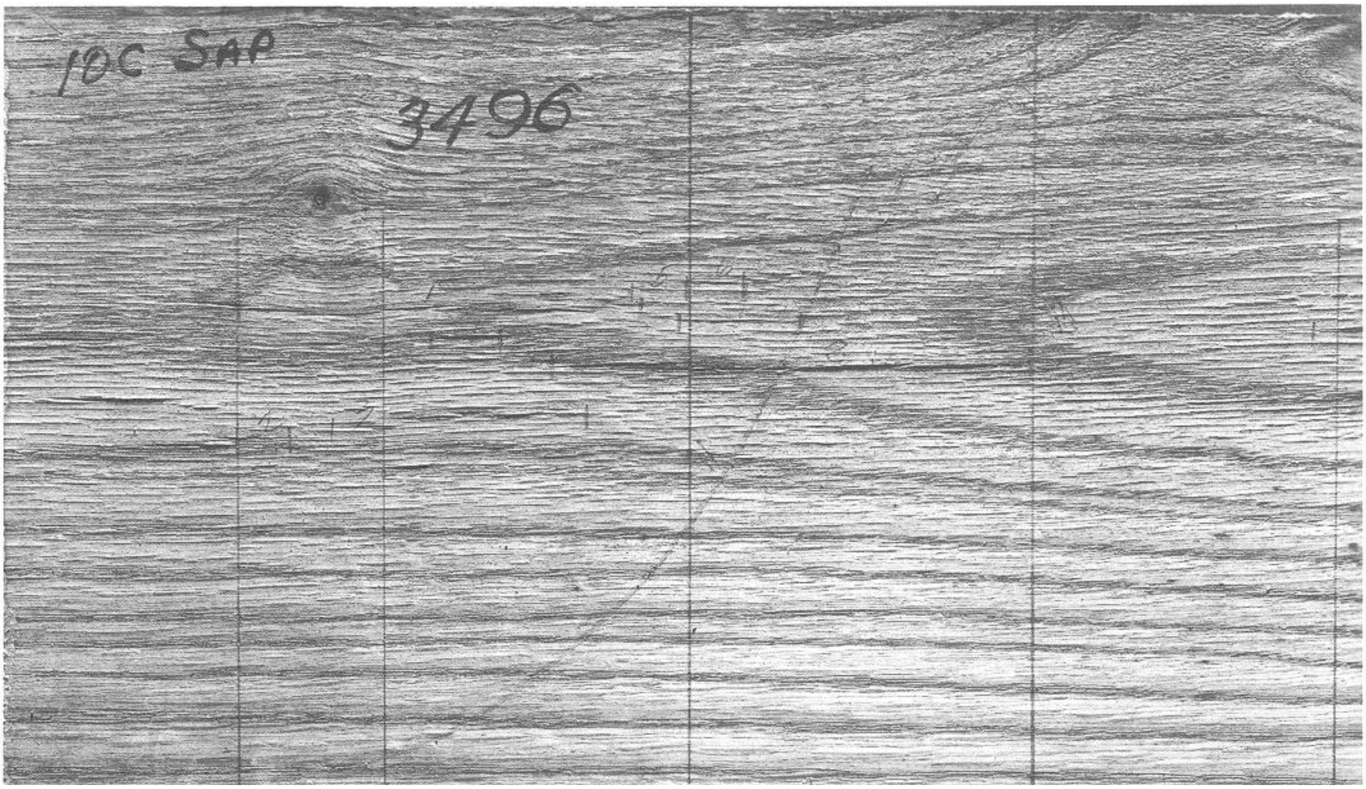

Figure 8-1—Surface checks in cherrybark oak. (M 137194)

Figure 8-2—Surface checks in Douglas-fir dimensional lumber. (M 22523)

ber surfaces get too dry too quickly as .a result of relative humidity that is too low. Surface checks can also develop during air drying. Thick, wide, flatsawn lumber is more susceptible to surface checking than thin, narrow lumber.

Many surface checks, particularly those in hardwoods, close in the later stages of drying This occurs when the stresses reverse and the shell changes from tension to compression (ch. 1). Closed surface checks are undesirable in products requiring high-quality finished surfaces, such as interior trim and molding, cabinets, and furniture. The checks will quite likely open to some extent during use because of fluctuations in relative humidity that alternately shrink and swell the surface. Superficial surface checks that will be removed during machining are not a problem. In products such as tool handles, athletic equipment, and some structural members, either closed or open surface checks can increase the tendency of the wood to split during use. In some products, such, as interior parts of furniture, wall studs, and some flooring applications, mild surface checking will not cause any problems in use.

Lumber that has surface checked during air drying should not be wetted or exposed to high relative humidity before or during kiln drying. Such treatments frequently lengthen, widen, and deepen surface checks. Lumber that has open surface checks after kiln drying should also not be wetted because subsequent exposure to plant conditions will dry out the wetted surface and enlarge the checks.

End Checks and Splits

End checks (fig. 8-3), like surface checks, usually occur in the wood rays, but on end-grain surfaces. They also occur in the early stages of drying and can be minimized by using high relative humidity or by end coat-

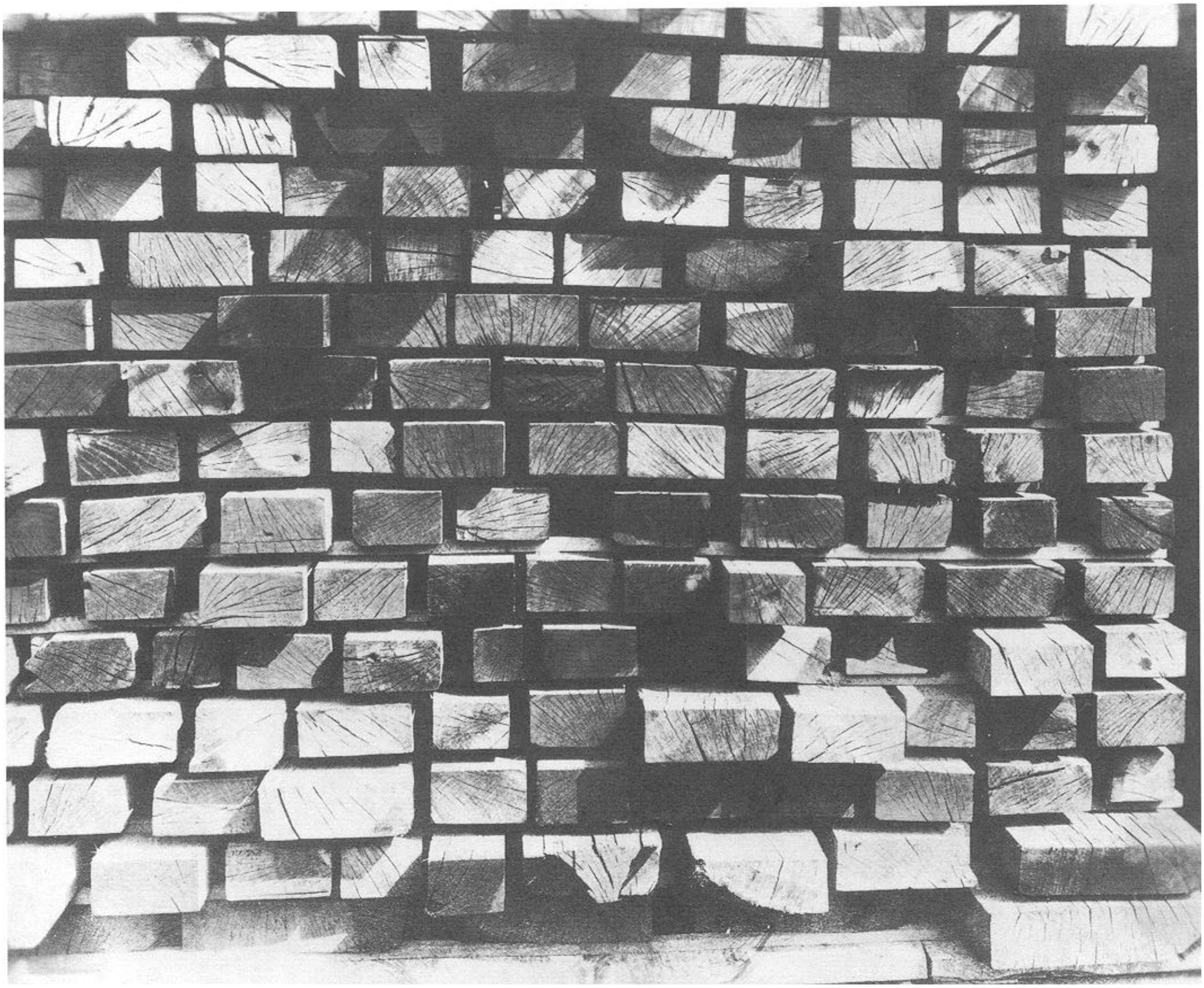

Figure 8-3—End checks in oak lumber. (M 3510)

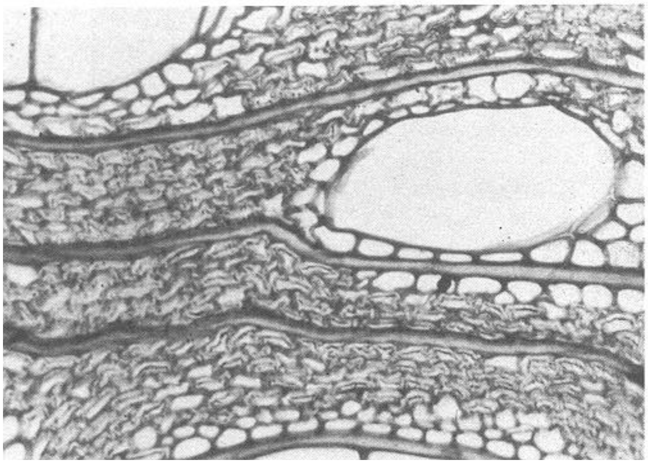

Figure 8-4—Photomicrograph showing collapsed wood cells. (M 69379)

ing. End checks occur because moisture moves much faster in the longitudinal direction than in either transverse direction. Therefore, the ends of boards dry faster than the middle and stresses develop at the ends. End-checked lumber should not be wetted or exposed to high relative humidity before any further drying, or the checks may be driven further into the board.

The tendency to end check becomes greater in all species as thickness and width increase. Therefore, the end-grain surfaces of thick and wide lumber squares, and gunstocks should be end coated with one of the end coatings available from kiln manufacturers and other sources. To be most effective, end coatings should be applied to freshly cut, unchecked ends of green wood.

End splits often result from the extension of end checks further into a board. One way to reduce the extension of end checks into longer splits is to place stickers at the extreme ends of the boards. End splits are also often caused by growth stresses and are therefore not a drying defect. End splits can be present in the log or sometimes develop in boards immediately after sawing from the log.

Collapse

Collapse is a distortion, flattening, or crushing of wood cells. Figure 8-4 shows collapse at the cell level, and figure 8-5 shows a severe case of collapse at the board level. In these severe cases, collapse usually shows up as grooves or corrugations, a washboarding effect, at thin places in the board. Slight amounts of collapse are usually difficult or impossible to detect at the board level and are not a particular problem. Sometimes collapse shows up as excessive shrinkage rather than distinct grooves or corrugations.

Collapse may be caused by (1) compressive drying stresses in the interior parts of boards that exceed the compressive strength of the wood or (2) liquid tension in cell cavities that are completely filled with water (ch. 1). Both of these conditions occur early in drying, but collapse is not usually visible on the wood surface until later in the process. Collapse is generally associated with excessively high dry-bulb temperatures early in kiln drying, and thus low initial dry-bulb temperatures should be used in species susceptible to collapse.

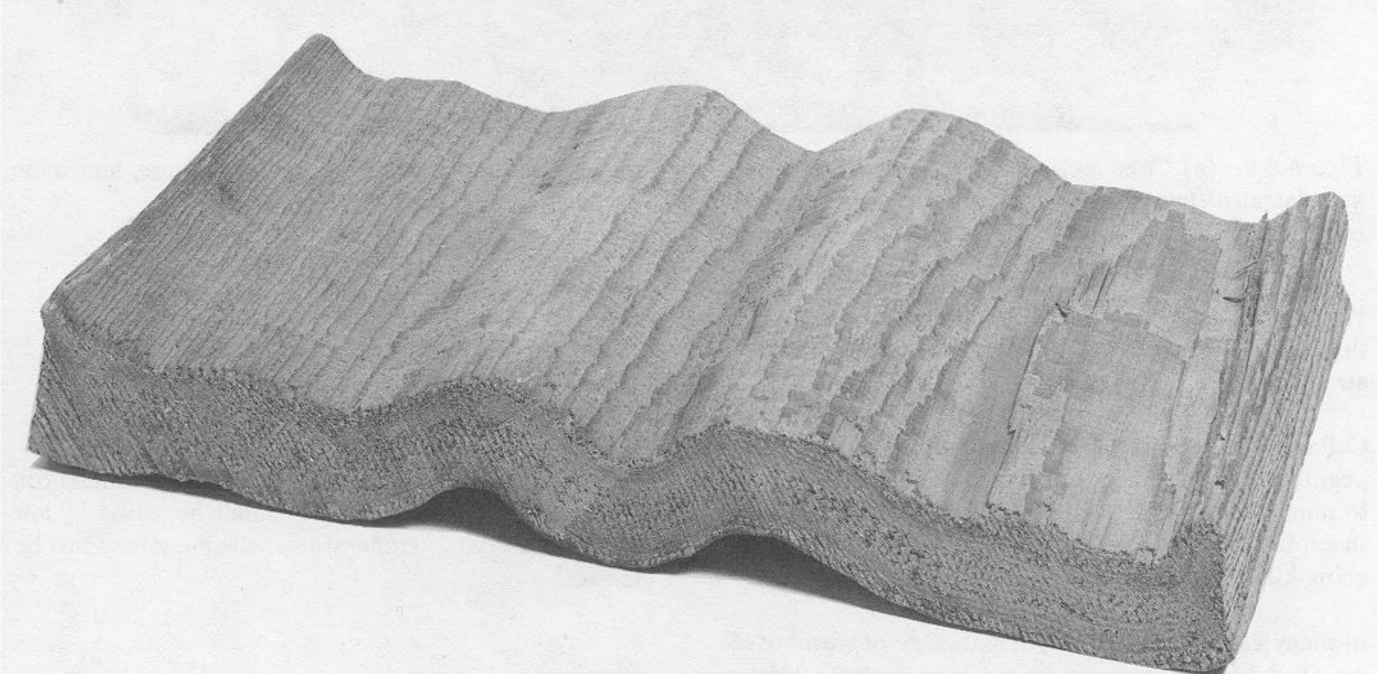

Figure 8-5—Severe collapse in western redcedar. (M 111997)

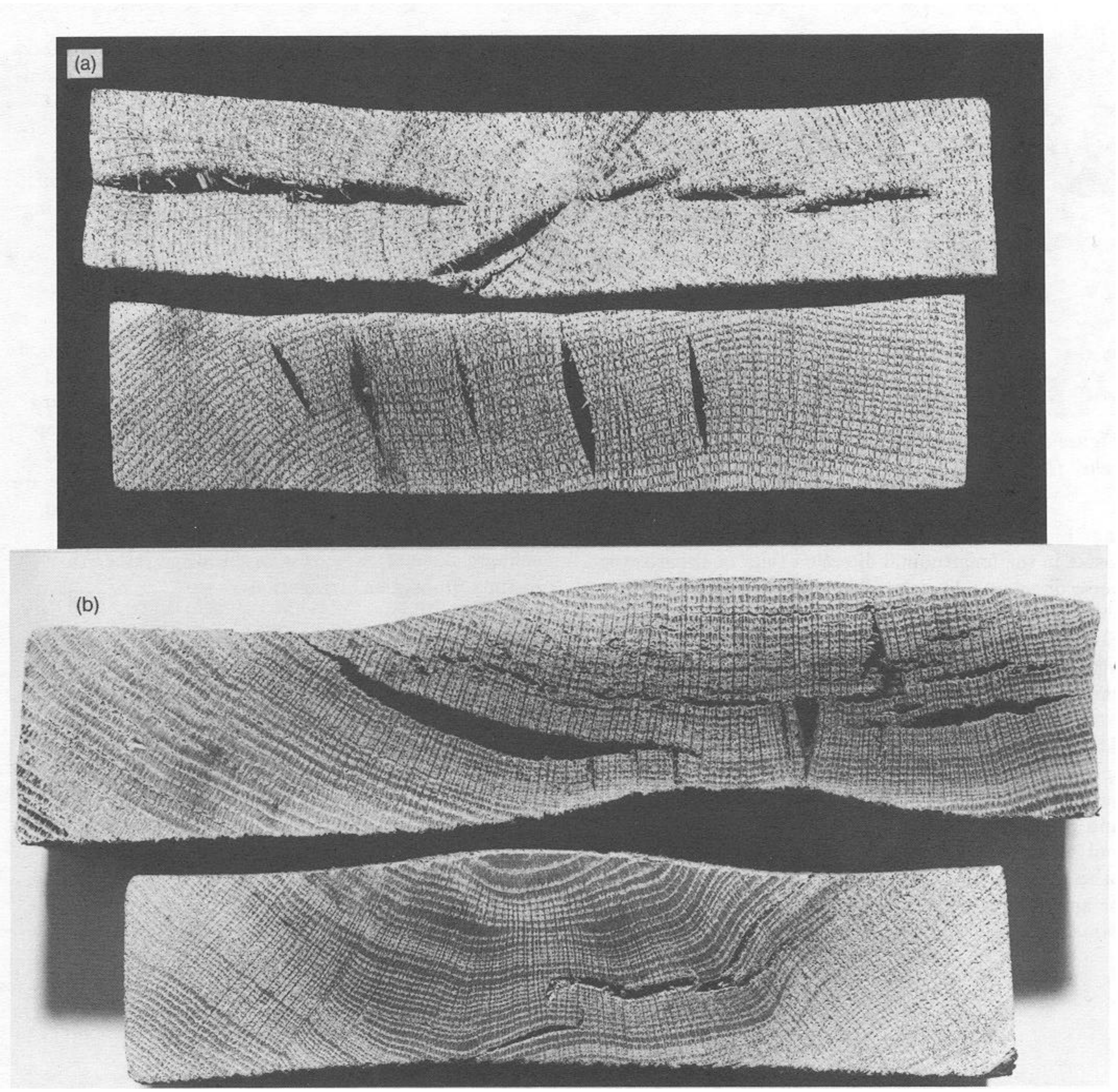

Figure 8-6—(a) Cross section of quartersawn (upper) and flatsawn (lower) red oak boards showing honeycomb and slight collapse; (b) cross section of flatsawn red oak boards showing ring failure, collapse, and some honeycomb. (MC88 9025)

Wetwood in particular is susceptible to collapse. Although rare, collapse has been known to occur during air drying.

Collapse is a serious defect and should be avoided if possible. The use of special drying schedules planned to minimize this defect is recommended. Some species susceptible to collapse are generally air dried before being kiln dried.

In many cases, much excessive shrinkage or washboarding caused by collapse can be removed from the lumber by reconditioning or steaming, a treatment first used commercially in Australia. This treatment basically consists of steaming the lumber as near as possible to 212 °F and 100 percent relative humidity. Reconditioning is most effective when the average moisture content is about 15 percent, and 4 to 8 h are usually required. Steaming is corrosive to kilns, and unless collapse is a serious problem that cannot be solved by lowering initial drying temperatures, steaming may not be practical.

Figure 8-7—Honeycomb that does not appear on the surface of a planed red oak board (lower) does appear when the board is machined into millwork (upper). (M 140291)

Honeycomb

Honeycomb is an internal crack caused by a tensile failure across the grain of the wood and usually occurs in the wood rays (fig. 8-6). This defect develops because of the internal tension stresses that develop in the core of boards during drying (ch. 1). It occurs when the core is still at a relatively high moisture content and when drying temperatures are too high for too long during this critical period. Therefore, honeycomb can be minimized by avoiding high temperatures until all the free water has been evaporated from the entire board. This means that the core moisture content of boards should be below the fiber saturation point before raising temperature because that is where honeycomb develops. When the average moisture content of entire sample boards is monitored for schedule control, there is no direct estimate of core moisture content. Depending on the steepness of the moisture gradient, which is often unknown in most kiln-control schemes, the core moisture content can be quite high even when the average moisture content of the whole sample is low. The danger is that schedule changes based on average moisture content that call for an increase in dry-bulb temperature can be made too soon while moisture content in the core is still high, thus predisposing the wood to honeycomb. Measurements of shell and core moisture content (ch. 6) should be taken before these dangerous schedule changes are made.

Deep surface and end checks that have closed tightly on the surface of lumber but remain open below the surface often called honeycomb, but they are also known as bottleneck checks.

Honeycomb can result in heavy volume losses of lumber. Unfortunately, in many cases the defect is not apparent on the surface, and it is not found until the lumber in is machined (fig. 8-7). Severely honeycombed lumber frequently has a corrugated appearance on the surface, and the defect is often associated with severe collapse.

Ring Failure

Ring failure occurs parallel to annual rings either within a growth ring or at the interface between two rings (fig. 8-6b). It is similar in appearance and often related to shake, which is the same kind of failure that takes place in the standing tree or when the tree is felled; wood weakened by shake fails because of drying stresses. In wood with ring failure, internal tension stesses, especially in high-temperature drying, develop after stress reversal. The failure frequently involves several growth rings, starting in one and breaking along wood rays to other rings. It can occur as a failure in the end grain in the initial stages of drying and extend in depth and length as drying progresses. Ring failure can be kept to a minimum by end coating and by using high initial relative humidity and low dry-bulb temperature schedules.

Boxed-Heart Splits

A boxed-heart split is shown in figure 8-8. These splits start in the initial stages of drying and become increasingly worse as the wood dries. The difference between tangential and radial shrinkage of the wood surrounding the pith causes such severe stresses in the faces of the piece that the wood is split. It is virtually impossible to prevent this defect.

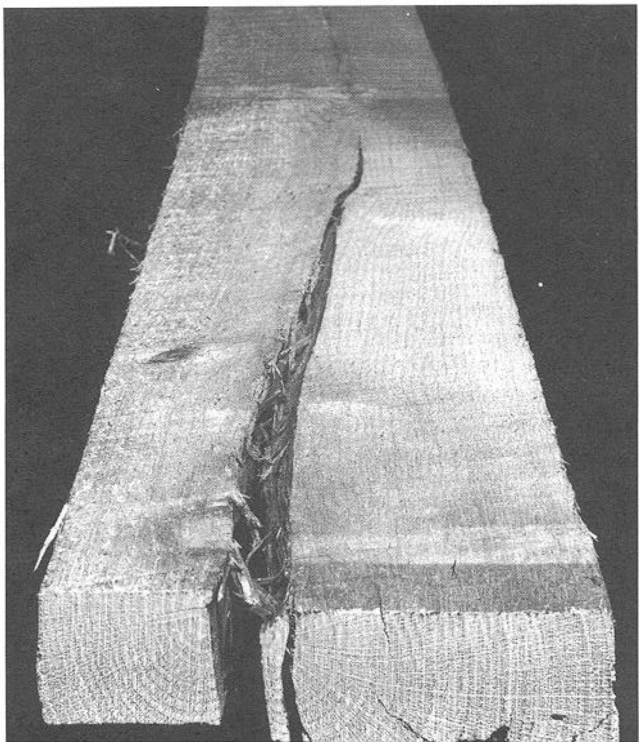

Figure 8-8—Boxed-heart split in red oak. (M 115582)

Checked Knots

Checked knots are often considered defects. The checks appear on the end grain of knots in the wood rays (fig. 8-9). They are the result of differences in shrinkage parallel to and across the annual rings within knots. Checked knots occur in the initial stages of drying and are aggravated by using too low a relative humidity. These defects can be controlled by using higher relative humidities and by drying to a higher final moisture content, but it is almost impossible to prevent them.

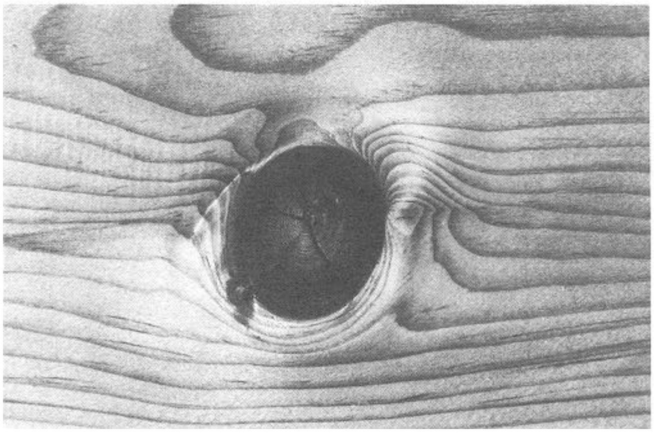

Figure 8-9—Checked knot in sugar pine. (M88 0157)

Loose Knots

Encased knots invariably loosen during drying (fig. 8-10) because they are not grown into the surrounding wood but are held in place by bark and pitch. These knots shrink considerably in both directions of the lumber face (across the width and along the length), whereas the board shrinks considerably in width but very little in length. Consequently, the

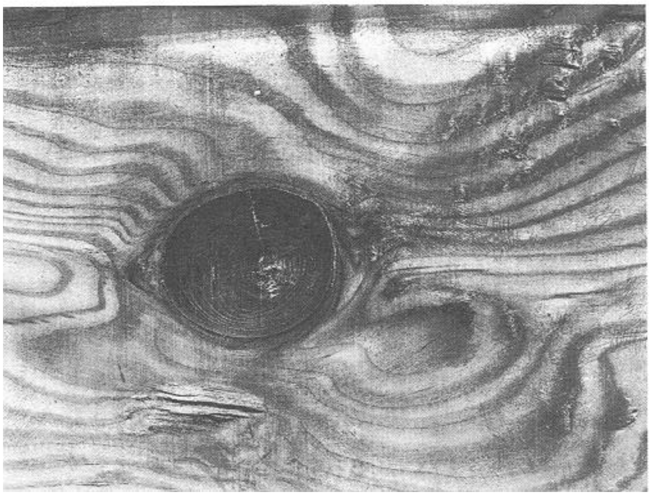

Figure 8-10—Loose knot in southern pine. (M 16268)

dried knot is smaller than the knothole and frequently falls out during handling or machining. Nothing can be done to prevent the loosening of dead knots during drying. Fewer dead knots will fall out during machining, however, if the final moisture content of the lumber can be kept as high as possible before machining.

Warp

Warp in lumber is any deviation of the face or edge of a board from flatness or any edge that is not at right angles to the adjacent face or edge (squares). It can cause significant volume and grade loss. All warp can be traced to two causes; differences between radial, tangential, and longitudinal shrinkage in the piece as it dries, or growth stresses. Warp is also aggravated by irregular or distorted grain and the presence of abnormal types of wood such as juvenile and reaction wood, Most warp that is caused by shrinkage difference can be minimized by proper stacking procedures (ch. 5). The effects of growth stresses are more difficult to control, but certain sawing techniques are effective and will be described later.

The five major types of warp are cup, bow, crook, twist, and diamonding (fig. 8-11). Cup is a distortion of a board in which there is a deviation flatwise from a straight line across the width of a board. It begins to appear fairly early in drying and becomes progressively worse as drying continues. Cup is caused by greater shrinkage parallel to than across the growth rings. In general, the greater the difference between tangential and radial shrinkage, the greater the degree of cup. Thinner boards cup less than thicker ones. Because tangential shrinkage is greater than radial shrinkage, flatsawn boards cup toward the face that was closest to the bark (ch. 1, fig. 1-10). A flatsawn board cut near the bark tends to cup less than a similar board cut near the pith because the growth ring curvature is less near the bark. Similarly, flatsawn boards from small-diameter trees are more likely to cup than those from large-diameter trees. Due quartersawn boards do not cup. Cup can cause excessive losses of lumber in machining. The pressure of planer rollers often splits cupped boards. Cup can be reduced by avoiding overdrying. Good stacking is the best way to minimize cup.

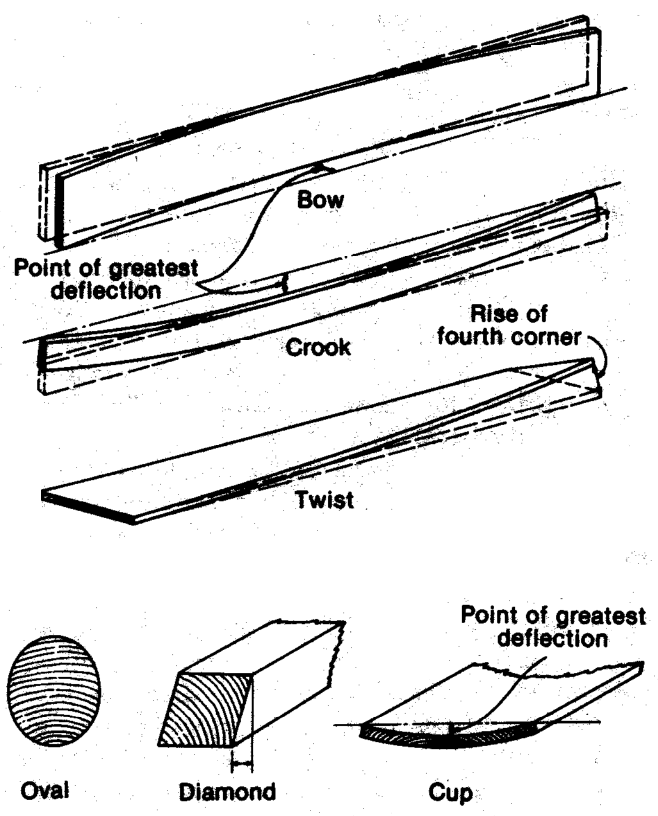

Figure 8-11—Various types of warp that develops in boards during drying. (ML88 5555)

Bow is a deviation flatwise from a straight line drawn from end to end of a board. It is associated with longitudinal shrinkage in juvenile wood near the pith of a tree, compression or tension wood that occurs in leaning trees, and crossgrain. The cause is the difference in longitudinal shrinkage on opposite faces of a board. Assuming that there are no major forms of grain distortion on board faces, bow will not occur if the longitudinal shrinkage is the same on opposite faces.

Crook is similar to bow except that the deviation is edgewise rather than flatwise. While good stacking practices also help reduce crook, they are not as effective against this type of warp as they are against cup and bow.

Twist is the turning of the four corners of any face of a board so that they are no longer in the same plane. It occurs in wood containing spiral, wavy, diagonal, distorted, or interlocked grain. Lumber containing these grain characteristics can sometimes be dried reasonably flat by wing proper stacking procedures. Twist, bow, and crook have definite allowable limits in the grading rules for softwood dimension lumber, so it is desirable to minimize these defects.

Diamonding is a form of warp found in squares or thick lumber. In a square, the cross section assumes a diamond shape during drying. Diamonding is caused by the difference between radial and tangential shrinkage in squares in which the growth rings run diagonally from corner to corner. It can be controlled somewhat by sawing patterns and by air drying or predrying before kiln drying.

Uneven Moisture Content

Wood is dried to an average moisture content that is compatible with subsequent processing operations and the use of the final product. Kiln operators in the United States generally aim towards a target moisture content of 15 percent for softwood dimension (construction) lumber and 6 to 8 percent for softwood and hardwood lumber to be manufactured into items such as furniture, flooring, or millwork. Uneven moisture content refers to a condition where individual boards in a kiln charge have a level of moisture content that deviates greatly from the target moisture content. These boards arc rejected for immediate processing and end we for two reasons: (1) the average board moisture content is either above or below an acceptable range for the intended moisture content or (2) the average moisture content of the entire board is within the acceptable moisture content range, but the core of the board has a water (wet) pocket that cannot be tolerated in the next processing step.

Board Rejects

Most boards are rejected because of moisture content that is too high, but boards with extremely low moisture content (overdried) can also be troublesome during later machining operations.-Softwood dimension lumber with an average moisture content of 19 percent or less is graded as “dry lumber,” and boards 20 percent and over in moisture content are defined as unseasoned lumber. Softwood dimension lumber dried below 10 percent moisture content is usually considered overdried because it is subject to serious planer splits and breakage when surfaced. Overdried lumber is not rejected by lumber-grading associations, but the kiln operator might receive complaints from operators of m-house machining.

After drying, boards with excess moisture content will shrink more than boards within the desired moisture content range and may not yield an end product of acceptable size or shape. Satisfactory glue bonds are difficult to obtain between “wet” and “dry” elements in composite products. If the wood moisture content is too high for the equilibrium moisture content inside buildings, then furniture will develop loose joints, cabinet doors and shelves will warp, and moldings will have unsightly gaps.

Water Pockets

Some boards will have acceptable overall average moisture content and yet have internal water pockets or streaks with moisture contents of 10 percent or more higher than the average. Surfacing of boards containing water pockets can result in surface depressions when the core eventually dries. Resawing boards with water pockets results in bowing and twisting of the new pieces from additional drying of the exposed cores. Water pockets can be a problem with dried stock that is used for glued cores in the manufacture of doors and panels. Even though the water pockets may be pencil thin, they will build up enough steam pressure during electronic gluing operations to explode and shatter the surface of the pieces. Dielectric moisture meter measurements will be erroneous for wood containing water pockets.

Control Measures

Uneven moisture content causes drying problems in the kiln when (1). there are wide differences in moisture content in the initial kiln charge and (2) boards within the charge have greatly different permeability. Wide moisture content differences occur when the kiln is loaded with a mixture of green and partially dried boards. The problem can also develop when the charge contains species such as pine or hemlock where the green moisture content of the sapwood is much higher than the moisture content of the heartwood. Problems with uneven moisture content also occur when She charge contains boards with wetwood or boards of mined species with different permeability.

Initial moisture content differences.—When the kiln is loaded with a mixed charge of boards containing high and low moisture contents, the final drying conditions must be coincidental with the target moisture content. The charge will be dried according to the rate of moisture loss in the wettest boards and equalized to a final acceptable moisture content range that includes the driest boards. The drier boards will be in the kiln longer than necessary, which is the price paid for eliminating wet boards. This procedure is used when the target moisture content is 8 percent or lower. It is not practical for drying softwood dimension lumber where the target moisture content is 15 percent and green moisture content values range from 50 percent for heartwood boards to 170 percent for sapwood boards. By the time the sapwood reaches the target moisture content the. heartwood will be overdried, and it is not economical to increase the moisture content of the heartwood boards from 8-10 percent to 12-15 percent.

When mixed charges of high and low moisture content boards will not be dried to a target moisture content of 8 percent or lower, then the lumber should be segregated into different board sorts and each sort dried separately. In commercial practice, however, sorting for moisture content differences is usually done after kiln drying. The boards are identified for moisture content on the dry chain with dielectric inline moisture meters and the wet boards redried. Redrying can increase drying costs by 25 percent or more. It would be preferable to identify high and low moisture content boards on the green chain before drying. Presorting green wood cannot be accomplished with inline dielectric moisture meters when the wood moisture content is above 30 percent.

Although presorting on the green chain is possible through weighing individual boards when heavy and light board sorts are to be dried separately, this is not done commercially. Existing mills are not equipped to install inline weighing devices or to handle boards of different sizes and weights but similar moisture content values. Recently, a new technique has been developed by the Canadian Forintek Laboratory in Vancouver, BC, that has promise for commercial presorting of lumber by moisture content differences. This Method uses infrared surface measurements, and through computer-controlled equipment identifies each board by moisture content. Moisture content values ranging from below 15 percent to above 150 percent can be measured; and the equipment can be installed on existing green chain production lines.

Permeability differences.— Presorting boards on the green chain can solve the problem of permeability differences when the lumber charge contains a mixture-of species. As a general guide to which species can be dried together and which cannot, the kiln operator can we the kiln schedules and tables of kiln-drying times in chapter 7. For example, 4/4 aspen and basswood are both dried under schedule T12-E7 from green to 6 percent moisture content in the same length of time. Two different species that have similar but not identical drying requirements, such as red and white oak, can still be dried together. However, the mixed oak charge must be dried under the milder white oak schedule using white oak kiln samples. This procedure can also be used for species with widely differing permeability although it may not be economically feasbile, For example, a mixed charge of soft maple and red oak must be dried under the milder red oak schedule with oak kiln samples. This will double the kiln residence time normally required for the maple.

When wetwood or sinker stock is responsible for uneven moisture content and water pockets, presorting on the green chain is the best solution, but this is not easily done with currently available techniques. For species such as hemlock, true fir, white pine, aspen, and cottonwood, the moisture content of wetwood will be higher than that of heartwood but equivalent to that of sapwood. Wetwood can be accurately presorted from normal lumber by hand, but this procedure has not been successfully applied to green chains in high-production mills. Research results from the Forest Products Laboratory indicate that electronic measurements could be employed to segregate green hem-fir lumber into three board sorts: sapwood, heartwood, and wetwood (Ward et al. 1985). To date, no method for commercial presorting of wetwood is available on the market.

Discoloration

The use of dried wood products can be impaired by discolorations, particularly when the end use requires a clear, natural finish. Unwanted discolorations can develop in the tree, during storage of logs and green lumber, or during drying. Discolorations may also develop when light, water, or chemicals react with exposed surfaces of dried wood. This section is mainly concerned with discolorations that develop in clear, sound wood before or during drying. Any discolorations beyond the control of the drying and related processing operations, such as mineral stain and decay in the tree, will be mentioned only when they might form the focal points for initiation of drying defects. Drying discolorations have been traditionally classified in association with fungal attack or chemicals in the wood. Current knowledge suggests that this dual classification needs to be broadened somewhat. Some discolorations once considered chemical in origin are caused by bacteria, which can only be detected underhigh-power microscopes, Also, the formation of unwanted color will vary with complex interactions of tree species, type of wood tissue, and drying conditions. Successful control of discolorations depends upon the ability of the dry kiln operator to recognize differences in the wood quality of the species being dried and environmental factors that will initiate discoloration.

To prevent discolorations, the dry kiln operator must know the wood species and determine the wood type (sapwood, heartwood, or wetwood). The third and sometimes hardest step is to determine if the causal factors are primarily chemical or microbial.

Sapwood Discolorations

When the tree is cut, sapwood contains living parenchyma cells, which are not present in fully formed heartwood. Sapwood parenchyma cells may still be alive when the logs are sawed into lumber; as these cells die, enzymes and chemical by products are produced that may darken the wood. This darkening is intensified by oxidative heating of, the moist wood or by attack by fungal molds or aerobic bacteria. Sapwood also contains starches and sugars that provide food for mold fungi and bacteria,

Chemical.— Chemical discolorations are the result of oxidative and ensymatic reactions with chemical constituents in the sapwood. They range in color from

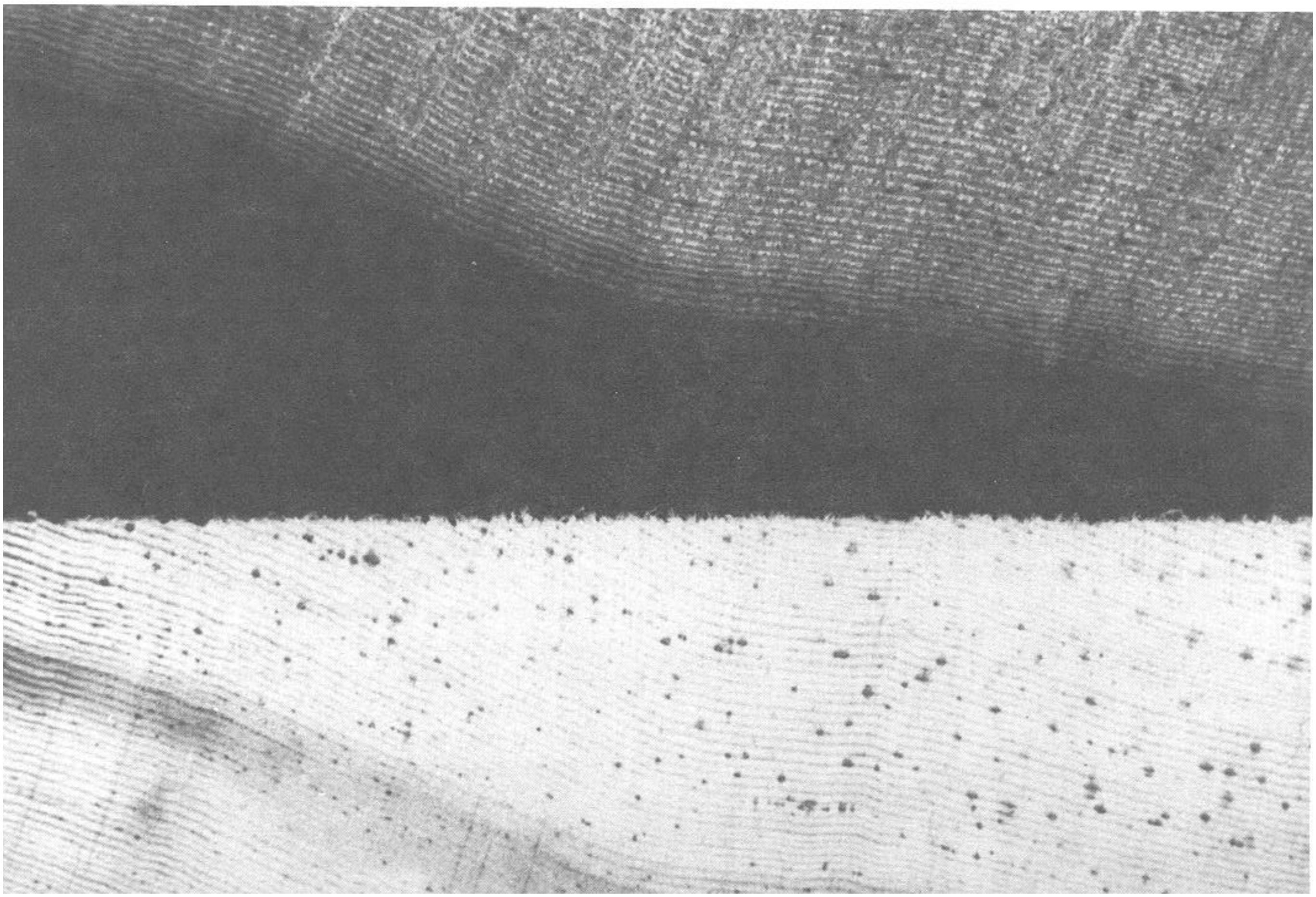

Figure 8-12—Chemical brown stain in sapwood of Douglas-fir. (Top) Board end exposed, to air; (bottom) internal wood. (M88 0162)

pinkish, bluish, and yellowish hues through gray and reddish-brown to dark brown shades. As a group, hardwoods are more subject to oxidative surface discolorations than softwoods. In some hardwood species such as alder and dogwood, intense discolorations will appear within an hour after the green wood surface is exposed to the air. Most oxidative discolorations are confined to within 1/16 in of the outer layer of the board and can be eliminated by planing.

A chemical brown stain that sometimes occurs in West Coast Douglas-fir penetrates deeper into the sapwood during kiln drying (fig. 8-12). Interior discolorations of this type cannot be satisfactorily prevented by treating the board surface with antistain chemicals. Miller et al. (1983) found that steaming the green wood to 212 °F inactivated the oxidative enzymes within the board and effectively eliminated the internal brown stain.

During drying, the degree of sapwood discoloration depends upon the chemical constituents of the sapwood and the drying temperature until the average moisture content of the board is well below the fiber saturation point. If drying temperatures are too high, chemical discolorations will penetrate deeply into the board. Above 140 °F, brown discolorations will become quite pronounced throughout sapwood boards of maple, beech, birch, and alder that is being dried from the green condition. Tan, yellowish, or pinkish hues may develop in the green sapwood of maple, hickory, and ash when dried under kiln schedules that are usually recommended for these species (fig. 8-13). Such seemingly mild discolorations are not acceptable for products requiring “white stock.” Drying schedules for producing white stock (ch. 7) usually start with a dry-bulb temperature less than 110 °F and a 10 °F wetbulb depression. Drying temperatures are kept below 130 °F until the average moisture content reaches 15 percent.

Distinct brown discolorations will develop in the green sapwood of southern yellow pine at drying temperatures above 160 °F. When southern yellow pine is dried at high temperatures in excess of 212 °F, a dark brown discoloration develops that penetrates to at least 1/8 in below the surface (fig:8-14).

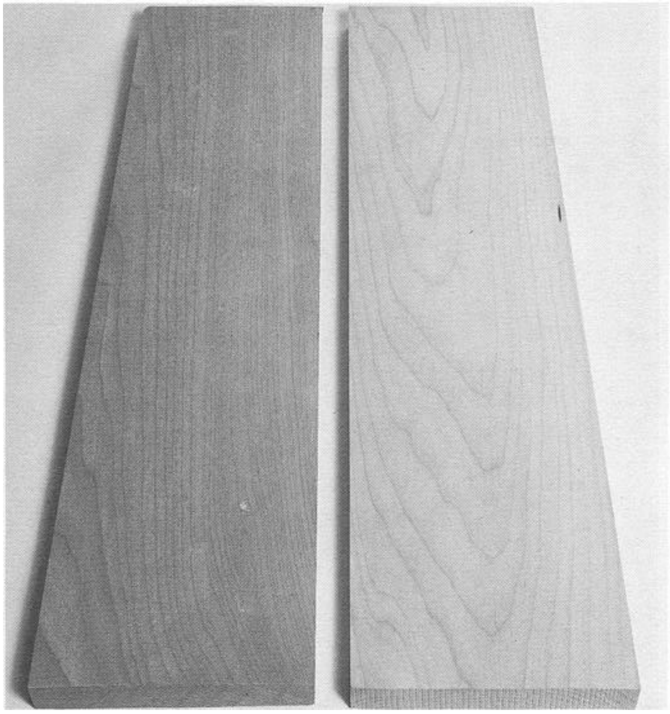

Figure 8-13—Kiln-dried and planed sugar maple with and without discoloration. (Left) General reddish-brown discoloration of sapwood from prolonged log storage and drying with conventional schedule T8-C3; (right) light sapwood board cut from fresh logs and dried with an anti-brown-stain schedule (ch. 7). (M 138652)

Sometimes oxidative discolorations are not evident until the outer 1/32- to 1/16-in surface has been planed off. This is because the outer surface of the green board has dried to below the fiber saturation point before oxidative chemical reactions can be completed, but the major inner portion of the board is still green. This can happen with stacked lumber that begins to air dry before kiln drying is started.

Deep grayish-brown chemical discolorations may occur in the sapwood of lumber from air-drying yards and predryers. These low-temperature sapwood discolorations are an important problem in oak, hickory, ash, maple, tupelo gum, magnolia, persimmon, birch, basswood, and Douglas-fir (fig. 8-15). In contrast to chemical discolorations that occur with high drying temperatures, these discolorations develop during very slow drying or wet storage of the sapwood at relatively low temperatures. In this situation, enzymes are produced by slowly dying parenchyma cells, which darken when oxidized. To avoid this, the green lumber should be stickered immediately after sawing, and drying should be started at temperatures above 70 °F. Good air circulation is essential. Heating or steaming the green lumber at 212 °F has been tried, with limited success, to inactivate the enzymes that contribute to the darkening reactions.

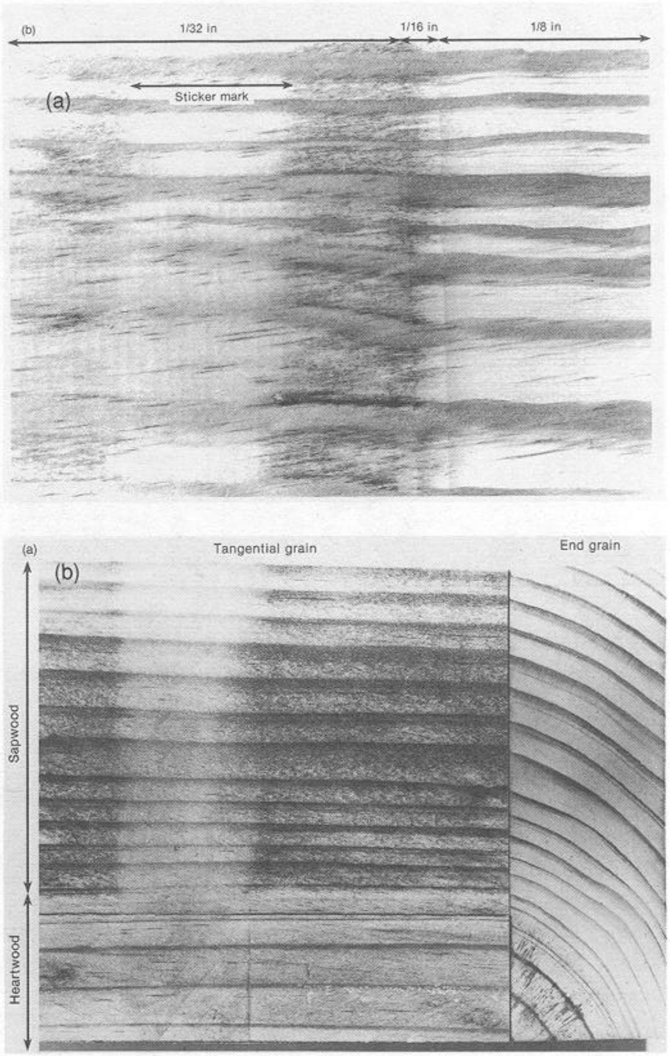

Figure 8-14—Brown sapwood stain in 8/4 southern pine kiln dried with a high-temperature schedule. (a) Rough, dry board showing surface darkening of sapwood but not of heartwood under sticker; (b) closeup of sapwood surfaced to 1/32 in, 1/16 in, and 1/8 in (left to right). (MC88 9041, MC88 9040)

Some kiln operators have observed that the tendency for sapwood to discolor varies in lumber from different areas and from trees growing on certain soils such as wet bottomlands.

Fungal.—Fungal stains, often referred to as blue stain, are caused by fungi that grow in the sapwood and use parts of it (such as sugars and starches) for food. Blue stain fungi do not cause decay of the sapwood, and they cannot grow in heartwood or wetwood that does not have the necessary food substances. However, poor drying conditions that favor the growth of blue-stain fungi can lead to infections by decay-producing fungi. With the exception of toughness, blue stain has little effect on the strength of the wood.

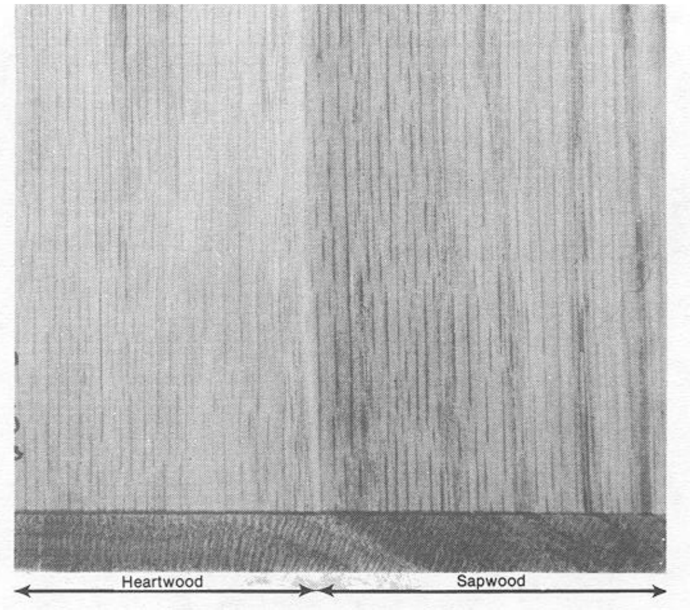

Figure 8-15—Gray sapwood stain in southern red oak dried green with humid, low-temperature conditions and with poor air circulation. (MC88 9037)

To prevent blue stain, it is necessary to produce unfavorable conditions for the fungi. Blue-stain fungi are disseminated by spores, which are produced in great abundance and are disseminated by wind and insects, or by direct growth from infected to uninfected wood. Blue-stain fungi will survive but cannot grow in wood with a moisture content of 20 percent or lower or a temperature of 110 °F. Temperatures higher than 150 °F are lethal to the fungi. This means the dry kiln operator may be able to employ drying schedules for control. In the summer months and in the tropics, the operator will need to chemically treat the wood with fungicides in addition to using proper kiln schedules.

Chemical fungicides, or biocides, make the sapwood unsuitable as food for blue-stain fungi (fig. 8-16). Sodium pentachlorophenol (PCP) has been one of the most effective and widely used fungicides for controlling sapwood stains in lumber, but its use has been recently curtailed by the U.S. Environmental Protection Agency (EPA) because of adverse effects on workers and the environment. New chemical formulations with lower mammalian toxicity appear promising for the control of sapwood stain (Cassens and Eslyn 1983, Tsunoda and Nishimoto 1985). For chemical control to be effective, the green lumber must be chemically treated soon after sawing fresh logs. Treating lumber from logs that have laid on the yard for a prolonged period and that are already infected with fungi will not be effective unless the lumber is kiln dried immediately under temperatures lethal to the fungi. However, under any conditions, chemically treated lumber should be stacked on stickers immediately after treatment.

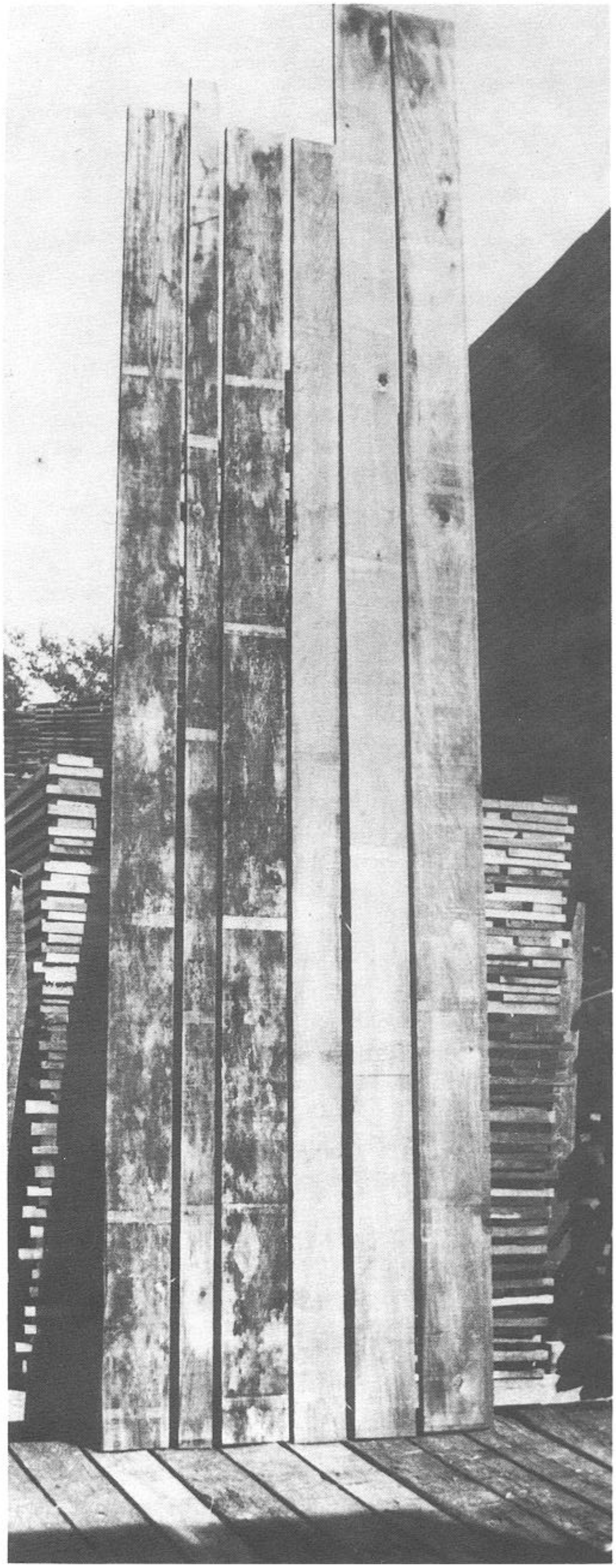

Figure 8-16—Untreated (left) and dip-treated (right) sweetgum lumber after 120 days in an air-drying yard. (M88 0158)

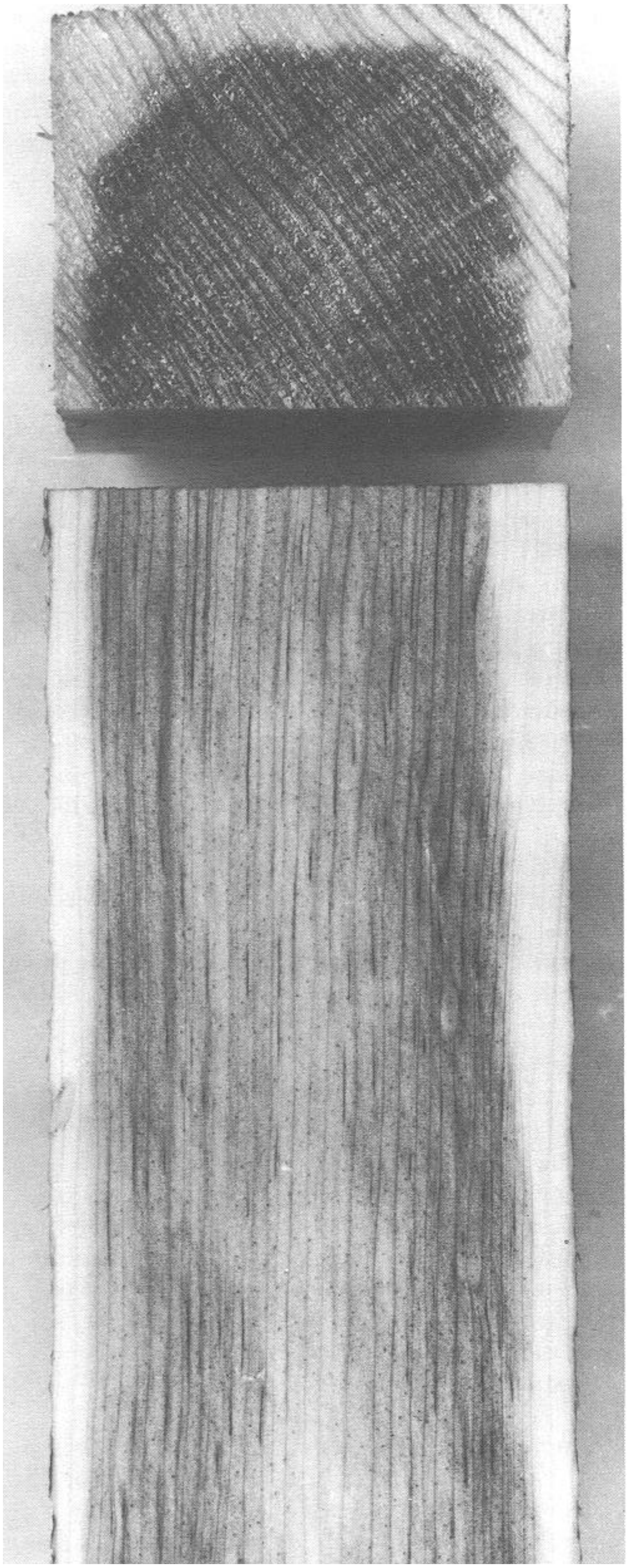

Figure 8-17—Interior sapwood stain in a section of 6/4 white pine lumber. Where lumber is bright on the surface but stained inside, conditions were initially suitable for infection. Later, chemical treatment or accelerated drying made the conditions unfavorable for further fungal growth in the outer portion of the piece. (M 39166)

Figure 8-18—Surfaced board of eastern white pine revealing blue stain that developed during the early stage of dehumidification drying. The lumber was from winter-cut Jogs and was not chemically treated. (M88 0160)

In warm, moist environments the airborne spores of sapwood-stain fungi seem to germinate very soon after landing on the surface of green, untreated sapwood. This means that the lumber must be chemically treated immediately after the logs are sawed or certainly no longer than 36 h afterward. Chemical fungicides will usually not soak into the board more than 1/32 in under commercial operating methods. Therefore, it is important to kiln dry the treated boards as soon as possible at initial dry-bulb temperatures above 130 °F to prevent the internal growth of fungi that have penetrated deep enough to escape the fungicide. Internal blue stain in the core of chemically treated sapwood is illustrated in figure 8-17.

Precautions must be taken with untreated lumber even when kiln dried within 1 day of sawing the logs. Sapwood-stain fungi will not grow at temperatures lower than 35 °F, and chemical treating is often curtailed, for economic reasons, during winter months in northern locations. Blue stain will develop on the surface of boards during drying at low temperatures and high humidities if the surface is not soon dried below 20 percent moisture content (fig. 8-18). This has occurred with dehumidification drying of untreated softwoods. Blue stain was found to develop under stickers in untreated southern pine sapwood that was kiln dried at 140 °F to avoid chemical brown stain.

Bacterial.— Bauch et al. (1984) in West Germany have associated the formation of dark discolorations in the sapwood of light-colored tropical woods with contamination of the logs and lumber by aerobic bacteria. They found that these bacteria grow on certain chemical components in the sapwood extractives, and the metabolic byproducts will discolor during kiln drying, especially on surface areas in contact with the stickers. These discolorations were controlled by spraying the green lumber with aqueous solutions of weak organic acids, such as propionic acid, before drying. The acid solution inactivates the discoloration reaction, which requires alkaline conditions.

Sticker stains and sticker marks.-Sticker stains and marks are both discolorations resulting from contact of the sticker with the wood surface. Sticker stains are imprints of the sticker that are darker than the wood between stickers (fig. 8-19). Sticker marks are lighter than the exposed surface of the board between stickers (fig. 8-14). Although these sticker discolorations can occur in heartwood, they are much more prevalent and troublesome in sapwood. The causes of these discolorations can be chemical, microbial, or a combination of these.

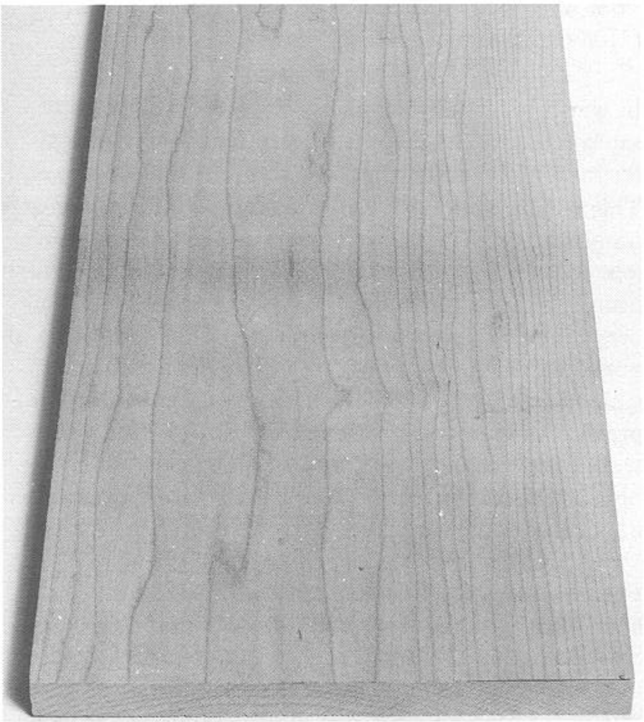

Figure 8-19—Residual sticker stain in sapwood of kiln-dried sugar maple after planing surface. (M 138660)

Sticker stains probably occur because the wood under the sticker remains moist longer or because it is rewetted. Sticker stains can be fungal sapwood stains that developed from stickers that were either too wet or contaminated with dirt and microoganisms. Even when using dry stickers, fungal sapwood stain can develop under stickers when drying conditions are poor and the wood is not chemically treated.

Sticker marks are chemical in nature-the exposed surface of a board oxidizes more readily than the surface under the sticker where oxidation is restricted. The intensity of oxidation staining is influenced by the chemical nature of the wood extractives and the presence of warm, moist drying conditions. High-temperature drying can also initiate sticker marking by degrading chemical extractives in the exposed surface of the board. Sapwood from a species such as red alder with highly oxidizable extractives is always subject to some degree of sticker marking depending on drying conditions.

Sticker discolorations are almost inevitable, but they can generally be eliminated with light surfacing of the dried wood. Control measures should be concentrated on drying procedures that will lessen the intensity and depth of the discolorations. These include using dry, narrow stickers or grooved stickers to reduce the contact area and starting the drying of green lumber as soon as possible. Dry-bulb temperatures should be moderate, and wet-bulb depressions should be sufficient for fast drying to avoid checking. There should be good air circulation of at least 200 ft/min across the load. Green boards should be chemically treated when sapwood-stain fungi or bacteria are contributing factors.

The photodegradation of extractives in green wood that is briefly exposed to bright sunlight can result in oxidative sticker stains and sticker marks during kiln drying (Booth 1964).

Heartwood Discolorations

Discoloration during the drying of heartwood will usually be chemical in nature and not as frequently encountered as when drying sapwood. Fungal discolorations will never develop under satisfactory drying conditions if the green heartwood is sound. Bacteria are not a problem when drying heartwood, but they do contribute to drying discolorations in wetwood, which is considered an abnormal type of heartwood and is discussed in the next section.

Chemical.— Heartwood of most species will darken uniformly during drying, and the intensity of the discoloration will depend upon the chemical nature of the extractives and the drying temperatures. In green heartwood, darkening intensifies with increasing drying temperatures. An example of unwanted, nonuniform darkening is the coffee-colored or oily-looking blotches that develop during the kiln drying of teak (fig. 8-20). These blotches develop just under the surface of the board and are chemically similar to the extractives that contribute to the normal warm, brown color of teak. Teak dried at kiln temperatures as low as 110 °F will

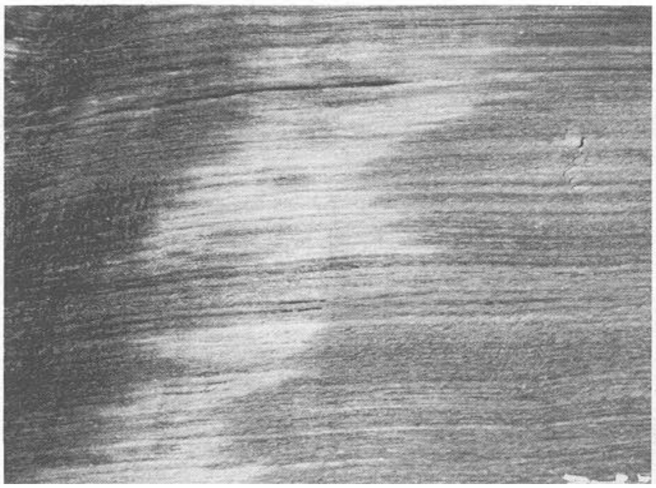

Figure 8-20—Chemical discoloration (coffee-colored blotches) that develop in heartwood of teak during kiln drying. (M88 0159)

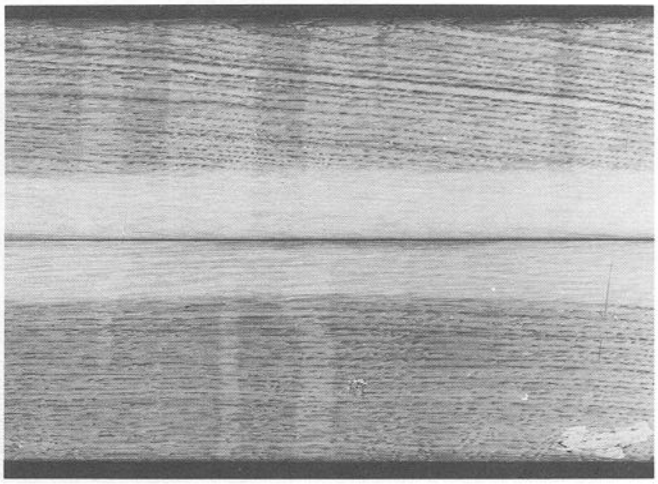

Figure 8-22—"Ghost" discolorations in white oak heartwood: middle zone, unfinished; outer zones, finished with stain. (M88 0163)

develop blotches, but they are much darker in wood dried at higher temperatures. The fundamental cause of teak blotching is not known; blotching occurs in lumber from trees grown in one region and not in another. The blotches can be lightened somewhat by exposing the dried wood to bright sunlight.

Fungal.—Most mold-type fungi, such as those causing sapwood blue stain, cannot grow on the chemical constituents in heartwood. There is one exception-the mold-type fungus *Paecilomyces varioti.* This fungus can feed on the tannins and organic acids found in the heartwood of species such as oak. It forms a tan mold on the surface of oak heartwood (not sapwood) under warm, humid conditions, particularly in predryers and dehumidification dryers with poor air circulation. The resulting discoloration is usually superficial and can be planed off, but it will penetrate more deeply into the board if the surface is not dried below 20 percent moisture content within the first week or two of drying (fig. 8-21). Control requires using the proper kiln schedule with adequate air circulation across the load.

Streaks of light-brown discoloration that run across the grain are sometimes found in white oak boards after drying and planing (fig. 8-22). These discolorations resemble sticker stains but they penetrate the entire thickness of the board and cannot be eliminated with

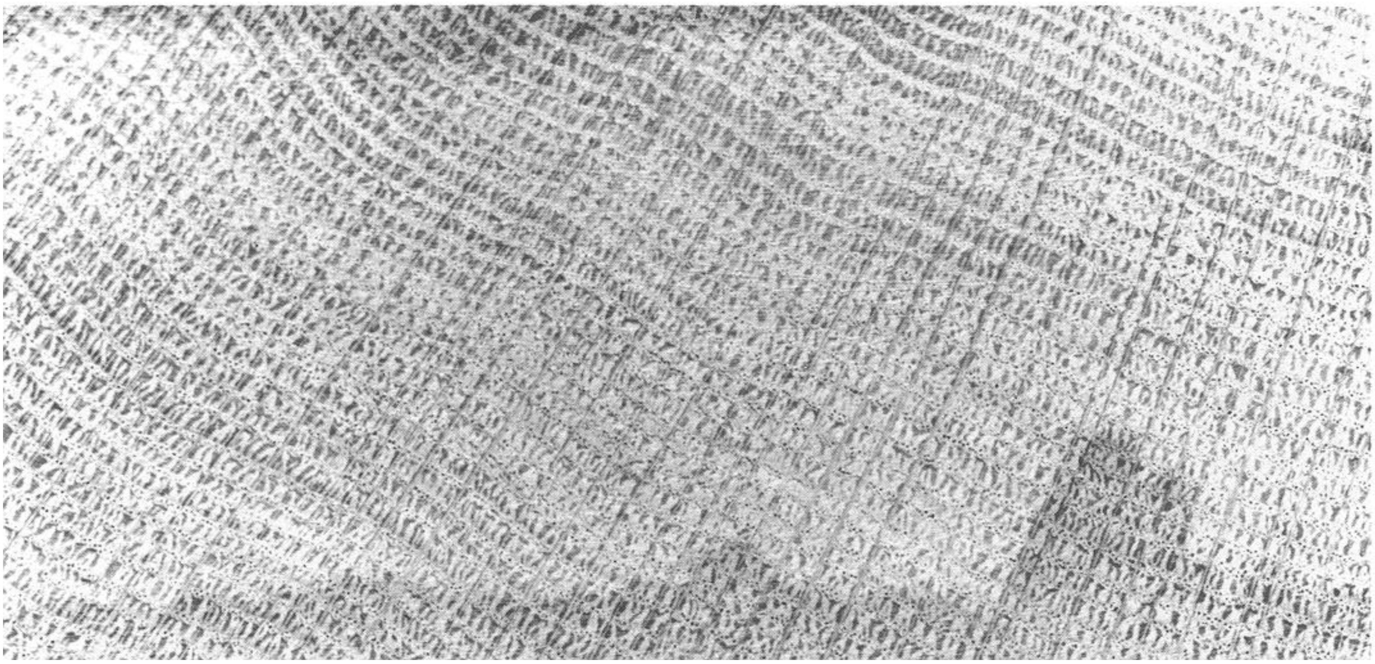

Figure 8-21—penetration of dark chemical discoloration into heartwood of white oak from surface growth of the mold-type fungus *Paecilomyces varioti.* (M86 0283)

Figure 8-23—Kiln-dried sugar pine shows chemical brown stain in center board that contained wetwood but not in boards with sapwood (left) or normal heartwood (right). End sections (top) were crosscut from rough, dry boards, and 1/16 in was planed from board surfaces (bottom). (MC88 9039)

planing. Clear finishes will intensify the streaks, and they may not be noticed until the last stages of production, which can be costly to the manufacturing operation. This discoloration is caused by a fungal infection in the heartwood of the living tree.

Discolorations in Wood Containing Wetwood

Wetwood is an abnormal, water-soaked type of heartwood; it is initiated by pathological rather than normal physiological changes in the living tree. Anaerobic bacteria are involved in the formation of wetwood, and they contribute to chemical changes in the extractives, which may later result in drying discolorations. Not all wetwood darkens during drying because of differences in tree species and bacteria associated with wetwood formation. For example, wetwood in white pine may or may not develop coffee-brown drying stains depending on the type of wetwood bacteria that infected the living tree.

Dark discolorations that develop in lumber with wetwood result from an oxidative or a metallic-tannate reaction. In both situations, wood extractives are chemically degraded by the bacteria (usually under anaerobic conditions in the tree), which results in the production of compounds that darken when heated under oxidative conditions or when placed in contact with metals such as iron.

The familiar coffee-brown stains that develop during the kiln drying of wetwood in white pine, sugar pine, and ponderosa pine, and to a lesser extent in aspen, cottonwood, and western hemlock, are the oxidative enzymatic type (fig. 8-23). Two methods have been used to control coffee-brown stains in softwood lumber: chemical treatment and special drying schedules. Treatment of the green wood with antioxidant chemicals such as sodium azide and sodium bisulfite is quite effective.. Untreated wetwood in high-risk species such as the white pines must be dried at low dry-bulb temperatures with large wet-bulb depressions (see anti-brown-stain schedules in ch. 7). Treated lumber can sometimes be kiln dried at higher temperatures with good results, but caution and pretesting are advised.

Organic acids are produced by bacterial growth in wetwood that catalyzes chemical reactions of tannins in the wetwood with iron, steel, and zinc, resulting in dark discolorations. Wetwood in oak, redwood, western redcedar, and western hemlock is very susceptible to these metallic stains when the outer shell of the board is green or wet. Galvanizing or coating steel straps will not always prevent these stains from forming in packages of green lumber with wetwood boards (fig. 8-24). Iron stains can generally be removed from wood by treatment with an aqueous solution of oxalic acid if surface penetration of the stain is not too deep.

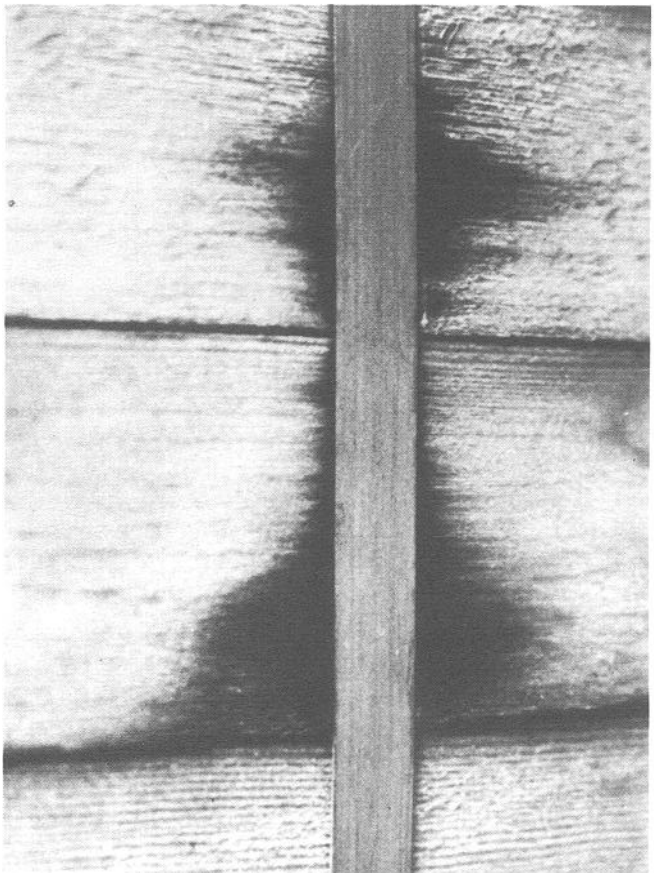

Figure 8-24—Dark discolorations in two green western hemlock boards (upper and middle boards) resulting from an acid chemical reaction of wetwood extractives with steel band that had an epoxy-powdered zinc coating. Lower green sapwood board did not react. (M88 0161)

Metallic and Alkaline Stains

Metallic discolorations can also develop in normal wood with high amounts of tannins and related compounds (polyphenols) but not as readily as in wetwood where higher amounts of organic acids are present to speed up the reaction. Metallic discolorations are mostly iron-tannate stains and are likely to develop in oak, chestnut, and walnut, and, to a lesser degree, in other species during kiln drying from steam condensates and water dripping from steel pipes, beams, and other kiln components.

Dark alkaline stains are caused by the chemical reaction of wood extractives with potassium and calcium hydroxides that leach out from concrete and mortar structures in contact with the wood. These stains might develop when lumber is dried in concrete or brick kilns that are not kept in good repair. They can also develop from contact of wood with solutions containing ammonia.

Removal of Discoloration From Dried Wood

Although preventative measures are advocated here, it may sometimes be economically necessary to remove discolorations that cannot be surfaced off on the planer. Some stains may be removed with a bleaching agent, but some trial and error method is often required to find the most effective agent for a particular stain. Bleaching operations can be costly in terms of handling and redrying the wood. To be effective, the bleaching treatment may have to be so severe that an objectionable amount of natural color is also eliminated. Of course, the bleached wood cannot be resurfaced without exposing interior discolorations.

If the stain is not too deep, it can often be removed or reduced in intensity with hydrogen peroxide. A concentrated aqueous solution of oxalic acid will bleach out chemical sapwood stains but not sapwood stains caused by mold fungi. **A** laundry bleach of 5 percent sodium hypochlorite solution can sometimes be used effectively (Forest Products Laboratory 1967, Downs 1956).

Drying Defects of Major Concern in Commercial Woods

All woods are subject to drying defects, but some species are more likely to develop certain defects than others. Refractory hardwoods such as oak and hickory will check more readily than basswood and yellow-poplar, which have less dense and more even-textured wood. Drying defects will develop more frequently in wetwood or sinker stock than in sapwood or normal heartwood. Wetwood occurs quite frequently in some tree species and rarely or not at all in other species. Common defects that occur during kiln drying are noted in tables 8-2 to 8-4 for U.S. softwood species, U.S. hardwood species, and imported species, respectively.

Relationships Between Drying Defects and Machining

Lumber can be damaged during machining if it contains certain drying defects. Planer splits, broken knots; knotholes, chipped and torn grain, raised grain, and warp can all occur as a result of improper drying. Precautions taken during drying can minimize or avoid these defects.

Planer Splits

A long split often develops when cupped lumber is flattened as it passes through the planer. End splits-already present aggravate planer splitting. This type of split, also called roller split, lowers the grade and value of lumber and causes waste. Not only does the amount of cupping increase as the moisture content of the wood is lowered but the wood becomes stiffer and is more likely to split when flattened.

Splitting on the planer can be reduced by taking steps to minimize cupping and end splitting through good stacking practices. Ensuring that lumber is not overdried will also reduce splitting. For example, softwood construction lumber is frequently dried to a target moisture content of about 15 percent. Drying below that target will increase the chance that planer splits will develop. The upper grades of both hardwood and softwood lumber are dried to 10 percent moisture content or less to meet end-use requirements. If the lumber becomes cupped in the process, splitting cannot be easily avoided during planing. Planer splitting can be reduced somewhat by relieving drying stresses and raising the moisture content of the surface of the lumber.

Broken Knots and Knotholes

In most grades of lumber, the knots in the surfaced boards should be smooth, intact, and unbroken. Knots check and loosen as drying proceeds, and they become more brittle as the moisture content of the wood decreases. While the lumber is in the planer, the knots are severely hammered as well as cut by the knives. The hammering breaks checked knots and knocks out loose ones, and it can thus lower the grade of the lumber.

In much of the softwood lumber industry, knotty grades of construction lumber are dried to a final moisture content of about 15 percent to permit better machining of the knots. At this moisture content the sound knots are not severely checked, and the encased knots are fairly tight: Therefore, common grades of softwood lumber are usually separated from upper grades and dried by different schedules; the upper grades are dried to 8 to 10 percent moisture content.

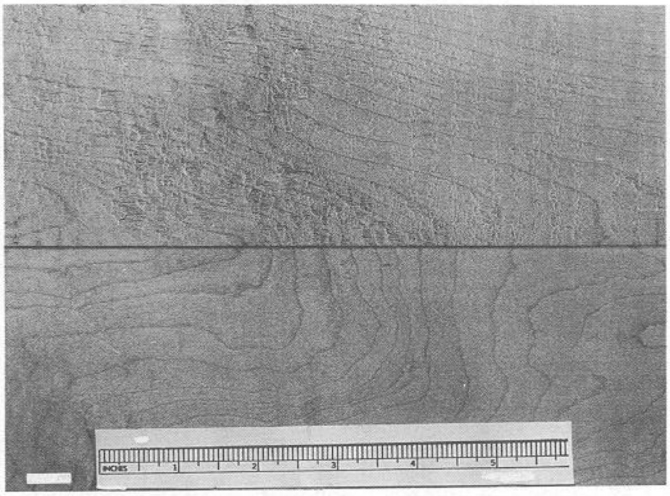

Figure 8-25—Chipped and torn grain in hard maple. (M 114737)

In some species, encased knots are held in place largely by pitch between the knot and the board. If the pitch is removed, the knots fall out of the board. Drying temperatures of 160 to 180 °F soften the pitch; it runs out from around the encased knot and the knot falls out. In these cases, knots can be prevented from dropping out by reducing the drying temperature.

Chipped and Torn Grain

When dry lumber is machined, wood may be chipped and torn from some areas on the surface (fig. 8-25). The occurrence of chipped and torn grain is influenced largely by the operating conditions of the machine, the sharpness and setting of the knives, the feed rate into the machine, and the slope of grain, including grain variations. To some extent, however, the susceptibility of lumber to chipping and tearing is affected by the moisture content of the wood layer being removed. Lumber of extremely low surface moisture content–5 percent and less-chips and tears more during machining than if the surface moisture content is 8 percent or higher. Consequently, kiln operators can prevent this problem to some extent by avoiding overdrying and by increasing surface moisture content with a conditioning treatment.

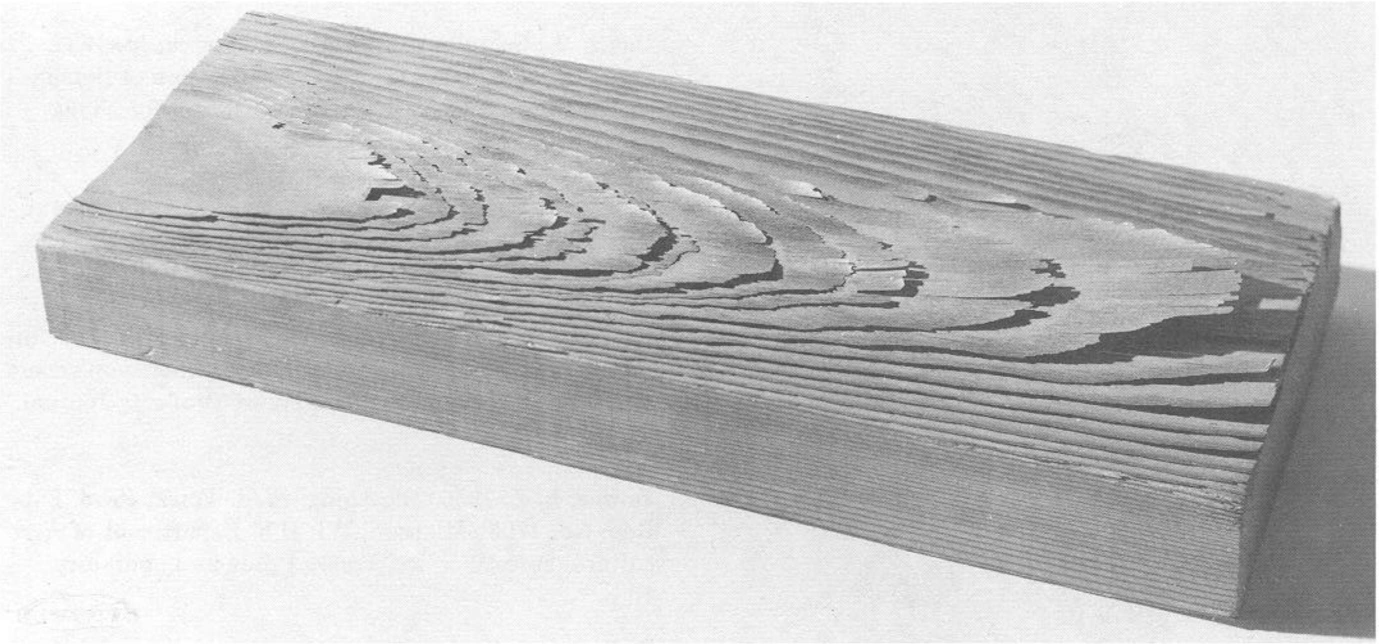

Figure 8-26—Raised grain in Douglas-fir. (M 97880)

Raised Grain

Raised grain (fig. 8-26) occurs primarily when lumber is not uniformly dried to a low enough moisture content at the time of machining. Generally, raised grain does not develop in wood that is machined while at 12 percent or leas moisture content. When wood is machined at a higher moisture content, the action of the knives forces the latewood bands into the softer earlywood bands on the flat grain surface. Subsequently, the compressed earlywood recovers and lifts the bands of latewood above the surface. The uneven surface usually reduces the grade and usefulness of the finished product.

Raised grain can occur in all species, but it is most pronounced in softwoods like Douglas-fir and southern pine that have distinct bands of earlywood and latewood that are different in density.

Residual Drying Stresses

Whether or not residual drying stresses (casehardening) are considered a defect depends on how the lumber is subsequently sawed or otherwise machined. The most common problems that occur in the use of casehardened lumber are end checking, planer splitting, and warping.

End Checks

End checks will frequently develop in the core of a freshly crosscut casehardened board that is exposed to low atmospheric relative humidity, even though the average moisture content of the board is fairly low. The tensile stresses present in the core, coupled with additional stresses brought on by end drying, exceed the strength of the wood. A check then develops, which can further extend into a split.

Planer Splits

Splits can occur in relatively flat casehardened boards that are being surfaced. The splits are caused by the internal drying stresses in the boards, coupled with the forces applied by the machine knives. A conditioning treatment will reduce planer splits from this cause.

Warp

If transverse or longitudinal stresses become unbalanced during sawing or any other machining operation on a casehardened board, the board will distort in an effort to rebalance the stresses. Resawing may cause cupping

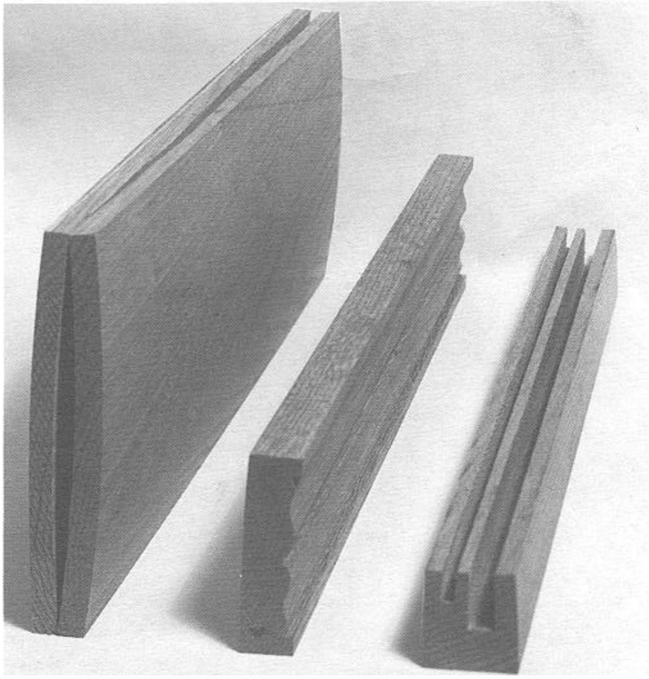

Figure 8-27—Distortion caused by unrelieved drying stresses: resawed board (left), lumber heavily machined on one face (center), and grooved lumber (right). (M 111992)

or bowing. The concave faces will be oriented towards the saw (fig. 8-27). Ripping may result in crook, in which the concave edges usually follow along the saw cut. In planing, the depth of cut is not likely to be the same on both faces; if the board is casehardened, it will cup with the concave face toward the most heavily cut surface. When casehardened lumber is edgegrooved, the lips of the groove may pinch inwards (fig. 8-27). A tongue or spline inserted into such a groove may break the lips. Cupping usually results when casehardened lumber is machined into patterns, as in the manufacture of molding and trim, or when unequal cuts are taken from the faces and edges of the lumber in routing and carving operations. Any warping of casehardened lumber that is due to sawing or machining is a source of trouble in further processing.

The relief of drying stresses by a conditioning treatment is strongly recommended for lumber that is to be used in furniture, architectural woodwork, sash and door stock, and other products that may require sawing or other machining that may unbalance residual drying stresses. It should also be used when the end use is unknown but could be one of the above-mentioned products.

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Table 8-1-Effect of high-temperature drying on modulus of elasticity and modulus of rupture of certain species[1]

Species	Reduction in property (percent) caused by high-temperature drying (225-240 °F)	
	Modulus of elasticity	Modulus of rupture
Douglas-fir	2	15-21
Western hemlock	0	10-14
Western white spruce	[3]4	0
Western redcedar	[4]0	0-3
Southern pine	4	4
Eastern spruce	0	11
Balsam fir	0	10
Jack pine	2	14
Trembling aspen	1	17
Balsam poplar	0	7

[1] Data derived from study by Gerhards and McMillen (1976). See Literature Cited.
[2] Compared to lumber dried by conventional temperatures below 180 °F.
[3] Conventional temperature in this study was 200 °F.
[4] Conventional temperature in these studies was 185 to 190 °F.

Table8-2—Common drying defects in U.S. softwood lumber species

Species	Drying defect	Contributing factor
Baldcypress		
Old growth	End checks, water pockets	Refractory wood, extractives
Young growth	Chemical brown stain	Wood extractives, poor air circulation
Cedar		
Alaskan yellow	Resin exudate	Extractives
Eastern redcedar	Knot checks, excessive loss of aromatic oils	Excessive drying temperatures
Incense cedar		
Heavy stock	Water pockets, collapse	Wetwood, excessive drying temperatures
Port-Orford	Resin exudate	Extractives
Western redcedar		
Heavy stock	Uneven moisture content, collapse, honeycomb, chemical stains, iron stains, resin exudate	Wetwood (sinker stock), extractives
Douglas-fir		
Coastal	Red-brown chemical stains	Wood extractives
	Gray sapwood stains	Sapwood extractive, slow drying
	Ring failure, honeycomb	Wetwood (infrequent occurrence)
Fir		
Balsam	Uneven moisture content	Wetwood
California red	Uneven moisture content, shake, splits, warp	Wetwood, compression wood
Grand	Uneven moisture content, shake, splits	Wetwood
Pacific silver	Uneven moisture content, shake, splits, chemical brown stains	Wetwood
White	Uneven moisture content, shake, splits, chemical brown stains	Wetwood
Subalpine	Uneven moisture content, shake, splits	Wetwood, compression wood
Noble	Warp, splits	Wetwood, compression wood
Hemlock		
Eastern	Uneven moisture content, warp, ring shake	Wetwood, compression wood
Western	Uneven moisture content, warp, chemical stains, shake, iron stains	Wetwood
Larch		
Western	Shake (ring failure, checks, resin exudate)	Wetwood
Pine		
Eastern white	Brown stain, ring failure	Wetwood
Western white	Brown stain	Wetwood
Sugar	Brown stain	Wetwood
Ponderosa	Brown stain	Wetwood (less common in ponderosa pine than in the soft pines)
Young growth	Warp	Juvenile wood, compression wood
Lodgepole	Warp	Compression wood
Loblolly	Brown sapwood stain, checks, splits	Excessive drying temperatures
Longleaf	Brown sapwood stain, checks, splits	Excessive drying temperatures
Shortleaf	Brown sapwood stain, checks, splits	Excessive drying temperatures
Slash	Brown sapwood stain, checks, splits	Excessive drying temperatures
Virginia	Brown sapwood stain, checks, splits	Excessive drying temperatures
Pond	Water pockets, dark chemical stains, honeycomb	Wetwood (infrequent occurrence)
Redwood		
Heavy stock	Uneven moisture content, collapse, honeycomb, chemical stains, iron stains	Wetwood (usually in old growth)
Spruce		
White	Water pockets, collapse, ring failure	Wetwood (rare occurrence in northern and southern limits of botanical range)
Sitka		
Young growth	Checks, splits, raised grain	Fast growth juvenile wood

Table 8-3—Common drying defects in U.S. hardwood lumbar species

Species	Drying defect	Contributing factor
Alder, red	Chemical oxidation stains (sticker marks)	Chemical wood extractives
Ash		
Black	Ring failure	Wetwood, drying temperatures
White	Gray-brown sapwood stain (sticker marks, stains)	Trees from wet sites, drying too slow, poor air circulation
	Surface checks	6/4 and thicker stock
Aspen	Water pockets, honeycomb, collapse	Wetwood, drying temperatures
Basswood, American	Brownish chemical stain	Sapwood from certain areas, drying too slow
Beech, American	End and surface checks	Normal wood is refractory
	Discoloration, honeycomb	Wetwood (occasional)
Birch		
Paper	Brownish chemical stain	Extractives in wood from certain sites
Yellow birch	End and surface checks	Refractory heartwood
	Collapse, honeycomb	Wetwood (heartwood), mineral streaks
Blackgum	Water pockets, collapse	Wetwood
Cherry, black	Ring shake, honeycomb	Wetwood (not common)
Chestnut	Iron stains	Extractives
Cottonwood	Water pockets, honeycomb, collapse	Wetwood
Cucumber tree	Sapwood discoloration	Poor air circulation
Dogwood		
Eastern and Pacific	Oxidative sapwood stains	Sapwood extractives, drying temperature
Elm		
American	Ring failure	Wetwood
	Warp	Grain orientation
Slippery	Ring failure	Wetwood
Rock	Boxed-heart splits	Growth stresses
Hackberry and Sugarberry	Sapwood discolorations	Slow drying with poor air circulation
Hickory	Chemical sapwood stains, ring failure, honeycomb	Slow drying with poor air circulation, wetwood
Holly	Sapwood stains	Extractives, poor air circulation
Laurel, California	End checks	Refractory wood from old-growth trees
Locust		
Black and Honey	End and surface checks	Refractory wood
Madrone	End and surface checks	Refractory wood
	Collapse	Wetwood

Table Common drying defects in U.S. hardwood lumber species—concluded

Species	Drying defect	Contributing factor
Maple		
soft		
Red and Silver	Sapwood discoloration, ring failure, honeycomb in heartwood	Wetwood, poor air circulation
Hard		
Sugar and black	Sapwood discoloration	Extractives, poor air circulation
	Collapse, honeycomb in heartwood	Mineral streaks, wetwood
Myrtle, Oregon (see California laurel)		
Oak, western		
California black	Honeycomb, collapse, ring shake	Wetwood
Oregon white	Honeycomb, collapse, ring shake	Wetwood
Oak		
Red upland	Ring failure	Severe wetwood
	Honeycomb	Severe drying of normal heartwood or wetwood with mild drying
	Iron stains	Extractives
Red lowland	Collapse, ring failure	Wetwood
	Honeycomb	Severe drying of normal heartwood or wetwood with mild drying
	Iron stains	Extractives
Southern red	Gray sapwood stains	Poor air circulation
White upland	End and surface checks	Severe drying
	Iron stains	Extractives
	Ring failure, collapse	Wetwood
	Gray sapwood stains	Poor air circulation
White lowland	End and surface checks	Severe drying
	Iron stains	Extractives
	Honeycomb, collapse, ring failure	Wetwood
	Gray sapwood stains	Poor air circulation
Pecan		
Water	Honeycomb, ring failure	Wetwood
Persimmon	End and surface checks	Severe drying
	Chemical sapwood stains	Slow drying at low temperature
Sapgum	Sapwood discoloration	Poor air circulation
Sweetgum	Surface and end checks	Severe drying
	Honeycomb, collapse, water pockets	Wetwood
Sycamore (heartwood)	Honeycomb, ring failure, water pockets	Wetwood
Tanoak	End and surface checks	Severe drying
	Honeycomb	Wetwood
Tupelo gum	End checks	Severe drying
	Honeycomb, collapse, water pockets	Wetwood
Walnut, black	End checks	Severe drying
	Iron stains	Extractives
	Honeycomb, collapse, ring failure	Wetwood
Willow, black	Honeycomb, collapse, water pockets, failure	Wetwood
Yellow-poplar	Mold, sapwood stains	Slow and poor drying, moderate kiln schedule
	Honeycomb, water pockets (rare)	Wetwood

Table 8-4—Common drying defects of hard-to-dry Imported species[1]

Species	Drying defect
Albarco	Slight tendency to check
Andiroba	Slow drying with tendency to split, check, and collapse
Angelique	Moderate tendency to check, slight warp
Apitong	Slow drying with considerable tendency to check, collapse, and warp
Avodire	End checks
Balata	Severe checks and warp
Balsa (heavy)	Water pockets, collapse, splits, honeycomb
Banak	Strong tendency to check, collapse, honeycomb, and warp
Benge	Mild checks and warp
Bubinga	Slow drying with tendency to warp and check
Caribbean pine	End splits in thick lumber
Cativo	Occasional collapse in dark streaks in heartwood
Cuangare	Brownheart or wet streaks, collapse
Degame	Some tendency to warp, surface and end check
Determa	Some tendency to warp and check
Ebony, East Indian	Very prone to checks
Ebony, African	Slight tendency to check
Goncalo alves	Some tendency to warp and check
Greenheart	Slow drying and quite prone to check and end split
Hura	Warp
Ilomba	Fast drying, but prone to collapse, warp, and split
Imbuia	Thick lumber may honeycomb and collapse
Jarrah	Prone to checks and collapse
Kapur	Mild warp and shake
Karri	Pronounced tendency to check
Kempas	Mild tendency to warp and check
Keruing	Slow drying with considerable tendency to check, collapse, and warp
Mahogany, African	Severe warp if tension wood present
Manni	Moderate warp and checks
Mora	Some tendency to warp
Obeche	Slight tendency to warp
Opepe	Considerable checks and warp
Parana pine	Dark-colored material prone to split and warp
Peroba rosa	Slight tendency to warp
Ramin	Marked tendency to end split and surface check
Roble (Quercus)	Severe checks, warp, and collapse
Roble (Tabebuia)	Only minor checks and warp
Rosewood (Indian)	Dries readily with only minor defects
Rosewood (Brazilian)	Prone to check
Rubberwood	Severe warp, prone to blue stain and borer attack
Sande	Warp if tension wood present
Santa Maria	Tendency to warp and slight surface check
Sapele	Severe warp
Sepitur	End splits
Sucupira	Considerable checks and warp
Wallaba	Marked tendency to check, split, and warp: honeycomb in thick lumber

[1] Species listed in table 1-2 of chapter 1, but not listed in this table, tend to dry easily with few drying defects.

Chapter 9
Operating a Dry Kiln

Chapter 9 was revised by William T. Simpson, Supervisory Research Forest Products Technologist.

A dry kiln, no matter how well equipped with controls, is only as efficient as the operator who runs it. Despite advances in control technology that give the operator more information than was possible in the past, it is still largely the operator's judgment that determines whether a charge of lumber will go through the kiln in a minimum time, emerge uniformly dried to the desired moisture content, and be free of undesired drying defects and stresses. The operator determines what kiln schedule to use, and whether it should be a time or moisture content schedule. If kiln samples are to be used, whether manually or automatically weighed or monitored with probes, the kiln operator is still responsible for selecting representative kiln samples. The kiln operator must monitor the progress of drying, whether manually or with the assistance of computer readouts, and apply judgment in deciding if adjustments are necessary during drying. Also, the operator must apply judgment in determining when the lumber has reached final moisture content with a minimum of moisture content variation and apply any necessary equalizing or conditioning treatments.

Most of these basic techniques are discussed in other chapters of this manual. The purpose of this chapter is to summarize and present various aspects of kiln operation to guide the operator in exercising good judgment in reaching decisions required before and during drying.

Kiln Samples

When kiln samples are used to control a drying schedule, their selection, preparation, and use are important in kiln operation. Poor procedures here can result in erroneous estimates of moisture content that may increase drying defects and drying time. The procedures described in chapter 6 should be followed as closely as possible.

Selecting a Drying Schedule

One of the first decisions in selecting a dry kiln schedule is whether to use a schedule based on moisture content or time. This is usually a routine decision because softwood-drying technology has developed time schedules and hardwood-drying technology has developed moisture content schedules. However, there are exceptions to this general division of schedules. If drying problems or customer complaints occur with high-quality softwood lumber dried by a time schedule, consideration should be given to changing to a moisture content schedule. Conversely, repeated experience with drying a hardwood species of constant thickness in the same kiln, particularly one of the easier drying low-density hardwoods, may well lead to the development of a time schedule.

Chapter 6 provides guidelines for selecting a kiln schedule. They include species, thickness, moisture content, heartwood or sapwood, and grain (quartersawn or flatsawn). Selection of a drying schedule is simplified when the charge consists of one species, one thickness, a uniform moisture content, all heartwood or all sapwood, and all quartersawn or flatsawn. The uniformity of variable factors should be maintained as much as possible for high drying uniformity and quality.

Schedules for Homogeneous Charges

For charges that consist entirely of one class of lumber, a schedule for that class as recommended in chapter 7 should be used as a start. After experience is gained with that particular class, the schedule can be modified as discussed in chapter 7.

Schedules for Mixed Charges

Sometimes it is necessary to dry lumber in mixed charges, even though this practice is not generally recommended. It reduces the production rate through kilns and increases the likelihood of variability in the dried lumber. Most mixing is caused by lack of enough kilns or improper kiln sizing to accommodate different classes of drying sorts (groups of sorted lumber). Some mixing is necessary to avoid undue delay in drying sorts that accumulate slowly and will degrade or stain if left in green storage too long. In selecting a drying schedule for a mixed charge of lumber, the drying characteristics of all the lumber to be included should be considered. Mixed charges can be dried according to moisture content or time schedules. The following examples and suggestions should be helpful guidelines in selecting kiln schedules for mixed charges.

Example 1: If a charge of lumber is composed of the same species and moisture content but of varying thickness, use the schedule recommended for the thickest lumber. For example, if the kiln charge is both 6/4 and 8/4 sugar maple, follow the drying schedule for the 8/4 lumber, T5-C2, rather than for the 6/4, T8-C3. If the charge is of 4/4, 5/4, and 6/4 sugar maple, schedule T8-C3 could be used. In both cases, the changes in drying conditions would be based on the kiln samples with the highest moisture content, which almost surely will be the thicker samples. Kiln samples from the faster-drying thinner lumber must also be used in order to equalize properly.

Example 2: If two or more species of the same thickness and moisture content are dried together, use the schedule recommended for the species that is the most difficult to dry, that is, the slowest or most susceptible to surface or internal checking. Make every effort to mix species that require much the same drying schedule and about the same drying time (ch. 7, table 7-33). For example, both 4/4 white ash and 4/4 black cherry call for the same drying schedule, T8-B4. Several species have approximately the same drying characteristics. These include 4/4 yellow birch, schedule T8-C4; 4/4 black cherry, T8-B4; and 4/4 sugar maple, T8-C3. These species have the sane temperature schedule, T8, but their wet-bulb depression schedules are different. Since the mildest drying condition is recommended, use the C3 wet-bulb depression schedule.

Example 3: Another example is two species or more of the same thickness but of varying moisture content, such as a mixture of green 4/4 black cherry and air-dried 4/4 sugar maple with an average moisture content of 25 percent. Green black cherry calls for schedule T8-B4 and green sugar maple for schedule T8-C3. The air-dried sugar maple with a moisture content of 25 percent calls for initial drying conditions of 150 °F dry-bulb temperature (step 3 of T8 schedule) and a wet-bulb depression of 35 °F (step 5 of C3 schedule), while the T8-B4 schedule for green black cherry calls for an initial dry-bulb temperature of 130 °F and a wet-bulb depression of 7 °F. To avoid damage to the green cherry, use the milder T8-B4 schedule.

Example 4: Sapwood of ponderosa pine of Common grades can be mixed with white fir dimension lumber, provided the white fir does not contain wetwood. A typical sapwood Common-grade schedule of moderate temperature and wet-bulb depression should be used to protect the pine and to equalize the final moisture content between the pine and white fir.

Example 5: Heartwood of Common-grade ponderosa pine can be mixed with Douglas-fir dimension lumber. The initial temperature should be 160 °F with a maximum wet-bulb depression of 10 to 15 °F.

Example 6: 4/4 sugar pine wetwood can be dried with 6/4 or 8/4 ponderosa pine Shop or Select. Use as large a wet-bulb depression as the ponderosa will tolerate without surface checking, but keep the starting temperature low enough to prevent brown stain in the sugar pine wetwood.

Example 7: Mill run mixtures of white fir, Englemann spruce, and lodgepole pine can be dried together. However, a moderate schedule should be used to reduce the variation in final moisture content. Care should be exercised to prevent overdrying.

Example 8: Green Douglas-fir and larch clear lumber does not always store well while enough wood to fill a kiln charge is being accumulated. Water spray is sometimes used to prevent checking during this storage. Another alternative is to mix the clear lumber with other sorts to avoid long storage while green.

In general, species that have a wide variation in schedule requirements should not be mixed for drying. The main concern here is stain and surface checking. Kiln conditions that are humid enough to avoid surface checking in some species may cause brown stain, blue stain, or mold to occur in others. For example, Douglas-fir may surface check at the low humidity needed to prevent brown stain in sugar pine.

These examples serve to illustrate that mixed charges can be dried successfully, but that caution should be used and that often there is a penalty, such as excessive drying time, nonuniform final moisture content, and the danger of drying defects.

Starting the Kiln

The danger of drying defects and excessive drying time can be reduced if prestart checks and proper starting procedures are followed. These checks and procedures vary somewhat with the type of kiln, but all are aimed at ensuring that the equipment is operated properly.

Prestart Checks

Several checks should be made before starting a kiln.

1. Calibration of the wet- and dry-bulb thermometers is not necessary for every charge, but the state of the calibration check should be kept in mind. If a long time has passed since the last calibration check or if previous performance suggests the possibility that the kiln is out of calibration, plans should be made for a check.
2. A check should be made for adequate steam pressure. Is more than one kiln starting up at once? If so, the demand on the steam system may be too great to attain desired initial conditions.
3. The air pressure to the recorder-controller should be checked and any water drained from the air line.
4. Water delivery to the wet-bulb reservoir must be fast enough to keep pace with evaporation. Experience will dictate the necessary rate of flow.
5. The wet-bulb wick should be changed if it is dirty or encrusted with mineral scale from the water. Ensure that the wick does wet.
6. Check that nothing is obstructing airflow over the wet bulb.
7. Consider sir velocity through the lumber. Have checks in the past indicated a sufficient and uniform flow? Is there anything different in the current charge that could change the flow? Are necessary end, bottom, or top baffles in place?
8. The vents should be inspected and checked for operation. See that all vents open and close completely.
9. Check the fan operation. See that all fans are turning correctly, no motors are malfunctioning, fans are not spinning on their shafts, and belts are not slipping.
10. Check that doors are in good repair and close tightly.

Steam-Heated Kilns

The following are the general startup procedures for steam-heated kilns.

1. Set the dry- and wet-bulb controls at the initial temperatures called for in the schedule.
2. Keep the hand valve on the steam spray line closed during warmup to avoid excessive steam consumption and condensation on the lumber. If there is no hand valve on the steam spray feedline, set the wet-bulb temperature to the lowest temperature possible to prevent opening the spray line valve. This procedure should only be used if it is possible to prevent the vents from opening. Au alternative procedure for adjusting the wet-bulb control is described in item 11.
3. Implosion can occur in cold climates for up to one or more hours after startup. To prevent implosion, open the small inspection door or leave the main door slightly open before starting the fans. After the fans have operated for several minutes, the door can be closed.
4. Open the hand valve on the main steam supply line.
5. Open the hand valves on the feedlines to all heating coils.
6. Open the hand valves between all the heating coils and steam traps and in the return lines from the steam traps to the boiler.

7. Open the main air supply valves to the control instrument and to the air-operated valves on the heat and spray lines. If the control system is electrically operated, turn on the power switches.
8. Blow all steam traps to the atmosphere for a short time to remove scale and dirt from them.
9. Just before the dry-bulb temperature reaches set point, open the hand valve on the steam spray line or reset the wet-bulb temperature to the recommended wet-bulb temperature.
10. If the kiln is equipped with auxiliary vents, keep them closed during warmup until the wet-bulb temperature reaches set point.
11. Sometimes when warming up a kiln charge of green lumber susceptible to surface checking, the wet-bulb temperature can be brought up gradually rather than according to the procedures in items 2 and 9. For example, if the initial drying conditions call for a wet-bulb depression of 4 °F, this temperature can be approximated during warmup by opening the hand valve on the steam spray line for short periods or by gradually raising the wet-bulb indicator if it was initially set at a low value. This procedure requires frequent monitoring of conditions during warmup.

Direct-Fired Kilns

Direct-fired kilns vary in type of burner and air delivery system, and many do not have a source of steam for humidification. The starting procedures do not differ much from those of a steam-heated kiln and can be summarized as follows:

1. Set the dry-bulb temperature, and wet-bulb temperature if the kiln is equipped with spray lines, at the initial set point or points called for in the schedule.
2. To prevent implosion, open the small inspection door or leave the main door slightly open before turning on the fans. After the fans have operated for a few minutes, the doors should be closed.
3. Start the burner system according to the manufacturer's procedures.
4. If the kiln is equipped with auxiliary vents, keep them closed during warmup.
5. If the kiln is equipped with steam or water spray, keep the spray shut off until the dry-bulb temperature has almost reached set point. In warming up a charge of lumber susceptible to checking, the procedure outlined for steam-heated kilns can be followed.

Dehumidification Kilns

Startup procedures for dehumidification kilns may depend on the particular manufacturer's recommendations. Certainly, the status of the heating and refrigeration systems should be checked for proper operation. Auxiliary heat is often added in a dehumidification kiln to reach set point. After that, it is turned off and the heat from the compressor is sufficient to maintain drying temperature in many cases.

Warmup Period

Spray During Warmup

Both heat and steam spray are sometimes used in the warmup period. This procedure will reduce to some extent the time required for warmup, but the potential problems may more than offset the gain in time.

When both the heating and spray systems are on during warmup, a large quantity of steam is used. The steam consumption may exceed the boiler capacity and thereby affect the drying conditions in other kilns already in operation.

When the steam spray is on, moisture condensing on the cold lumber, cold kiln walls, ceiling, and other metal parts will have several effects. Condensation does not allow much drying during warmup, and in fact the lumber will usually pick up moisture. Condensation can cause water stain on the lumber and contribute to corrosion of kiln parts. Another danger is the effect on partially dried lumber that may contain some surface checking. Rewetting the surface will usually widen and deepen surface checks.

Time Needed for Warmup

The time required for warmup depends on many factors and can vary from 1 to 24 h. Warmup time is lengthened if (1) lumber and kiln structure temperatures are low, (2) lumber is frozen, (3) temperature of the outside air is low, (4) initial moisture content of the lumber is high, (5) lumber is thick, (6) density of the species is high, (7) heat losses through the kiln walls and roof are high, (8) seals around closed vents and doors are poor, (9) some heating coils are inactive, and (10) boiler output is too low.

Operating a Kiln After Warmup

Reducing Heat

About 1 h after the kiln has reached set point, the heating system can be cut back. In direct-fired kilns, the rate of firing can be reduced. In steam-heated kilns, the amount of heat-transfer surface area, steam pressure, or both can be reduced. Surface area is decreased by closing valves in the feed and drain lines of some heating coils, and steam pressure is reduced by adjusting the steam pressure regulator. The usual procedure in reducing radiation surface area is to cut off the larger heating coils first and gradually work down to the smallest coil that will maintain the desired dry-bulb temperature. This procedure should be followed unless past experience has shown how much radiation is required to maintain the desired temperature. Experience will establish the best combinations of coils and steam pressure for given situations, and these can be noted for future reference.

Controlling Dry-Bulb Temperature

Variations in dry-bulb temperature on the entering-air side of the loads are a major source of poor control of drying conditions. These variations are sometimes associated with faulty kiln design or poor trap maintenance (chs. 2 and 4). The most common cause of temperature variation is excessive heat-transfer area, that is, too many active coils. Excessive coil heat-transfer area can result in large temperature cycles and waterlogging or air binding of the active heating coils, and these in turn can cause excessive temperature variations along the length of coils. To reduce these effects, the smallest amount of radiation and the lowest steam pressure necessary to maintain the desired dry-bulb temperature at any stage of drying should be used.

If the division of coils is not fine enough to have the correct amount of heat transfer area and the steam pressure cannot be regulated, the kiln may have to be operated at a dry-bulb temperature slightly lower than desired to obtain a nearly constant flow of steam. In that event, the wet-bulb temperature will also have to be adjusted downward to obtain the desired wet-bulb depression.

Controlling Wet-Bulb Temperature

Poor control of wet-bulb temperature is usually associated with inadequate kiln maintenance (ch. 4). Quite often, however, the use of a high-pressure steam spray causes wide variations in both the dry- and wet-bulb temperatures. The use of wet, low-pressure steam should overcome this difficulty. If the reduction in pressure does not have the desired effect, desuperheaters may have to be installed on the steam spray line. The flow of water should not be excessive and may be controlled by a needle valve. To make this possible, the water pressure must be greater than the steam pressure. Ordinarily, water is used to saturate the steam spray only during equalizing and conditioning, or during the early stages of drying a species that requires a low initial dry-bulb temperature with a small wet-bulb depression.

Proper venting is also required to obtain good control of wet-bulb temperature. Such control is attained by good maintenance and operation of the vent system (ch. 4). Excessive venting will add steam consumption and favor the development of drying defects. On the other hand, operating the kiln for extended periods with insufficient venting and at wet-bulb temperatures above those called for in the schedule will prolong drying time and favor the development of stain.

Direct-fired kilns, particularly as employed in softwood drying, often have no steam spray lines, and the only means of controlling the wet-bulb temperature is through venting. Wet-bulb temperature control often is not as critical here as in hardwood drying, and for many species the drying rate is fast enough that vents can adequately control wet-bulb temperature. Also, at temperatures very much above the boiling point, venting often is not necessary because equilibrium moisture content is low at these high temperatures. The main problem occurs if equalizing or conditioning is desired because direct-fired kilns are not capable of raising the wet-bulb temperature to high levels at the end of drying when very little water is evaporating from the lumber.

Some hardwood schedules call for low wet-bulb temperatures at certain stages in the schedule. Au example of this is the schedule for 4/4 red oak (T4-D2). When the lumber reaches 30 percent moisture content, the recommended wet-bulb temperature is 90 °F. In the southeastern part of the United States, the wet-bulb temperature of the outside air may be near that temperature, and either excessive or continuous venting will occur as the control system attempts to reach the wet-bulb temperature. When this occurs, the wet-bulb set point must be raised to a level that the control system can achieve. The dry-bulb temperature should not be raised above that called for in the schedule.

Part-Time Kiln Operation

Kilns are usually operated full time in industrial practice; drying is uninterrupted from the start to the finish of the process. However, some plants, particularly secondary producers, operate kilns part time. In part-time operation, the kiln may be shut down during certain hours in order to take advantage of savings in labor, power, or fuel costs.

Most species, particularly when air dried, can be dried in a part-time kiln successfully. However, equalizing and conditioning treatments usually require full-time operation to be effective. For green hardwoods, redwood, and cedars that are susceptible to surface checking, part-time operation during the initial stages may result in checking because of the more rapid drop in the wet-bulb compared to dry-bulb temperature during the off period. Therefore, for these species, operate the kiln on a full-time basis until the danger of surface checking is past. The vents should be kept closed during the off period to reduce heat losses.

Drying Process

After the kiln has been started, the lumber is dried according to the schedule selected from chapter 7. Chapter 7 deals mainly with the mechanics of selecting schedules, and the purpose of this section is to discuss the operational aspects of kiln schedules.

Operation on a Moisture Content Schedule

A moisture content schedule requires changes in drying conditions based on the average moisture content of the controlling kiln samples (ch. 6). Operation on a moisture content schedule is best illustrated by examples.

Example 1: A charge of 4/4 sugar maple is to be kiln dried from green moisture content. In the example we will use six kiln samples, and the average moisture content of the three wettest samples will be used to control kiln conditions. The drying schedule is given in table 9-1, and the schedule is applied in the following way.

Because the lumber is green, the initial moisture content will be above 40 percent. Therefore, the initial drying conditions will be those of step 1 for moisture content above 40 percent.

Subsequent changes in drying conditions are made when the average moisture content of the controlling samples reaches the value given in the schedule. For example, when the average moisture content of the three wettest samples is less than 30 percent but more than 25 percent, the dry-bulb temperature is 140 °F and the wet-bulb temperature is 121 °F. Because the drying rate of the kiln samples may vary from day to day, the same three samples may not be the wettest during all stages of drying. Therefore, the moisture content of all the samples in the charge should be determined each time they are weighed or sensed with a probe. The last step in the schedule is maintained until the desired final moisture content is reached.

In manual control, the controlling kiln samples occasionally lose more moisture between weighings than the interval given in the schedule. When this occurs, a step in the schedule can be skipped. For example, if the kiln is operating at 130 and 119 °F dry- and wet-bulb temperatures, respectively, and the next weighing indicates that the average moisture content of the controlling kiln samples is 24 percent, the drying conditions should be set at 150 and 115 °F dry- and wet-bulb temperatures, respectively, rather than at 140 and 121 °F. In some instances, even two steps can be skipped.

As soon as the final moisture content is reached, the kiln is shut off unless equalizing and conditioning treatments are required.

Example 2: A charge of partially air-dried 4/4 sugar maple is to be kiln dried. Eight kiln samples are used. Therefore, drying conditions will be governed by the average moisture content of the four wettest samples. The drying schedule will be the same as that used in example 1, and the procedure is as follows:

If the initial moisture content of the four wettest samples averages more than 40 percent, the initial drying conditions will be those listed for this moisture content. Subsequent drying procedures will be the same as for example 1.

If the average moisture content of the four wettest samples is 34 percent, the initial drying conditions will be 130 and 119 °F dry- and wet-bulb temperatures, respectively. Subsequent drying conditions will be as given in the schedule.

If, however, the lumber has regained moisture just before entering the kiln, modify the drying procedure to conform to the recommendations given for air-dried hardwoods in chapter 7.

Operation on a Time Schedule

In a time schedule, drying conditions are changed at predetermined times. No kiln samples are used, and the timed changes are based on experience.

Example 1: A time schedule for 8/4 white fir dimension lumber is shown in table 9-2. The kiln is started at 180 and 170 °F dry- and wet-bulb temperatures, respectively; after 12 h the change to step 2 of 180 and 165 °F dry- and wet-bulb temperatures, respectively, is made. After step 2, the change to step 3 is made after 36 h, and to step 4 after 60 h. Step 4 is held until a total time of 96 h has elapsed since the start of drying. At this time, the lumber is expected to be approaching the target moisture content of approximately 15 percent for softwood dimension lumber. The decision to terminate drying should be based on whatever criteria are being used and whether or not the lumber is ready to be removed from the kiln.

Example 2: A time schedule for lower grade 4/4 white fir is shown in table 9-3. It differs from the schedule in table 9-2 only in the expected time required to reach a final moisture content of approximately 15 percent. Thus, the check for final moisture content should be made at 84 h rather than 96 h.

Example 3: A time schedule for upper grade 4/4 white fir is shown in table 9-4. This schedule is milder than the schedule for lower grade lumber given in table 9-3; that is, the initial dry-bulb temperature and the wet-bulb depression are lower. The time intervals are also different, and more total time is allowed before the final moisture content is determined. This not only reflects the milder drying schedule but also the likelihood that the upper grade lumber may have a lower target moisture content than the lower grade lumber.

Final moisture contents are often estimated by moisture meter readings taken inside the kiln. Any required temperature correction factors should be applied. Alternatively, kiln samples may be used, especially with upper grade softwood lumber, to help establish the duration of the final step in the schedule.

Intermediate Moisture Content Checks

Near the final stage of drying high-quality lumber, particularly hardwoods, the moisture content should be known within fairly close limits. Otherwise, the actual final moisture content will not be the same as the desired final moisture content. Furthermore, equalizing and conditioning treatments will not be effective if the moisture content of the kiln samples is not an accurate estimate of the moisture content of the lumber. Intermediate moisture content checks are discussed in chapter 6, and they are often used in the final stages of drying to correct the moisture content estimates. Intermediate checks are sometimes made on a routine basis, but if they are not, certain danger signals indicate that such tests should be made. If the moisture content of one or more kiln samples is suspiciously different from most or if the rate of change of moisture content during drying seems quite different, intermediate checks should be made.

Equalizing and Conditioning Treatments

Good moisture uniformity and stress-free lumber can be obtained by equalizing and conditioning treatments described in chapter 7. The following discussion expands on that of chapter 7 and will be helpful in applying the treatments.

Equilibrium Moisture Content Table

To apply the equalizing and conditioning procedures, an operator must know how to determine the wet-bulb depression needed to give the required equilibrium moisture content (EMC) condition. Equilibrium moisture content values are given in chapter 1, table 1-6. In the example presented here, however, the use of this table is the reverse of the explanation given in chapter 1. Assume, for example, that a dry kiln is operating at a dry-bulb temperature of 170 °F, and the operator wants to know the wet-bulb temperature required to obtain an EMC of 6 percent. The dry-bulb temperature of 170 °F is found in the left column of table 1-6. In the row to the right of this temperature, the EMC of 6 percent is found in the column indicating a wet-bulb depression of 29 °F. Therefore, to obtain an EMC of 6 percent at a dry-bulb temperature of 170 °F, a wet-bulb temperature of 170 °F minus 29 °F, or 141 °F, would be used.

General Considerations

1. The recommended procedures for equalizing and conditioning a charge of lumber will produce good results in a kiln that is performing satisfactorily, but it is important that the control instruments are in calibration. If poor calibration causes the wet-bulb depression in the kiln to be different than the recommended setting, the EMC condition in the kiln will not be correct, and the treatments may not be entirely effective.
2. An equalizing treatment is not necessary if the driest and wettest kiln samples at the end of the drying process have moisture contents within an acceptable range.
3. Some operators prefer drying the driest samples in the kiln to a moisture content 1 percent below the value recommended in table 7-30 (ch. 7) before starting equalization. This may reduce equalizing time and might even eliminate the need for equalizing.
4. If the recommended EMC value for conditioning at a specific temperature cannot be found in table 1-6, use the next highest value given in the table for that temperature. For example, conditioning a charge of lumber at 170 °F with an EMC condition of 11 percent is required. Referring to table 1-6, no wet-bulb

depression is given for an EMC condition of 11 percent at a temperature of 170 °F. Use the next highest value—11.3 percent. The wet-bulb depression for the 11.3 percent EMC condition is 10 °F.

Conditioning Temperature

The higher the dry-bulb temperature used in conditioning, the faster the relief of casehardening. Generally, the required conditioning EMC can be obtained at a dry-bulb temperature of about 180 °F in most well-maintained kilns operated on low steam pressure or equipped with a desuperheater on the spray line or auxiliary water sprays. Sometimes it is impossible, however, to obtain the required high EMC conditions at a temperature as high as desired.

If the required EMC cannot be obtained at a dry-bulb temperature of about 180 °F, the temperature will have to be reduced. In such instances, lower the setting on the control instrument 12 to 24 h before conditioning is started. For example, assume the kiln is operating at a dry-bulb temperature of 180 °F, and the temperature must be reduced to 170 °F to obtain the desired EMC for conditioning. Twelve to twenty-four hours before conditioning is started, the dry-bulb temperature should be reset to 170 °F.

Conditioning Time

High dry-bulb temperatures coupled with high EMC conditions hasten deterioration of dry kiln buildings and metal in the kiln. Also, large amounts of steam are required for conditioning. Therefore, conditioning should not be extended any longer than is necessary to relieve drying stresses (chs. 6 and 7). Conditioning time depends on the degree of stress in the lumber; lumber species, thickness, and moisture content; and kiln performance. It may vary from 4 h for 1-in-thick softwoods to 48 h or more for thick, high-density hardwoods, The minimum time required is determined by making casehardening (prong) tests at times when it is believed that stresses are nearly relieved. Recorded results of these tests will establish good estimates for required times in future charges. The casehardening test is described in chapter 6.

When air-dried lumber is kiln dried, the conditioning time varies from charge to charge because the degree of drying stress in the air-dried lumber varies. Case hardening tests made on air-dried lumber at the time kiln samples are prepared will give an estimate of the amount of stress present and thus a rough indication of the amount of conditioning required.

Stress Relief at High Equilibrium Moisture Content

To reduce the time required for conditioning, some kiln operators use an EMC higher than that recommended. This approach may be satisfactory if conditioning is not continued for too long. If it is, reverse casehardening, which is as serious as casehardening, will result. No satisfactory method of relieving reverse casehardening has been established. In many instances the use of very high EMC values during conditioning gives only superficial relief of drying stresses. Therefore, to obtain good conditioning without incurring risk of reverse casehardening, conditioning should be done at the recommended conditions (ch. 7).

Moisture Content and Stress Tests

Kiln samples are generally used for final moisture content and casehardening tests to make sure that the lumber is at the desired final moisture content and is free of drying stresses. Other boards from the kiln charge can also be used, provided they are representative of the charge.

Method of Testing

To properly interpret the reaction of stress test sections, certain information about the final moisture content and moisture gradient is required. The method of cutting sections for such tests is given in chapter 6. One section should be weighed immediately after cutting, ovendried, reweighed, and the moisture content calculated. This calculation will give the average moisture content of the kiln sample or board from which it was cut. If this test is made immediately after the conditioning treatment, the moisture content obtained will be about 1 to 1-1/2 percent higher than before conditioning because the surface will have regained moisture during conditioning. If, however, the test is made after the lumber has cooled for about 24 h, in most cases the regained moisture will have evaporated.

A second section should be cut as shown in chapter 6, figure 6-3, to obtain two outer shells, each with a thickness of about one-fourth the total thickness of the lumber and a core of about one-half the total thickness. The core and shell are weighed separately as quickly as possible after cutting, ovendried, reweighed, and their moisture contents calculated. A third section should be cut into prongs, as described in chapter 6, for the stress test.

Evaluation of Casehardening Tests for Stress

If the prongs of the stress section turn out to only a slight degree immediately after sawing, the lumber can be considered stress free, and conditioning can be terminated. If, however, the prongs remain straight or pinch in, continue conditioning. The amount of additional time required depends on the amount of movement of the prongs, and some experience is necessary before judgments can be made. If the prongs move in only slightly, only a few more hours of conditioning may be required. If they move so far as to cross, the remainder of the day or overnight may be required for conditioning.

Whether or not to continue conditioning must be decided fairly soon after the casehardening test is made; however, all the information required to make that decision is not always immediately available. The prongs may continue to react over a period of time after cutting, and unless a microwave oven is available and the exact drying procedure worked out, the average moisture content and moisture content of the shell and core are not known for 24 h. Observation of the prong movement after 24 h as well as the moisture content values at this time will provide useful information for future charges. The following conditions may be observed after 24 h:

1. If the prongs do not move in significantly immediately after cutting, if they do not move any further after 24 h, and if the moisture content values of the shell and core are within about 1 percent of each other, then the lumber is well equalized and conditioned.
2. If the prongs do not move in immediately after cutting but do after a period of time, the core moisture content is probably greater than the shell moisture content. Longer equalization is then required.
3. If the prongs do not move in immediately after cutting and do so after standing but the shell and core test does not indicate that the core is at a higher moisture content than the shell, then the conditioning period should be lengthened.

Modifying Kiln Schedules

A major cause of excessive drying defects or drying time is to blindly follow a recommended kiln schedule that has not been proven for specific circumstances. No schedule will produce the best drying results on a specific item or species in all types of kilns under all types of conditions. The schedules recommended in chapter 7 are generally conservative, and they are meant to be a starting point for modification to an optimum level. Before modifications can be made, the recommended schedule should be tried. Information for justifying schedules can be obtained by observing (1) the type and severity of drying defects, their time of occurrence, and their effect on degrade or volume loss, (2) the drying time required, and (3) the final moisture content. Systematic procedures for modifying schedules are given in chapter 7.

Cooling a Charge After Drying

After lumber has been kiln dried, it is usually cooled before machining. Sometimes, if kiln demand is low, the charge is cooled in the kiln. More often, the charge is removed from the kiln and held in a protected cooling area at the dry end of the kiln. Lumber dried to a low moisture content should not be stored outdoors or exposed to high humidity for extended periods because it will regain moisture (ch. 10). Sometimes cracking noises are heard as lumber cools. This is usually caused by movement between the stickers and the lumber as thermal contraction occurs and is not the result of the lumber actually cracking or splitting.

Operating Precautions for Safety

Working in or around dry kilns is not hazardous if ordinary precautions are taken. As is the case with most machinery and equipment, carelessness is the major cause of accidents, which can be serious or fatal in and around kilns. Care should always be exercised around high-temperature burners, steam plants and steam lines, and operating fans, belts, and shafts. The following rules and precautions will help prevent accidents.

1. Do not touch the outside surfaces of kilns operating at high temperature because they can be dangerously hot-particularly any part that allows continuous metal conduction from inside to outside.
2. Shut off the heat, spray, and fans before entering an operating kiln. If the kiln has been operating at high temperatures, it should be cooled to a safe level by opening doors and vents before entering.
3. Never enter a kiln in use without the knowledge of a coworker-preferably someone who remains close to the kiln in case assistance is needed.
4. When an access or main door is opened, stand away from the door. Hot and often humid air rushes out and can be an uncomfortable or dangerous shock, particularly if breathed.
5. Occasionally it may be necessary to enter a kiln when the heat, spray, or fans are operating in order to check their operation. In this case, another person should be stationed immediately outside the kiln to ensure the safety of the person inside.

6. Never enter a kiln when the wet-bulb temperature is 120 °F or more without wearing protective clothing that covers the head and body. This temperature limit applies to people in good health. Anyone with heart or respiratory problems should not enter kilns where the wet-bulb temperature is 110°F or more. The critical dry-bulb temperature depends on the individual. In any case, no one should enter or remain in a kiln if either the temperature or the humidity makes the person feel ill or more than mildly uncomfortable.
7. Equip all small access doors with a latch that can be operated from both sides. Repair faulty latches immediately. Never use props to hold a door closed-there is always the possibility that such propping could inadvertently trap someone in the kiln. Set up an emergency signal that can be used if someone is accidentally trapped inside. A signal rapped on steam pipes will carry a considerable distance.
8. Provide sufficient lighting in kilns to provide safe movement for anyone who enters the kiln. As an added precaution, a portable light should be carried.
9. A person should not attempt to open or close kiln doors that are too heavy for a single person.
10. Door carriers should be kept in good repair to guard against a door jumping the track.
11. Fans should obviously be shut off when inspected closely or lubricated, but precautions should then be taken to ensure that the fans are not inadvertently started at these times. If the fan switch is not equipped with a lock in the off position, a sign "Do Not Start Fans" should be placed at the switch.
12. Fan floors are often oily, and precautions should be taken to prevent slipping.
13. Shafts and pulleys should be adequately guarded.
14. When truckloads of lumber are loaded and unloaded, devise a system for workers to know each other's whereabouts so that no one gets crushed between trucks.
15. When loaded kiln trucks are moved by cables, procedures should be established to ensure that all workers stay clear of the cables when they are under tension.

Fire Prevention in Kilns

Fires in dry kilns we usually caused by carelessness, poor maintenance, or poor housekeeping. Precautions for minimizing the possibility of fire are as follows:

1. In direct-fired kilns fueled by wood residue, ensure that the burner is operated according to manufacturer's instructions so that live embers do not enter the kiln.
2. Do not allow smoking in a kiln.
3. Use care with welding or cutting torches.
4. Keep electrical circuits in good repair.
5. Keep all moving parts well lubricated. A hot bearing can cause a fire.
6. Do not allow uninsulated steam pipes to contact flammable material.
7. Keep the kiln and surrounding area free of excess debris.

Kilns should be checked regularly outside of regular working hours so that if a fire starts, it can be fought promptly. A definite procedure should be established for workers to follow if a kiln fire should occur. The following procedures may extinguish the fire or will reduce the spread of fire in a kiln until a firefighting crew arrives.

1. Install a water sprinkler system and check its operation regularly.
2. Have fire extinguishers available in the area.
3. Keep all kiln doors closed.
4. Close the ventilators.
5. Shut off the fans.
6. In a steam-heated kiln, saturate the air in the kiln with steam. If there is a bypass around the steam spray control, open that valve or, if not, set the wet-bulb control point as high as possible.

Sources of Additional Information

Boone, R. S.; Kozlik, C. J.; Bois, P. J.; Wengert, E. M. 1988. Dry kiln schedules for commercial woods temperate and tropical. Gen. Tech. Rep. FPL-GTR-57. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 158 p.

Knight, E. 1970. Kiln drying western softwoods. Moore, OR: Moore Dry Kiln Company of Oregon. 77 p. (Out of print.)

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Table 9-1—Moisture content schedule for 4/4 sugar maple (T8-C3)

step	Moisture content (percent)	Temperature (°F)		Equilibrium moisture content (percent)	Relative humidity (percent)
		Dry-bulb	Wet-bulb		
1	Above 40	130	125	16.2	86
2	40 to 35	130	123	14.3	81
3	35 to 30	130	119	11.5	71
4	30 to 25	140	121	8.3	57
5	25 to 20	150	115	5.0	34
6	20 to 15	160	110	3.4	21
7	15 to final	180	130	3.5	26

(Equalize and condition as necessary)

Table 9-2—Time schedule for 8/4 white fir dimension lumber

step	Time(h)	Temperature (°F)		Equilibrium moisture content (percent)	Relative humidity (percent)
		Dry-bulb	Wet-bulb		
1	0 to 12	180	170	11.2	79
2	12 to 36	180	165	9.1	70
3	36 to 60	180	155	6.5	54
4	60 to 96	180	145	5.0	41
5	Or until dry				

(Equalize and condition as necessary)

Table 9-3—Time schedule for 4/4 white fir, lower grade

step	Time(h)	Temperature (°F)		Equilibrium moisture content (percent)	Relative humidity (percent)
		Dry-bulb	Wet-bulb		
1	0 to 12	180	170	11.2	79
2	12 to 36	180	165	9.1	70
3	36 to 60	180	155	6.5	54
4	60 to 84	180	145	5.0	41
5	Or until dry				

(Equalize and condition as necessary)

Table 9-4—Time schedule for 4/4 white fir, upper grade

step	Time (h)	Temperature (°F)		Equilibrium moisture content (percent)	Relative humidity (percent)
		Dry-bulb	Wet-bulb		
1	0 to 12	170	164	14.1	86
2	12 to 24	170	160	11.4	78
3	24 to 48	175	160	9.1	69
4	48 to 72	180	160	7.7	62
5	72 to 96	180	140	4.5	36
6	Or until dry				

(Equalize and condition as necessary)

Chapter 10
Log and Lumber Storage

Kiln drying is only one step in the harvesting, handling, and processing of wood products. The best results can be obtained in kiln drying, therefore, when adequate attention is paid to related phases of wood processing. Although a dry kiln operator may have no responsibility for these related phases, knowledge of them is required to understand how they interact with drying. Problems that occur in drying, or that are erroneously blamed on drying, are sometimes related to the methods used to store logs and lumber before drying and those used to store kiln-dried lumber and finished products.

Logs and lumber go through various storage and transport periods while moving through the processing sequence. Log storage and transit really begin when the tree is felled and continue until the log is sawed into lumber. Similarly, lumber storage and transit include the time between sawing and drying and the time between drying and end use. The moisture content of lumber should be controlled in storage and transit. Large increases in moisture content during storage may make lumber unsuitable or out of specifications for many uses, cause lumber to warp, or cause the development of stain or decay. Large decreases in moisture content may cause checks and warp to occur or make machining and fastening difficult.

Chapter 10 was revised by William T. Simpson, Supervisory Research Forest Products Technologist, and James C. Ward, Research Forest Products Technologist.

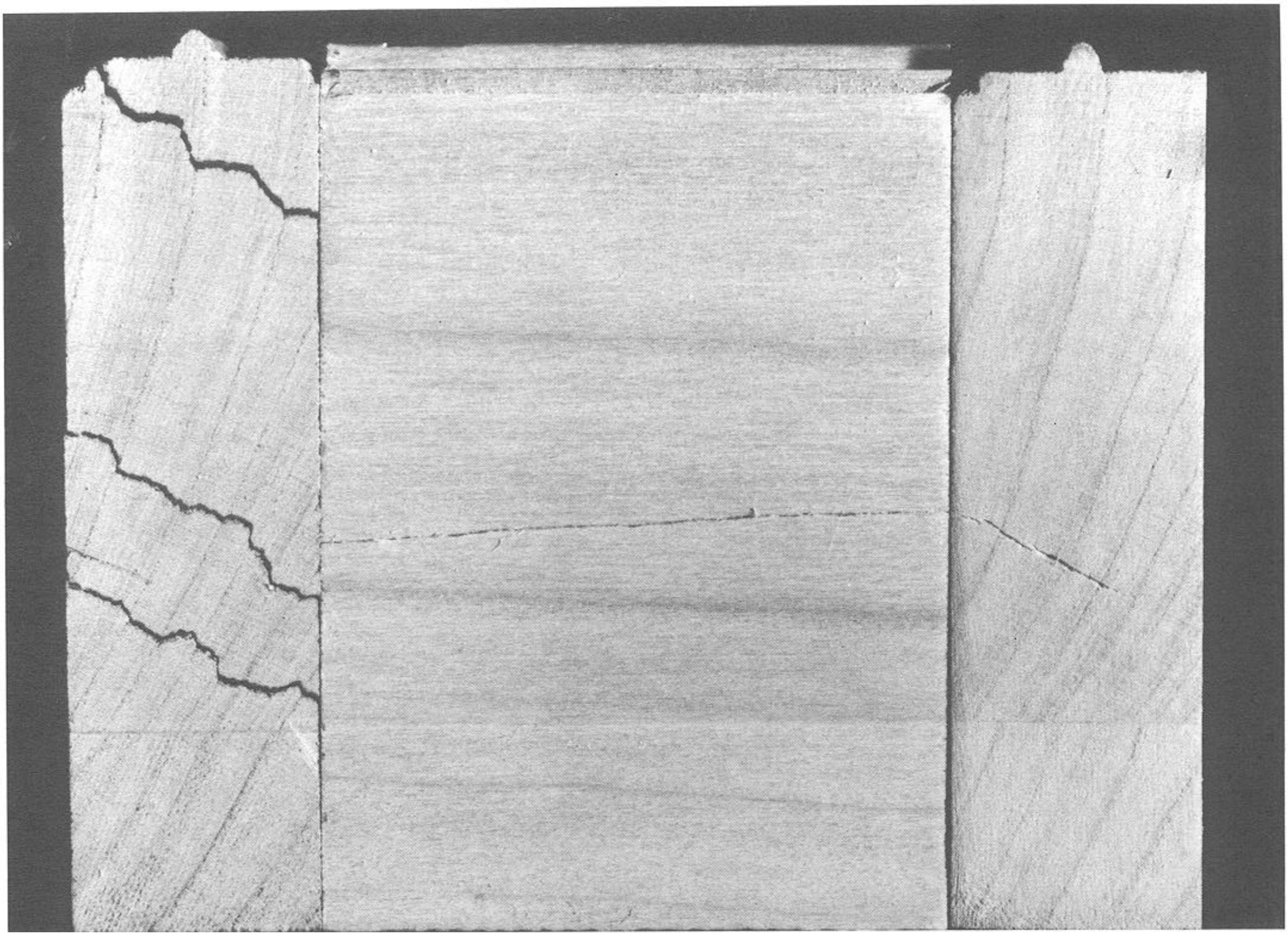

Figure 10-1—Splits in black cherry millwork from lumber that was sawn from a wind-damaged tree. (M88 0170)

Log Storage

The source of some lumber drying problems can be traced to changes in the wood that began in the tree just before or during the timber harvesting operation. Logs that have been salvaged from forests that were damaged by hurricanes or tornadoes may yield lumber that is likely to split during drying and subsequent machining (fig. 10-1). Felling the tree with a clipping or shearing machine can initiate radial splits and ring failures in the end of the log, which may lengthen considerably with lumber drying.

After felling, the main stem of the tree is detached from the crown, except when transpiration drying is desired. At most commercial logging operations in North America, the main stem of the felled tree is either left full length (tree-length log) or cut (bucked) into shorter logs with lengths that correspond to lengths of the intended lumber. Tree-length and standard-length logs should be sawed into lumber as soon as possible after felling, especially during warm weather. However, prompt sawing of logs is not always possible because of log transportation difficulties or the economic need to stockpile logs at the sawmill. This section suggests methods for reducing drying defects that result from prolonged storage of logs.

Logs need to be stored under conditions that will minimize defects associated with shrinkage, mainly end checking, and attacks by fungi, bacteria, and insects. Defects associated with shrinkage are minimal during periods of cloudy, wet weather and low temperatures. Fungi and insects are inactive at temperatures below 32 °F or under conditions of wet storage with low levels of oxygen. On the other hand, many types of bacteria can grow in wood under wet, anaerobic conditions, but not at subfreezing temperatures. There are two general methods for storing logs: dry storage and wet storage. Precautions must be taken with each storage method to ensure defect-free lumber.

Dry Storage

Most sawlogs in North America are stored under dry conditions with the bark intact. Occasionally, kiln

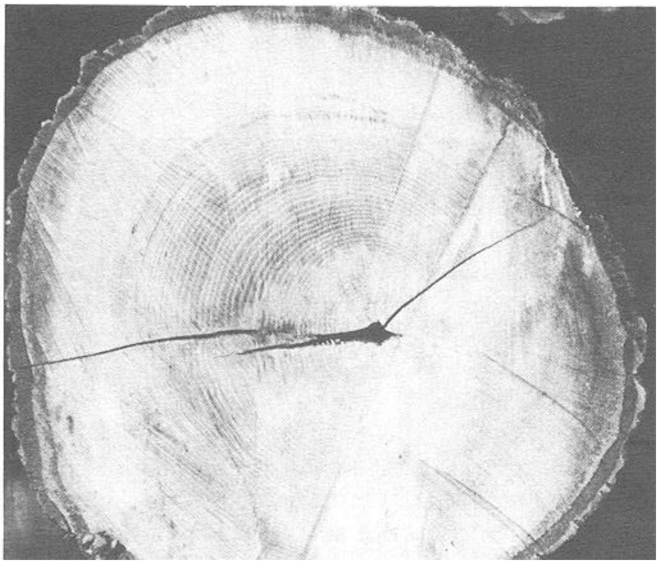

Figure 10-2—Splits in the end of a red oak log resulting from ruptures caused by an imbalance in tree growth stresses after felling. (M88 0169)

operators may encounter logs from diseased or insect-damaged trees where most or all of the bark has fallen off.

Because lumber from logs subjected to transpiration drying may show up in the drying operation, this subject will be discussed as a part of dry storage.

Logs With Bark

Most lumber that needs to be kiln dried will be sawed from logs that were stored on land with the bark intact. If the logs do not contain wetwood, then any lumber drying problems will usually be associated with serious end checking of the logs, insect attack, and sapwood stains.

End checks can occur in all species of logs and are more pronounced in the denser hardwoods. Deep end splits can sometimes occur in the log ends, but these are the result of residual tree growth stresses that become unbalanced after the log is bucked, and they **can**not be prevented by measures for reducing end checking (fig. 10-2). End checks are minimized by keeping the log ends in cool, moist, and shaded locations. If the logs are valuable and cannot be sawed into lumber within a short time, then the ends should be coated with a suitable end-sealing compound (fig. 10-3). The end coating should be thick enough to cover all wood pores, cracks, and irregularities on the surface, yet viscous enough so that it neither cracks nor “sags” excessively. It is good practice to treat the log ends with chemical fungicide before end coating to prevent sapwood staining.

Figure 10-3—Oak logs 8 months after they were cut and the ends treated with preservatives. All but two logs were also end sealed; no end checking developed in these logs. The preservative treatment of the unsealed logs (topmost and lower left) was of little value once the barrier of the surface-treated wood was ruptured by seasoning checks. (M 81288).

Figure 10-4—Sweetgum logs with heavy sapwood stain at the ends. Under conditions favorable for staining, end stain may appear within 2 weeks and the discoloration may penetrate into the log as rapidly as 1 ft per month. (M 38236)

Fungal blue stain will develop in the sapwood of exposed log ends and debarked surfaces during warm weather within 2 weeks after the tree is felled (fig. 10-4). Applying or spraying chemical fungicides on all exposed log surfaces will provide adequate protection if the wood does not check or split. These chemically treated areas should then be coated with a log end-sealing compound to prevent checking and the opening of untreated inner wood to fungal attack. Since wood-boring insects can carry spores and hyphae of sapwood-staining fungi into the logs, even through areas with attached bark, logs may need to be sprayed with a mixture of chemicals that control both insects and fungi.

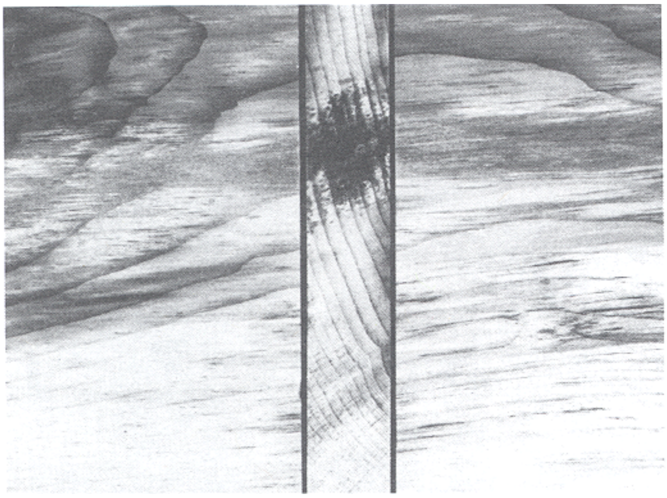

Figure 10-5—Fungal blue stain and chemical brown stain in sapwood and wetwood of a kiln-dried eastern white pine board sawed from a log stored during early spring on a log deck in the forest. (M88 0168)

Chemical changes will occur in moist sapwood during log storage that may cause chemical discolorations during subsequent drying. These discolorations can vary from gray, yellow, and pinkish to deep brown. Chemical stains are likely to occur in lumber from logs that were stored under moist, shaded conditions for the purpose of preventing end checking. Brown stain and blue stain will develop together in lumber from logs that were stored in the forest or similarly shaded locations (fig. 10-5). Prompt sawing of freshly cut logs is the easiest way to control chemical sapwood stains because treating the logs with fungicides that prevent blue stain will not be effective.

The most effective method for controlling chemical stains is to freeze freshly cut sapwood. This can be done economically only by sawing winter-cut logs in northern climates during cold weather and using proper kiln-drying conditions. At some northern mills, short logs of birch, maple, and pine that are to be sawed into specialty products are frozen to ensure white color. The short logs from winter-cut timber are placed in ground depressions and sprayed with water to form a coating of ice. The frozen log decks are covered with sawdust, wood shavings, or other available insulating material so that the wood remains frozen well into the summer months.

Debarked Logs

Most logs intended for lumber are debarked on the day of sawing; the problems associated with the storing of debarked logs are thus not carried over into the drying operation. Logs intended for poles and pulpwood are debarked soon after felling to reduce losses from insect borers and decay and to lower sapwood moisture content. The disadvantages of early debarking are extensive surface checking and end splitting. Sapwood staining can also be quite substantial.

Transpiration Drying

After a tree is cut or girdled, the main stem will lose more moisture if the crown is left attached than if the stem is bucked into logs. This method of drying is called transpiration drying. Teak trees in the forests of southeast Asia are girdled and left standing for at least a year before felling so that the logs will be light enough to float to the sawmills via the river systems. In North America, there is some interest in transpiration drying because of its potential application to wood energy production. If tree-length logs are stored in the woods for a short time, leaving the crown attached also seems to provide some protection from ambrosia beetle attack.

The amount of moisture lost depends upon viable foliage in the crown and the amount of sapwood in the stem. Softwoods will undergo transpiration drying throughout the year if winter temperatures are not below freezing, but deciduous hardwoods can only be dried during the summer when the leaves are present. During transpiration drying, oak logs with narrow rings of sapwood will not lose much more than 10 percent moisture content whereas sweetgum and yellow-poplar, species with wide bands of sapwood, can lose over 30 percent moisture content. The maximum moisture loss from hardwoods will occur in 1 to 2 weeks, but this period will usually be longer for conifers. On the west coast of Washington, Douglas-fir will undergo a maximum moisture loss of 30 to 50 percent in about 90 days.

In South Africa and Holland, Visser and Vermaas (1986) found that transpiration drying of both hardwood and softwood trees resulted in total energy savings because of easier handling of green lumber and reduced kiln-drying times. A mass loss of 30 percent after 1 month of transpirational drying resulted in an energy saving of approximately 55 percent in the kiln, while a maas loss of 10 percent after 1 week of drying resulted in an energy saving of approximately 25 percent. These authors also noted that the sudden drop in moisture content with transpirational drying helps to suppress the development of blue stain in South African timber.

Wet Storage

When logs must be stored for a long time at temperatures above freezing, it is desirable (when possible) to keep them soaking wet. This prevents drying and checking and inhibits attacks by insects and sapwood-stain fungi. However, some types of bacteria are not inhibited, and the wood may become predisposed to developing chemical stains.

Pond Storage

Pond storage includes logs that are stored in lakes, rivers, and salt water estuaries as well as mill ponds. Although pond storage was once a regular practice, it is now rare in North American mills. Nevertheless, a dry kiln operator may receive lumber from logs that have been submerged in water. Considerable volumes of logs are rafted from woods to mills along the coast of the Pacific Northwest. Foreign lumber is frequently sawed from pond-stored logs, and some lumber is salvaged from old submerged logs and timber.

Pond-stored logs are usually banded together to increase the log-holding capacity of the pond and to prevent wetwood (sinker) logs from sinking to the bottom (fig. 10-6). Some logs in the bundle will be above water and are subject to insect attack, stain, and decay. Until recent Environmental Protection Agency (EPA)

Figure 10-6—Logs banded together in a log pond in northern California. Some logs are completely submerged while others are entirely out of the water. (M88 0167)

Figure 10-7—Water sprinkling of decked hardwood logs. A fine mist effectively covers log surfaces and ends. (M 144876).

prohibitions, these types of damage were controlled for several weeks by spraying the exposed parts of the log bundles with insecticides and fungicides. Logs rafted and stored in ocean water are also subject to attack by marine borers and salt water micro-organisms.

Most damage to submerged logs can be traced to growth of bacteria in the sapwood. In softwoods, pit membranes in the sapwood are destroyed so that the wood becomes more permeable, and the wood will dry somewhat faster. However, the lumber will also overabsorb chemicals used to stabilize and preserve the wood, and finishing can be a problem. Honeycomb, ring failure, and collapse are likely to develop in lumber from logs and timber that have been submerged for over a year. Chemical brown stain has been a frequent problem with the drying of ponderosa pine and sugar pine lumber from pond-stored logs. In rare situations, the iron content of the water is unusually high, and woods gradually acquire a grayish color because of an iron-tannate reaction.

Water Sprinkling

Where log decking is a preferred manner of storage, sprinkling the decks with water provides an effective method for reducing checking, sapwood stains, and decay when temperatures are above freezing (fig. 10-7). Sprinkling will not provide certain protection from insect attack although it tends to be more effective than dry log storage in some localities. Nevertheless, the beneficial effects of using water sprays during warm weather have been reported for western softwoods and eastern hardwoods, especially in the South.

For sprinkling to be effective, the log ends and exposed, debarked wood surfaces must be kept continuously wet during the entire period of storage. This prevents shrinkage and checking of the exposed wood. Water sprays reduce temperatures in and around the log decks, but the reduction of oxygen from continuous soaking of the wood is the major deterrent to sapwood-staining and decay fungi.

Bacteria and slime molds, less common in dry-stored logs, may develop extensively in sprayed logs. Bacteria can be responsible for chemical stains and increased porosity in lumber from wet-stored logs, but these problems are greater in pond-stored logs than in logs stored on sprinkled decks. Bacterial problems with sprinkling can be prevented by not drawing the water from stagnant reservoirs where drainage from the wetted logs is returned and recycled. Under water sprays, bacteria from wetwood zones in the log may extend their growth into the sapwood, which will then develop brown stains during drying.

Water sprinkling requires constant maintenance to guard against clogging of hoses and spray nozzles from debris and slime in the water. Adequate drainage must be provided in the log yard to prevent handling problems with forklift vehicles.

Effects of Climate On Lumber Storage

Relative humidity, air temperature, and rainfall of the storage region are the main factors that determine the rate and amount of moisture content change in the lumber and the procedures necessary to protect lumber stored outdoors or in unheated sheds.

Relative Humidity

Relative humidity has a much greater effect on wood equilibrium moisture content (EMC) than does temperature (table 1-6). The more humid a region, the more moisture the lumber will absorb and the more rapid the rate of absorption. Seasonal estimates of the average wood EMC for a region can be helpful when trying to control moisture change in lumber stored outdoors.

Storage methods to retain low moisture content in kiln-dried lumber will differ between humid regions like the gulf coast and dry regions like the Southwest. Likewise, storage requirements may differ from month to month in regions where average relative humidity varies considerably with the season, such as inland California.

Temperature

Air temperature has a minor effect on EMC (table 1-6), but its main effect is on the rate of moisture content change. Moisture content changes occur faster at warm temperatures than at cool temperatures. Therefore, if lumber has to be stored at EMC conditions different than the moisture content of the lumber, the temperature should be taken into consideration. Some moisture equalization can be effected in storage; the warmer the temperature, the faster the rate of equalization.

Warm temperatures also increase the hazard of fungal infection in stored lumber. All lumber is practically immune to fungal infection below 30 °F. When green lumber is solid piled, mold, stain, and decay fungi will grow at temperatures from 40°F to 100 °F with the rate of attack increasing rapidly at higher temperatures in this range. Dipping or spraying freshly sawed lumber with an approved fungicide reduces the chance of fungal growth.

Rainfall

When lumber is protected while stored outdoors, rainfall does not greatly affect its moisture content. Solid-piled green lumber is often unprotected while temporarily stored outdoors before stacking for air or kiln drying. Some wetting of green lumber is not considered hazardous. If, however, green lumber has been treated with a fungicide for extended green storage or shipment, protection from rain is needed to prevent leaching of the chemicals.

Solid-piled dry lumber should be protected from rain, preferably in storage sheds. Redrying solid-piled lumber that has been wetted by rain is difficult. Solid-piled lumber that has been thoroughly soaked requires stickering before it is redried, and redrying may result in drying losses. Also, if rain increases the moisture content of the lumber to 20 percent or more, fungi may grow and cause stain and decay.

Average Equilibrium Moisture Content Conditions by Region and Season

Estimated monthly wood EMC conditions at various locations throughout the United States are given in table 10-1. They represent average values from climatological data and thus may vary from year to year. Also, EMC conditions are often influenced by microclimates within regions, so more localized values can be determined from local weather stations.

The Southwestern States are generally the driest regions, and the coastal regions, the wettest. During summer months, the states west of the Mississippi River are much drier than during the spring months. East of the Mississippi, the summer months are slightly more humid than the spring. Fall is usually more humid than spring or summer in most of the United States, and winter is generally even more humid.

Lumber Storage

Lumber storage can be classified into five major types: outdoors, open shed, closed and unheated ‘shed, closed and heated shed, and conditioned shed. The desirable type of storage depends on the moisture content of the lumber and the weather conditions during storage.

Outdoor Storage

Lumber is often stored outdoors because shed or warehouse facilities are not available. Unprotected outdoor storage is satisfactory for small timbers and lumber for less exacting end uses, although precautions to prevent stain, decay, and insect infestation may be necessary.

Kiln-dried lumber stored outdoors without protection will have a rapid increase in moisture content.

Protection against rain is more important for solid-piled lumber than for stickered lumber because rainwater cannot evaporate readily from solid piles. Furthermore, rain that penetrates solid-piled lumber may in time increase the moisture content enough that stain and decay can grow. Storage areas should be open, well drained, and kept free of weeds and debris that restrict air movement along the surface of the ground, harbor fungi and insects, and create a hazard when dry. The ground, particularly along runways for lumber-handling equipment, should be surfaced with gravel, crushed rock, asphalt, or concrete. Surfacing or paving permits vehicles to operate efficiently in all weather and restricts weed growth. The method of piling for outdoor storage depends on the species involved, its moisture content, and the degree of drying desired during the storage period.

Green Lumber

Green lumber dries during storage. To reduce drying defects and kiln-drying time as much as possible, the principles of good air-drying practice should be followed (Reitz and Page 1971). Briefly, these include (1) stacking the lumber properly with dry stickers spaced correctly so as to minimize warp, (2) providing good pile foundations, (3) laying out the yard with adequate spacing between piles and rows of piles, and (4) providing good pile roofs.

If green lumber must be stored in solid piles for more than 24 h in warm weather, it should be dipped in an approved antistain solution. Green lumber properly stacked and protected on a good site will lose moisture rapidly with a minimum of defects and can remain outdoors indefinitely without excessive deterioration.

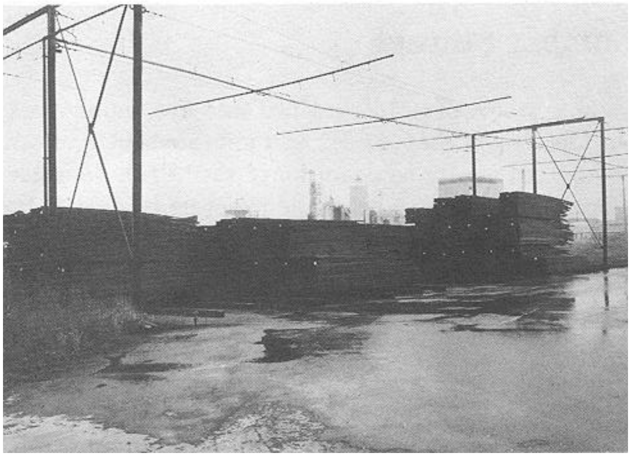

Figure 10-8—High-grade Douglas-fir stored temporarily under water spray while the mill accumulates enough for a full kiln load. (M88 0165)

Sometimes high-quality green lumber is stored temporarily under water spray (fig. 10-8), while lumber is being accumulated for a kiln load.

Partly Dried Lumber

If the moisture content of lumber is above 20 percent or if further drying is desired, the lumber can be stored like green lumber. Lumber that is below 20 percent moisture content can be solid piled if no additional drying is desired. The piles should be fully protected against infiltration of rainwater. Water that penetrates a solid lumber pile is not readily evaporated and is likely to cause stain or decay. Lumber surfaces that are alternately wetted and dried are likely to check.

Kiln-Dried Lumber

Lumber kiln dried to a moisture content of 12 percent or less can be stored outdoors in dry weather in stickered or solid piles for a short time. Extended storage will result in excessive moisture regain. Figure 10-9 shows the change in moisture content of southern pine during yard and shed storage in solid piles in inland Louisiana. If the lumber had been piled on stickers, its moisture content would have risen to the maximum of about 13-1/2 percent in a much shorter time. During the warm, dry season in areas such as the arid Southwest and in parts of Idaho, Montana, Nevada, Oregon, and Washington, the outside storage period can be extended considerably without serious effects if pile covers are used.

Kiln-dried lumber can and often is afforded temporary protection, particularly in transit, by wrapping in various types of coated paper. Such wrap for unit packages of lumber (fig. 10-10) will adequately protect kiln-dried softwood lumber under short-term storage conditions such as long-haul transport on flatcars, interim storage at distribution centers, and short-term outdoor storage at construction sites. However, coated paper wrappings should not be considered a substitute for storage sheds when long-term storage of dried lumber is involved. The lumber could deteriorate during storage and is susceptible to tearing during handling. If such storage is unavoidable, the protective wrap should be inspected periodically for tears or other deterioration. Water that enters packages through tears in the protective wrapping can collect and cause more regain of moisture than if no wrap were used. To avoid trapping water in torn packages, the bottom is often left open. However, moisture from ground water can enter packages if not enough ground clearance is provided by the pile foundations.

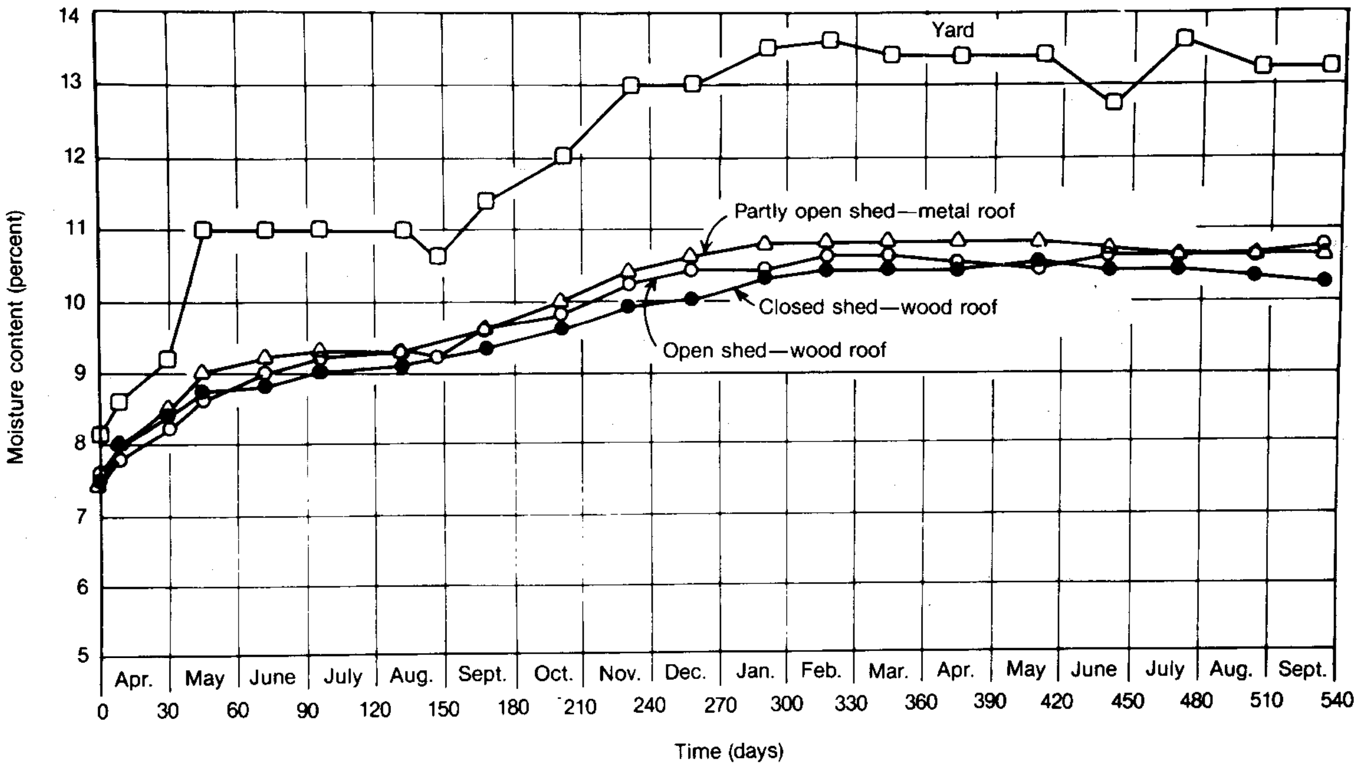

Figure 10-9—Change in average moisture content of kiln-dried southern pine 1- by 4-in flooring and 1- by 8-in boards during storage in solid piles within sheds and in a yard with a protective roof over each pile. (ML88 5557)

Figure10-10—Covering packages of lumber with waterproof kraft paper wrap. The wrap does not cover the package bottom, and thus will not be damaged by forklift handling nor will it trap rainwater. (M 120954)

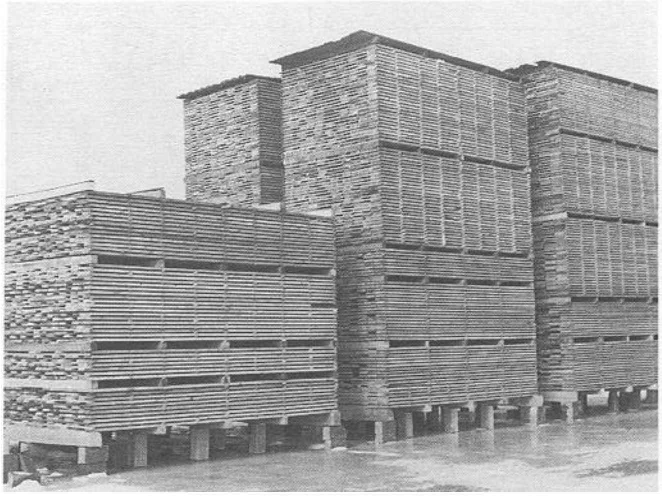

Figure 10-11—Stickered lumber yarded for air drying. The well-braced pile foundations of stringers and crossbeams prevent tipping. Most piles are covered with a prefabricated board and batten roof (M 134963)

Pile Covers

High-grade lumber stored in a yard, whether solid piled or stickered, green or dried, should be protected from the weather. Lumber surfaces exposed to alternate wetting and drying will check, warp, and discolor. Stacks of lumber in storage yards can be provided with pile covers the same as are used in air-drying yards **(fig. 10-11).**

Open Shed Storage

Open sheds provide excellent protection for green and partially dried lumber. Lumber that has been kiln dried to a low moisture content can also be stored in open sheds for varying periods, depending on weather conditions.

An open shed is a roofed lumber storage yard. Lumber dried to moisture contents as low as 12 to 14 percent can be stored in open sheds without significant regain of moisture. The atmospheric conditions within an open shed are the same as those outdoors except that lumber is protected from direct contact with rain and sun. A shed may be open on all sides or on one side only (fig. 10-12). Often the side facing the prevailing winds can be closed to keep out driving rain.

The shed should be located on an open, well-drained area. It should be large enough to permit rapid handling of the lumber and have a floor of gravel, crushed rock, blacktop, or concrete firm enough to support the piles of lumber and the weight of lumber-handling equipment. The roof should overhang far enough beyond the piles of lumber to protect them from driving rain and snow.

Figure 16-12—Open storage for packages of dry, surfaced lumber. (M88 0164)

Green Lumber

Green lumber can be stored for long times in open sheds without danger of serious deterioration, provided it is stickered. Such sheds protect the lumber from the sun, rain, and snow, thereby keeping end and surface checks and splits to a minimum. To obtain good air drying in open sheds, adequate spaces should be provided between the sides and ends of the stacks. By allowing this free circulation of outdoor air, lumber will dry to as low a moisture content as it does in the open air. The drying time in an open shed is usually shorter and the lumber brighter than if stored outdoors because rewetting is avoided.

Partly Dried Lumber

Open sheds afford excellent protection to partly dried lumber. If the moisture content is above 20 percent, the lumber should be stacked on dry stickers. If it is below 20 percent, it can be solid piled unless further drying is desired, in which case it should be stickered.

Kiln-Dried Lumber

Kiln-dried lumber can be well protected from sun, rain, and melting snow when stored in open sheds. An open shed will not, however, prevent regain of moisture during periods of high humidity, especially if temperatures are also high. Therefore, storage time should be limited during warm, humid weather. Lumber piles can be either solid or stickered. Solid-piled lumber will regain moisture more slowly than stickered lumber. Increase in moisture content will be greatest at the ends and in the outer tiers of a solid pile, as illustrated in figure 10-13. The effect of long-term storage in an open shed on moisture content of solid-piled, kiln-dried lumber is also shown in figure 10-9.

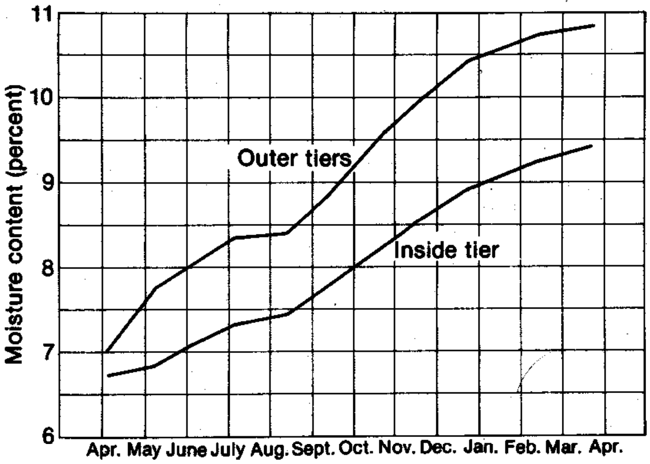

Figure 10-13—Change in average moisture content of solid-piled, surfaced 1- by 8-in Doughs-fir boards stored in an open shed. (ML88 5556)

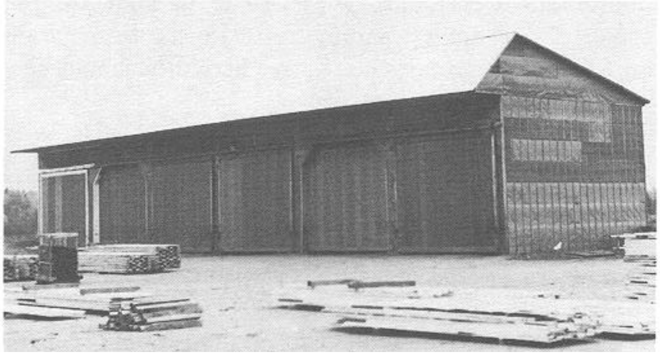

Figure 10-14—Closed, unheated storage shed at a distributing yard. (M88 0166)

Closed, Unheated Shed Storage

Closed, unheated sheds (fig. 10-14) are generally used for storing kiln-dried lumber, although they also can be used for storing green or partly dried lumber. This type of shed should be provided with reasonably tight-fitting doors. Ventilators are sometimes provided, and their need depends on the moisture content of the stored lumber and the tightness of the building.

Green Lumber

Green lumber is sometimes stored in closed sheds, although this type of storage will retard drying. The drying can be retarded enough that the growth of mold becomes a problem. Some drying capability can be added to closed-shed storage by exhaust vents and circulation fans. The solar heat that is absorbed through the roof and walls of a shed will provide some energy for drying. Care should be exercised for species that are susceptible to surface checking. If air circulation is inadequate, the temperature near the roof will rise and could cause surface checking.

Partly Dried Lumber

Partly dried lumber that is properly piled can be stored in a closed shed without developing drying defects. Lumber should be stickered if it has a moisture content greater than 20 percent. If below 20 percent and no further drying is desired, lumber can be solid piled. If further drying is desired, the lumber should be stickered, and it may be advantageous to add fans to circulate air through the lumber. High shed temperatures from solar energy generally will not cause checking or splitting in partly dried lumber because these defects usually occur when moisture contents are higher.

Kiln-Dried Lumber

The object of storing kiln-dried lumber in closed sheds is to minimize pickup of moisture. Thus, lumber should be solid piled. Although kiln-dried lumber will regain some moisture during periods of high relative humidity, the percentage regained will be less than if the lumber were stored outdoors. In dry regions, kiln-dried lumber can be stored indefinitely during hot, dry weather.

The ultimate moisture content lumber will reach in a closed shed depends on the local weather. If sunny weather prevails, the roof and walls of the shed will absorb solar radiation and heat the air inside. This lowers the relative humidity in the shed and thus the EMC conditions. Prolonged periods of sunshine can thus result in low moisture contents. Conversely, if cloudy weather prevails, moisture contents will not be much lower than in an open shed.

Lumber dried to a moisture content of 10 percent or less, and items manufactured from it, will regain moisture if stored for extended periods under conditions of high relative humidity. Excessive regain of moisture frequently results in (1) swelling of whole pieces or of certain parts, such as the ends of the pieces, (2) warping of items such as glued panels, and (3) wood or glueline failures in solid-piled items where the moisture regain is confined to the ends.

During fabrication and use, lumber and items that have adsorbed excessive moisture during storage may (1) end check and split when the high-moisture-content surfaces are exposed to low relative humidities in heated buildings, (2) shrink excessively, (3) warp, (4) suffer extension of end splits, and (5) open at glue joints.

Closed, Heated Shed Storage

If air in a shed is heated, the relative humidity and EMC are lowered as long as no additional moisture is added to the air. Thus, storage in closed, heated sheds provides excellent protection in preventing kiln-dried lumber from regaining moisture. Lumber for use in final products such as furniture and millwork that will be used in a heated environment should be stored in heated sheds. A heated shed should be reasonably tight and can be insulated or uninsulated. Heat can be supplied by any convenient means as long as the system can maintain up to 30 °F above outside temperatures. Circulation is desirable to maintain uniform temperature. Ventilators are generally not necessary but should be provided if any drying is anticipated. Temperature can be controlled by a simple thermostat that regulates the heating system.

The shed should be located on a well-drained site. Its floor should be of gravel, crushed rock, asphalt, or concrete, and it should be sufficiently firm to support piles of lumber.

Green Lumber

Green lumber is not ordinarily stored in heated sheds because the higher temperatures within the shed may cause end and surface checks or splits. If drying in a heated shed is considered, predryers should be used, as described in chapter 2.

Partly Dried Lumber

Partly dried lumber can be stored in heated sheds for further drying. Stickering and ventilating are necessary. If further drying is not desired, lumber should be stored in open or unheated sheds because it will dry further in a heated shed.

Kiln-Dried Lumber

Closed, heated sheds are ideal for storing lumber kiln dried to 12 percent moisture content or less. The desired EMC of the lumber can be regulated simply by increasing the temperature in the shed by a certain amount over the outside temperature. This can be done with thermostats that measure temperature differentials. When outside air is heated without adding moisture, even though the absolute humidity remains the same, the relative humidity decreases and thus the EMC decreases. The outside temperature and relative humidity must be known to determine the amount by which the temperature in the shed must be increased to attain a certain EMC. For example, if the outside air is at a temperature of 50 °F and is at 80 percent relative humidity, how much must the temperature in the shed be raised to attain an EMC of 6 percent? The answer can be determined by using figure 10-15. Enter the graph along the arrows that lead from 50 °F and 80 percent relative humidity to the point where they intersect. Note that this is at an EMC of about 16.5 percent and an absolute humidity of about 0.0625 pound of water per pound of dry air (at a barometric pressure of 29.92 in Hg). Since no moisture is being added to the air in the shed, the absolute humidity will remain the same as we raise the temperature. Therefore, follow the arrowed line down parallel to the absolute humidity lines to the point where it intersects the 6 percent EMC line. From this point drop straight down to the temperature axis and read the required temperature in the shed as 80 °F or a 30 °F temperature rise.

An alternative way to control conditions in a heated shed is to control the heater with a humidistat. When the relative humidity is above the set point of the humidistat, the heater will be on until the relative humidity falls to set point. For example, we know from table 1-6 of chapter 1 and figure 10-15 that to maintain an EMC of 6 percent, the relative humidity should be controlled at about 30 percent.

Conditioned Storage Sheds

Kiln-dried lumber and finished products can also be held at any desired moisture content in storage by controlling both relative humidity and temperature. This is the most costly method of controlling EMC because of the equipment involved. However, when it is desirable or necessary to maintain temperature within certain limits, then it may not be possible to maintain relative humidity simply by manipulating temperature. For example, to attain 6 percent EMC when the outside air is at a temperature of 85 °F and a relative humidity of 80 percent, the temperature must be raised to 114 °F. This temperature is unreasonable in a work area where people must spend any length of time. In this case, refrigeration equipment is required to attain 6 percent EMC at a comfortable temperature.

Treating Stored Lumber

Fungal infection and insect attack both pose serious hazards to stored lumber. Fungal infection was found to be the principal cause of degrade in a study of grade loss in l-in southern pine lumber. Insect infestation also causes serious losses in stored lumber, particularly in the warmer parts of the United States. For protection from fungi and insects, lumber may require a dip or spray treatment in a chemical solution at the storage installation. In some cases, this treatment will supplement an earlier dip or spray at the sawmill.

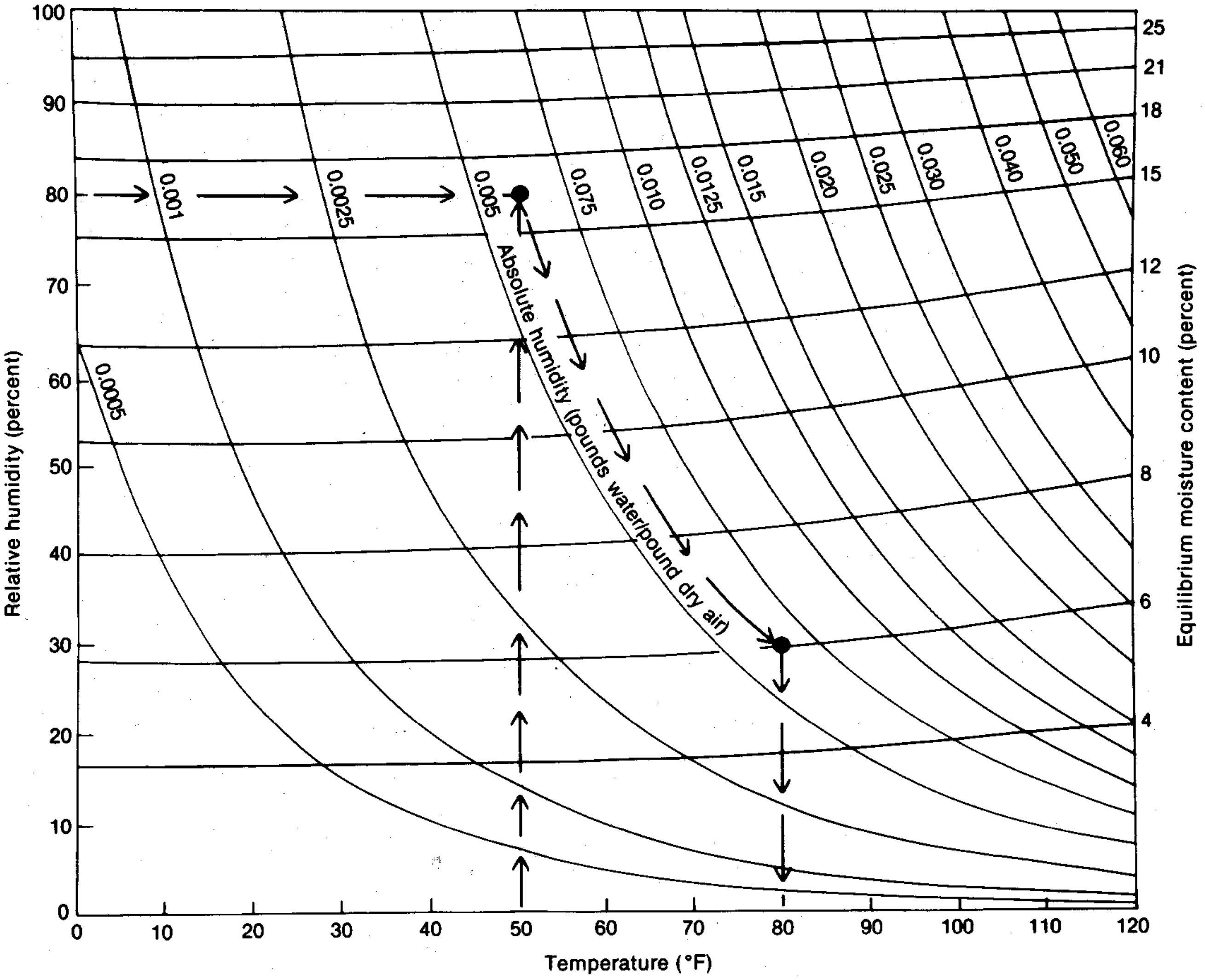

Figure 10-15—Psychrometric chart showing the relationship between temperature, relative humidity, absolute humidity, and equilibrium moisture content (EMC) of wood at a barometric pressure of 29.92 in Hg. The chart and arrowed lines illustrate the temperature rise required to attain 6 percent EMC by heating outside air originally at 50 °F and 80 percent relative humidity. (ML88 5558)

To minimize fungal and insect attacks on stored lumber, air-drying yards should be kept sanitary and as open as possible to air circulation. Recommended practice includes locating yards and sheds on well-drained ground. Remove debris, which is a source of infection, and weeds, which reduce air circulation. Piling methods should permit rapid drying of the lumber and also protect against wetting.

Open sheds should be well maintained, with an ample roof overhang to prevent wetting from rain. In areas where termites or water-conducting fungi may be troublesome, stock to be held for long periods should be set on foundations high enough to be inspected from beneath.

When Is Chemical Treatment Needed?

Prompt drying will often protect untreated lumber from attack by stain, decay, and some insects. For instance, untreated lumber uniformly below 20 percent moisture content is immune to attack by fungi. With protective storage it will keep that immunity. However, dried lumber that regains moisture to a level of more than 20 percent again becomes susceptible to stain and decay.

The sapwood of all wood species is more susceptible than heartwood to decay, stain, or insects. Therefore, the hazards are highest for woods that usually contain a high percentage of sapwood. The heartwood of such species as redwood, the cedars, and some white oaks has high natural resistance to fungi and most insects. But few products--even from these woods-are of heartwood only.

Damp weather can increase the damage from stain and decay fungi. Rainfall and humid conditions increase the hazard to unprotected wood in both open and solid piles.

Air temperature is highly important. The stain and decay fungi grow most rapidly at 70 to 90 °F, grow no more than one-fifth as rapidly at 50 to 60 °F, and cease growth at about 32 °F. As a result, wood at about 25 to 30 percent moisture content, stored in solid piles in warm weather, may show evidences of stain within a week and early decay infection within a month. The initial infections, which are not visible, probably started shortly after the wood was sawed. With temperatures of 50 to 60 °F, similar deterioration requires five or more times as long. At 32 °F or below, the lumber can remain in solid piles indefinitely without adverse effects.

High humidity favors subterranean termites but does not affect drywood termites or powder-post beetles. The influence of temperature on insect activity, however, is pronounced. Insects are inactive at temperatures of 50 °F or below but increase their activity rapidly as the temperature rises above this level. Insects will approximately double their activity with each increase of 10 ° above 50 °F, reaching maximum activity levels at about 80 °F.

When and Where to Apply Treatment

Stain and decay in lumber are normally controlled at sawmills, collection points, and drying yards by drying the wood as rapidly as possible below 20 percent moisture content. Lumber to be air dried may be treated with fungicidal solution by dip or spray before the drying period begins. Sometimes an insecticide is mixed into the solution if insects are likely to be a problem.

The layer of wood chemically protected by a dip or spray is only “skin deep” and will not stop fungi or insects that have already entered the wood. This is why stock is dipped as soon as possible after it is sawed. To illustrate how quickly the dipping must be accomplished, the safe times are estimated as follows: 1 day at temperatures of 80 °F or above; 2 days at 70 °F; 1 week at 60 °F; and 1 month at 50 °F. Longer delays at these temperatures progressively lower the benefit from surface treatments.

Generally, dip or spray treatments immediately after cutting are designed to protect green stock only when it is drying. If treated green lumber is not air dried to below 20 percent moisture content, prolonged storage may require redipping or respraying of the lumber.

Lumber properly dipped in an antistain solution at the sawmill can be stored in solid piles for up to 1 month in warm weather if further drying is not required. If longer bulk storage is anticipated, dip-treated stock should be redipped. Additional dipping can protect pines and hardwoods from stain and decay for 6 to 8 weeks in warm weather and western softwoods other than pines for 4 to 6 months.

If the lumber was not dipped at the sawmill, dipping at the storage yard may still protect it from fungi during bulk storage provided the stock is not already infected. Infection would not occur if daytime temperatures in the interval between sawing and receipt at the yard did not exceed about 40 °F. If temperatures were higher, however, fungus infection may have already taken place, and solid piling should be avoided. Instead, lumber may be dipped in a fungicidal solution and open piled.

Because a number of factors affect safe storage time, all dipped bundles should be labeled with the date on which they were treated. Representative bundles should be opened from time to time to determine the condition of the stock. Any lumber that shows signs of being inadequately protected should be designated for early use, redipped, or stickered for air drying.

How to Apply Treatment

Lumber to be dipped at the storage installation will probably be in unit packages. Thus, the dipping procedures explained here are for unit packages. When lumber is dipped, the amount of solution absorbed will be about 4 to 8 percent of the wood weight, depending on type of wood and moisture content at the time of treatment.

Treating Area and Equipment

Location of the treating plant affects the costs and efficiency of the treating operation. Ready access of the plant to packaging and storage areas-and to railroad spurs or shipping docks-will keep costs to a minimum and ensure an efficient handling operation.

Equipment for treating lumber often includes an electric hoist that runs on a monorail attached to the ridge of a long, open shed. The treating vat can be installed in or above the ground but should be located in the center of the shed. This leaves protected areas in both ends of the shed where untreated packages can be brought in or the treated packages loaded out. Dead or electrically operated rollers are often used in both ends of the shed.

The vat should be sufficiently large to admit the largest unit package to be dipped and should hold sufficient solution to treat a number of packages without replenishment. Provision also should be made for easily adding and removing the treating solution. A well-designed vat is about 1-1/2 times the height and width of the largest package to be dipped and about 3 ft longer. A drainboard wide enough to accommodate several packages should be provided at the removal side of the vat to free the hoist for continuous treating.

Some type of hold-down device, such as weights or a heavy iron cradle, is required to keep the packages submerged in the solution. Weights should be attached to the pallet that supports the packages (not to the load) in such a way as to compress the packages against the vat bottom. In fact, the boards should be compressed against one another as little as possible to allow the treating solution to penetrate between them.

The vat should be supplied from a mixing tank of known capacity. This tank shall hold extra treating solution, which can be prepared without interrupting treating operations. Steam or electrical heating coils are a desirable supplement to the mixing tank to ensure that chemicals dissolve rapidly and completely.

Dipping Operation

Packages of lumber should be submerged in the protective solution for at least 5 min and for up to 15 min if long storage periods are expected. Packages treated in a waterborne solution should be turned on edge with the board faces parallel to the sides of the vat. This can be done as the packages are placed in the vat. Packages treated with an oilborne solution need not be turned entirely on edge during treatment. However, some means should be provided to tilt the bundles as they are immersed to let air escape from the voids and to allow solution to flow in.

Packages removed from the treating solution should be drained for a sufficient time to recover most runoff. A drainage period at least as long as the treating period usually will be adequate.

Treating for Insect Control

All insects that cause damage to sound (nondecayed) lumber during storage will be either beetles or termites. Wood-destroying beetles cause annual damage amounting to $50 million in hardwood lumber and secondary manufactured products such as flooring, furniture, and millwork. Losses from termites can be much higher, although most of this loss occurs in wood in buildings; nevertheless, termites can damage lumber stored for some time in contact with the soil. Treatment may be needed to control insect damage in both dry and green wood, regardless of the wetness or dryness of the storage location.

The principal beetles that attack stored wood vary in their need for moisture. Ambrosia or pinhole beetles invade green or partially dried wood but usually are only a minor hazard in lumber stored away from forested areas or sawmills. The destructive golden buprestid beetle lays its eggs in western softwood trees, preferably Douglas-fir, but viable eggs and wood-boring larvae can persist for as long as 15 to 20 years in air-dried lumber that was not kiln dried.

Among the most troublesome and damaging insects to stored lumber are those belonging to the true powder-post beetle group because they infest wood after it is dry. These insects chiefly attack partially dried sapwood and are particularly damaging to such large-pored hardwood species as oak, ash, hickory, walnut, and pecan.

The other principal insect that might attack stored lumber is the termite. There are two general types of termites: subterranean and drywood. Practically all woods are susceptible to their attack. Subterranean termites are by far the most prevalent type in the United States. They must have contact with some source of moisture, almost always the ground. Drywood termites occur only in limited areas along the gulf and Pacific southwest coasts, particularly in Florida and southern California. Drywood termites and powder-post beetles are the only insects that primarily attack dry wood.

Properly applied treatments that are commercially available generally provide protection to stored lumber against powder-post beetles and termites. Environmentally safe boron compounds such as boric acid and borax are toxic to many wood-destroying insects and have been successfully used in the wood industries of Australia and New Zealand for over 40 years. Lumber is immersed for 1 min in a borate solution and stored under cover for 7 days. Storage permits the borate to thoroughly diffuse through and penetrate the wood and ensures excellent protection from damage by powder-post beetles. There is also considerable protection from damage by termites and brown-rot decay fungi.

It is important to realize that the dip treatments described here apply only to the protection of lumber in storage. Preservation of wood for use requires different types of solutions and methods of application.

For wood that might be treated only because of the danger of subterranean termites, a more efficient method of protecting the lumber is to treat the ground under the storage piles or sheds.

Precautions for Handling Chemicals

All treating solutions should be so handled that none, or as little as possible, gets on the skin and clothing of workers. In particular, contact of the skin with the dry chemicals should be avoided.

When lumber dipped in water solutions is to be painted, sufficient time must be allowed during storage or before painting to allow the wood to dry adequately. Only rather short drying periods will be necessary to remove excess moisture resulting from treatment with waterborne chemicals because dipping or spraying results in only a small increase in moisture content. Residual oil should be cleaned from any dry hardwood lumber to be painted.

Lumber Handling and Storage in Transit

If carelessly shipped, dry lumber can regain enough moisture to require redrying, and green lumber can stain or decay. Such waste is totally unnecessary. With proper transport procedures, even kiln-dried lumber can cross the United States or be shipped to foreign ports without any appreciable loss of quality.

Lumber moves from sawmills to locations of end use either directly or through wholesale and retail lumberyards. Softwoods are usually shipped as finished lumber. Hardwoods more often move from the sawmill to the woodworking plant as rough lumber, although kiln drying and surfacing may take place in transit. Coastal sawmills ship lumber by ocean-going vessels to domestic and foreign ports.

Present-day lumber shipments are usually unitized for mechanical handling. The strapped unit-handling packages are loaded by forklift into wide-door railroad boxcars, onto flatcars, and into trucks. Ocean-going vessels are loaded by ship gear.

Generally, when l-in dry softwood lumber is shipped in tightly closed boxcars, in enclosed trucks, or in packages with complete and intact wrappers, average moisture content changes can generally be held to 0.2 percent per month or less. In holds of ships, dry material usually absorbs about 1.5 percent moisture during normal shipping periods. If green material is included in the cargo, the moisture regain of the dry lumber may be doubled. (On deck, the moisture regain may be as much as 7 percent. However, dried lumber is seldom stowed on deck.)

Precautions are also necessary in shipping green lumber by truck or open flatcar. Air flowing over unprotected green lumber as it moves along a highway or rail causes uncontrolled surface drying that may result in severe surface checks. This is especially likely to occur with oak, maple, or beech. Green lumber of these species should be covered with a tarp or reinforced paper to prevent this uncontrolled surface drying.

Truck Transport

Considerable quantities of air-dried lumber are shipped by truck from sawmills to factories or custom kiln-drying plants. Tractor-trailer units are usually used for this purpose, and in most instances the trailer is a flatbed unit that can be loaded and unloaded by lift truck. The lumber is anchored to the trailer by chains tightened with load binders.

Few data are available on moisture changes during truck shipment. Time in transit is short, seldom exceeding a week even on longer hauls, so little change in the lumber's moisture content would be expected from atmospheric humidity. Many lumber-hauling trucks have flatbeds that are fully enclosed with canvas coverings over skeleton frameworks. When kiln-dried lumber is transported in these covered trucks during cold, moist weather, the outer boards will gain 3 to 7 percent moisture content in their outer shell. This moisture uptake can develop within a week, and such boards will give a casehardened reaction even though they were properly conditioned during kiln drying. Trucked lumber can also be wet by rain or splashed road water.

High-value, air-dried lumber is often protected by covering the load with canvas tarpaulins (fig. 10-16). Lower grade lumber is seldom protected at all, especially on short hauls. Some protection is recommended during truck transport within a wet or moist climate zone during wet periods. Precautions should also be taken when a shipment will cross several climate or elevation zones.

Figure 10-16—Packages of kiln-dried hardwood lumber on a truck trailer are covered with a tarpaulin. (M 142893)

Rail Transport

Some years ago, the Forest Products Laboratory studied the changes in moisture content of softwood lumber shipped in tight railroad boxcars from West Coast sawmills to midwestern U.S. markets. These studies involved five boxcar loads of l-in clear Douglas-fir shipped from a West Coast sawmill to the Chicago, IL, area during late winter and spring. The time in rail transit averaged 18.5 days; the shortest period was 14 days and the longest, 22 days. Average moisture content of the five carloads of kiln-dried boards at the time of loading was 8 percent, and the average gain in moisture content was 0.2 percent. These values were baaed on an average of 18 teat boards distributed throughout the boxcar load in each shipment. In another study, test boards in a carload of Douglas-fir quarter-round and crown molding, which were at 8 percent moisture content when loaded, regained 0.8 percent in moisture in a 20-day transit period from the West Coast to the vicinity of Chicago. Thus, no significant change in moisture content of dry lumber need be expected during the usual haul in tight boxcars.

A study of moisture changes in rail shipments of kiln-dried hardwood lumber was conducted by the Forest Products Laboratory. These shipments were of kiln-dried pecan lumber, transported in wide-door boxcars from midsouth Mississippi to a furniture company in North Carolina, a distance of about 900 mi. Each load of unitized lumber packages contained four test boards for moisture analysis. Test shipments were made from June through November, and the increase in moisture content was less than 0.5 percent moisture content. Conventional flatcars have become widely used for the transport of dried lumber because they can (1) save handling time and shipping cost, (2) hold twice the load of conventional boxcars, and (3) be loaded by lift trucks to save handling time. Improvements in unitized package wrapping have made it possible to obtain these advantages without much increase in moisture content, even on long hauls.

Unitized packages on flatcars are usually protected, either partially by tarpaulins or entirely by flexible, waterproof packaging that completely “tailor-wraps” each package. One common type of waterproof packaging uses composite kraft paper that is reinforced with glass fiber coated with polymer. The packaging is frequently supplied with additional reinforcement at stress points such as edges and corners. Improvements in packaging materials have made possible the shipment of kiln-dried lumber with little change in moisture content and a good retention of brightness.

Wrapping for unitized packages of lumber should be free from rips to be effective. Rain that enters through rips is held by the sheeting, and the package may act as a humidifier. If so, moisture regain may be higher than if the lumber were unprotected.

Ship Transport

Lumber is often transported overseas in ships while it is either green, partly dried, or kiln dried. A study conducted in Canada, which involved 33 shipments of l-in lumber from the Canadian west coast to five different ports, concluded that seasoned lumber stored below decks, either by itself or together with green lumber, will not undergo moisture regain of serious proportions (table 10-2). This study also indicates that well-dried lumber may undergo significant moisture regain if stored on deck, although it is not commonly stored in this way.

Similar tests were made with 2-in Douglas-fir lumber. The kiln-dried lumber had a moisture content of 9 to 10 percent when stowed. The overall average moisture gains for the seasoned 2-in lumber were as follows:

Lumber stowed below decks with dry lumber	1.3 percent
Lumber stowed below decks with green lumber	2.4 percent
Lumber stowed on deck with green lumber	4.2 percent

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Table 10-1—Equilibrium moisture content of wood, exposed to outdoor atmosphere, in the United States

	Equilibrium moisture content in different months (percent)[1]											
Location	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Portland, ME	16.9	15.5	15.8	14.8	15.0	13.4	13.9	15.5	17.2	15.4	16.3	14.9
Concord, NH	14.9	14.0	14.3	13.0	13.0	11.7	12.6	14.1	14.2	14.2	15.4	14.6
Boston, MA	13.0	12.3	12.3	12.0	12.3	10.9	11.7	12.6	12.9	12.7	13.0	11.9
Providence, RI	13.7	12.4	13.1	12.4	12.9	12.1	12.6	14.5	14.6	14.2	13.6	11.8
Bridgeport, CT	14.8	12.3	13.4	12.9	13.0	12.6	13.2	14.1	14.3	13.6	14.5	13.2
New York, NY	13.7	11.7	12.7	11.7	12.6	11.2	11.3	12.2	12.0	11.9	12.6	12.5
Newark, NJ	14.0	11.9	13.2	12.0	12.4	11.4	11.5	12.9	13.0	12.3	13.3	13.4
Wilmington, DE	15.1	12.1	13.4	12.3	13.4	12.7	12.6	12.9	14.5	13.9	14.6	13.7
Philadelphia, PA	14.3	11.3	12.4	11.9	12.7	12.0	11.7	13.5	13.3	12.3	13.0	12.9
Baltimore, MD	13.7	10.8	12.5	11.7	12.9	12.2	11.8	13.3	13.3	12.3	13.6	13.0
Norfolk, VA	13.9	12.7	13.0	12.4	13.0	13.2	13.4	14.9	14.5	14.7	14.5	14.0
Wilmington, NC	15.7	15.4	15.0	13.7	13.5	13.5	15.4	16.7	16.8	15.8	15.9	16.3
Charleston, SC	14.8	15.1	13.2	13.4	14.1	15.5	16.2	16.8	17.3	16.1	15.6	16.0
Savannah, GA	14.3	14.7	12.5	12.9	12.9	13.9	14.5	15.4	15.6	14.3	14.6	15.4
Key West, FL	14.7	14.7	14.3	12.9	13.7	14.0	14.0	13.0	14.5	16.3	15.9	14.8
Burlington, VT	14.9	14.3	14.9	13.1	13.0	11.7	11.8	13.1	14.7	14.5	14.6	14.9
Cleveland, OH	16.9	14.9	15.0	13.6	13.0	11.8	11.6	12.6	12.2	10.0	13.3	15.2
South Bend, IN	18.9	15.4	15.2	13.3	14.1	13.0	12.9	14.5	13.7	13.3	14.3	17.4
Charleston, WV	14.3	12.1	12.0	11.9	12.7	13.8	14.1	13.8	12.6	11.7	12.2	13.4
Louisville, KY	15.4	12.8	12.9	12.3	12.8	12.2	12.0	11.8	11.3	11.5	11.9	14.3
Nashville, TN	15.4	14.0	12.9	12.1	12.3	11.4	11.8	11.9	11.8	11.7	12.0	14.8
Mobile, AL	15.8	16.2	14.6	13.3	15.0	14.2	15.4	16.7	14.3	12.0	13.0	14.9
Jackson, MS	14.7	14.5	12.6	12.7	13.5	11.9	12.7	12.5	11.4	10.3	11.5	13.9
Detroit, MI	17.5	14.3	15.2	12.2	12.2	11.4	11.5	12.4	12.5	11.9	14.0	15.8
Milwaukee, WI	15.8	14.6	14.9	12.4	13.0	13.7	13.2	14.2	13.0	11.8	13.2	15.8
Chicago, IL	16.1	13.7	14.2	11.8	12.4	11.9	11.9	12.5	11.6	10.9	10.3	15.2
Des Moines, IA	16.9	16.0	14.9	12.4	12.8	13.6	13.5	13.3	11.6	10.1	12.4	16.4
Kansas City, MO	14.3	13.1	13.4	12.0	12.5	10.3	10.9	11.1	9.5	9.3	11.2	13.7
Little Rock, AK	15.7	13.6	12.7	12.5	13.6	11.7	12.0	12.5	11.2	10.6	11.8	13.7
New Orleans, LA	16.2	15.6	14.0	13.4	14.6	14.5	15.7	17.1	16.8	13.1	14.5	15.3
Duluth, MN	15.5	15.2	16.0	12.8	12.7	14.9	14.8	16.1	16.5	13.9	15.9	16.9
Bismark, ND	17.2	17.6	17.0	12.4	11.9	12.9	11.6	11.6	11.2	11.0	14.3	16.1
Huron, SD	17.0	18.0	16.0	12.7	12.1	13.0	11.8	12.2	10.1	10.2	13.4	17.6
Omaha, NE	18.0	15.5	15.2	12.2	12.6	11.3	12.1	12.9	11.3	10.4	12.4	15.7
Wichita, KS	13.7	12.4	13.0	12.0	11.9	9.9	11.0	10.5	8.3	8.5	11.9	15.5
Tulsa, OK	14.0	12.2	12.2	12.6	12.6	11.0	12.4	11.2	9.7	9.7	12.0	12.7
Galveston, TX	18.2	18.2	18.1	15.8	16.9	15.7	15.4	15.7	15.5	14.2	16.6	15.9
Missoula, MT	16.1	15.1	12.5	10.2	11.6	11.5	8.2	8.7	9.3	10.5	14.6	16.4
Casper, WY	11.0	12.3	11.5	10.3	11.2	8.4	8.6	8.1	7.0	8.2	11.0	12.8
Denver, CO	8.4	8.3	9.3	10.3	9.8	7.6	8.2	8.9	6.9	7.2	9.9	10.4
Salt Lake City, UT	14.3	12.5	12.4	10.8	9.3	7.8	7.8	7.4	7.5	9.1	12.1	15.8
Albuquerque, NM	9.2	8.1	8.0	6.9	6.3	5.7	7.9	7.7	7.1	6.9	10.5	11.1
Tuscon, AZ	8.8	7.0	7.9	6.8	5.3	4.6	8.1	8.0	5.2	5.2	7.7	8.0
Boise, ID	15.8	14.3	12.1	10.3	10.9	10.5	7.3	7.3	7.6	8.6	10.3	18.0
Reno, NV	13.2	11.3	11.0	9.4	9.0	8.6	8.0	7.8	8.9	9.6	11.3	13.4
Seattle-Tacoma, WA	21.0	18.9	16.8	14.8	14.2	15.3	13.7	14.6	14.7	17.2	18.9	18.9
Portland, OR	19.6	16.8	14.7	13.0	14.1	14.5	12.1	13.4	13.1	15.9	18.5	20.0
San Francisco, CA	18.5	14.8	14.7	16.0	14.7	15.6	15.8	16.6	15.5	15.9	16.0	16.3
Juneau, AK	19.8	20.2	17.9	15.8	16.3	14.8	16.2	18.2	21.4	—	22.0	18.6
San Juan, PR	14.7	15.3	14.4	15.2	14.6	15.7	16.2	15.7	15.7	15.7	15.5	14.7
Honolulu, HI	13.8	13.5	13.2	12.6	12.0	12.1	12.3	12.6	11.9	12.8	12.9	13.5

[1] **The values were calculated by means of average monthly temperatures and relative humidities given in Climatological Data monthly reports of the Weather Bureau and the wood equilibrium moisture content to relative humidity relationship.**

Table 10-2—Average gain in lumber moisture content during ocean shipment[1]

			Lumber moisture content increase (percent)		
Number of shipments	Shipment destination	Time in transit (days)	Stowed with dry lumber below decks	Stowed with green lumber below decks	Stowed on deck with green lumber
11	England	54	2.9	4.7	—
10	Australia	66	1.7	3.2	—
6	South Africa	85	2.2	1.8	7.6
3	Eastern Canada	47	.7	3.7	6.5
3	Trinidad	37	1.7	3.2	—
(Average)		—	1.9	3.3	7.1

[1] Lumber used was 1-in kiln-dried Douglas-fir.

Chapter 11
Energy in Kiln Drying

Chapter 11 was written by John L. Tschernitz, Chemical Engineer.

Drying of materials in general and of wood in particular is energy intensive, primarily because a high amount of energy is required to evaporate water (liquid to gas). Depending upon the type of equipment used to dry wood, the efficiency level of the operation may require one and one-half to four times the energy actually needed to evaporate the water. In addition, green wood to be dried may contain, by weight, as much as two-thirds water. Wood can be successfully dried in different types of dryers. However, even when optimally operated, the dryers may have different levels of efficiency as an inherent property of their physical design and the materials of construction, and their efficiency may also be affected by environmental factors. Certain practices or maintenance procedures may further reduce dryer efficiency. In this chapter, we discuss energy demand as related to various methods of drying, types of environmental and geographical factors, fuel, and equipment misuse.

Energy Consumption in Drying Systems

Definition of Terms

A list of symbols is provided at the end of this chapter.

Units of Thermal Energy

In English notation, the unit of energy is the British thermal unit (Btu), which is defined as the amount of energy required to heat 1 lb of liquid water 1 °F at 40 °F. Because the quantity of energy used in any one process is such a large number, the unit therm (100,000 Btu) is often substituted for Btu. Very often, energy is quoted as cost per million Btu (10^6 Btu). Some economists use an even larger unit, the quad (10^{15} Btu).

Latent Heat of Evaporation

The energy consumed at constant temperature for phase change from solid to liquid (heat of fusion) and liquid to gas (heat of evaporation) is called latent heat. For drying, the latent heat of vaporization (liquid to gas) of water is about 1,000 Btu/lb, a value that at low temperatures is a slightly decreasing function of temperature (for example, 1,054 at 70 °F to 970.3 at 212 °F). For water, the latent heat of fusion (ice to liquid) is considerably lower, 144 Btu/lb.

Heat Capacity

The heat capacity (or specific heat relative to water) of solids, liquids, and gases is by definition the amount of energy (Btu) required to heat 1 lb of material 1 °F. The actual value will differ with the physical or chemical composition of the material and again is a function of temperature. For the materials associated with drying of wood, values for heat capacity are given in table 11-1.

Heat of Adsorption

At any moisture content greater than 30 percent (fiber saturation point), the water content exists in two states: (1) water as liquid in the cellular structure of the wood and (2) adsorbed water within the wood substance--so-called hygroscopic water. The latter state represents a molecular invasion of the complex wood polymer structure. The energy associated with removing this water in drying (liquid to gas) is now greater than the latent heat of vaporization. For levels of moisture less than 20 percent, the heat of adsorption increases exponentially as the moisture content drops from 20 to 0 percent. Table 11-2 shows some values that must be added to the latent heat of vaporization. These values are sometimes referred to as the heat of wetting, so called after an experimental technique used for measurement. The values in table 11-2 are derived from an equation that approximates experimental data (Weichert 1963):

$$\Delta h_a = \exp[-14.5(M_i/100) + 6.18] \qquad (1)$$

where

Ah, is the differential heat of wetting (Btu/lb) and

M_i is intermediate moisture content (percent).

Thermal Conductivity

One property of matter is that energy flows (is transferred) from a higher to a lower temperature. For the same difference in temperature (identical areas and thicknesses), various substances will transfer energy at different rates. This variation in heat transfer rate is characterized by a thermal conductivity coefficient k, defined by means of the following equation:

$$Q = \frac{kA\,\Delta t}{\ell} \qquad (2)$$

where

Q is energy transferred (Btu/h),

At the temperature difference between hot and cold (°F),

A surface area (ft^2), and

ℓ thickness of substance (ft).

The units of k are then Btu/h/ft/°F. Some typical values of thermal conductivity are shown in table 11-1.

Sometimes the units of k are expressed differently. Equation (2) can be rearranged as

$$k = \frac{Q\ell}{A\,\Delta t}$$

putting the dimensions for k as

$$\frac{(\text{Btu/h})(\text{ft})}{(\text{ft}^2)(^\circ\text{F})} \text{ or } \frac{\text{Btu}}{\text{hr}\cdot\text{ft}\cdot{}^\circ\text{F}}$$

If ℓ and A are given in inches, then k' is given in

$$\frac{\text{Btu}}{\text{h}\cdot\text{in}\cdot{}^\circ\text{F}}$$

Therefore, $k = 12k'$.

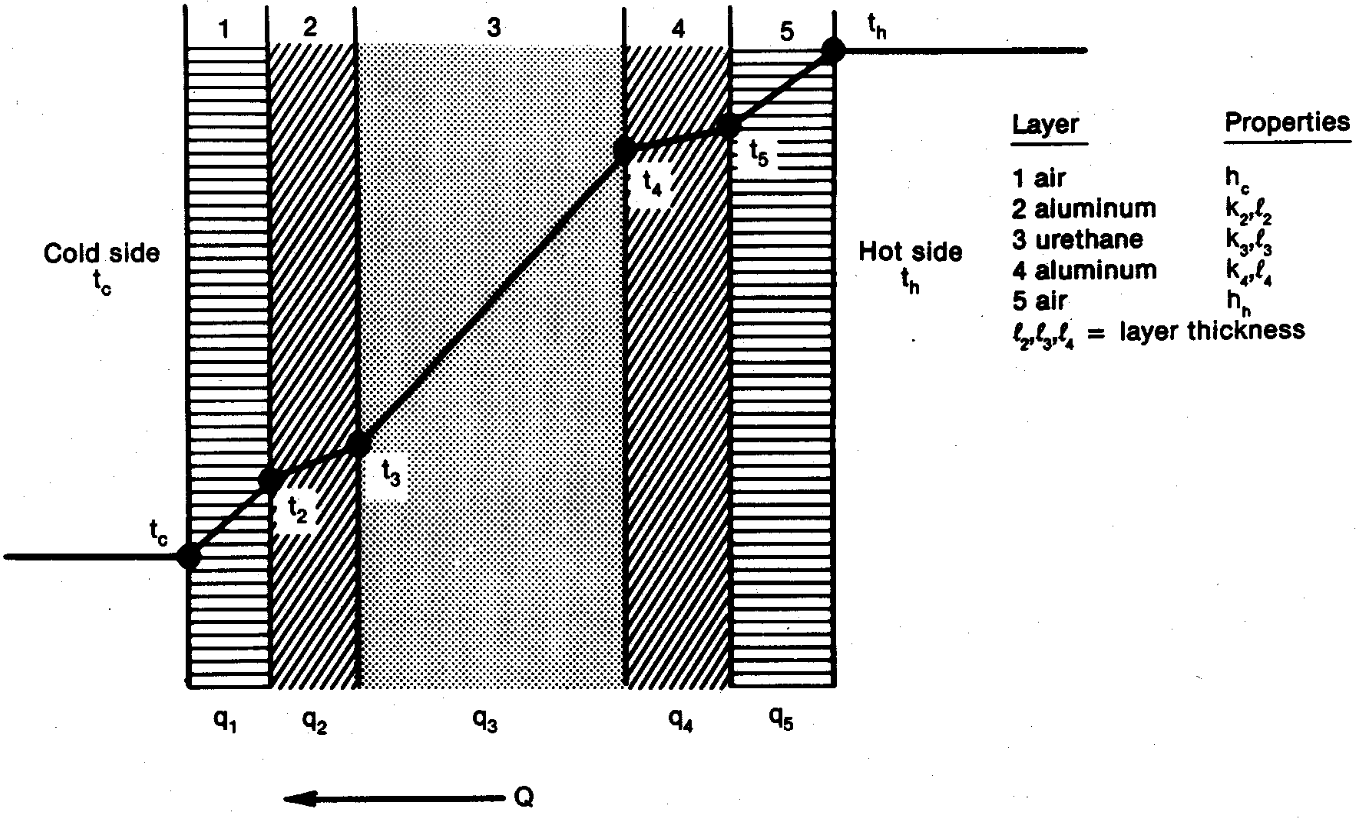


Figure 11-1—Diagram of panel construction. (ML885612)

Overall Heat Transfer Coefficient

Thermal conductivities defined by equation (2) are not directly useful in considering heat losses from dryers since in dry kiln construction, multiple layers of different materials exist in series; for example, gas, aluminum, urethane foam, aluminum, and gas. (Note: To a lesser degree, parallel layering may be used.) The more useful coefficient is the overall heat transfer coefficient *U*, defined by

$$Q = UA(t_h - t_c) \tag{3}$$

where

U is the overall heat transfer coefficient (Btu/h/ft^2/°F),

t_h air temperature within the dryer, and

t_c air temperature outside the dryer.

The coefficient U is very often expressed as an R value, where $R = 1/U$. The reason for expressing heat loss in this form is that when the characteristics of a given construction are known, the heat loss can be calculated simply by knowing the area and the difference in high (inside) and low (outside) temperature.

When manufacturer specifications (U or R values) for multilayer walls are not known, it is possible to estimate U from known thermal conductance (table 11-1) and heat transfer coefficients. In a steady-state operation (fig. 11-1),

$$Q = q_1 = q_2 = q_3 = q_4 = q_5$$

The heat flow through each layer can be expressed in the form of equation (2):

$$q_2 = \frac{k_2 A}{\ell_2}(t_3 - t_2)$$

or

$$t_3 - t_2 = \frac{q_2 \ell_2}{k_2 A}$$

and

$$q_1 = h_c A(t_2 - t_c)$$

or

$$t_2 - t_c = \frac{q_1}{h_c A} \qquad t_h - t_5 = \frac{q_5}{h_h A}$$

where h_c is heat transfer coefficient of the surface air layer outside the kiln, h_h is the heat transfer coefficient of the surface air layer inside the kiln, and

$$t_h - t_c = (t_h - t_5) + (t_5 - t_4) + (t_4 - t_3) + (t_3 - t_2) + (t_2 - t_c)$$

Substituting for temperature drops in each layer,

$$\begin{aligned} t_h - t_c &= \frac{q_1}{h_c A} + \frac{q_2 \ell_2}{k_2 A} + \frac{q_3 \ell_3}{k_3 A} + \frac{q_4 \ell_4}{k_4 A} + \frac{q_5}{h_h A} \\ &= \frac{Q}{AU} = \frac{Q}{A}\left(\frac{1}{h_c} + \frac{\ell_2}{k_2} + \frac{\ell_3}{k_3} + \frac{\ell_4}{k_4} + \frac{1}{h_h}\right) \end{aligned}$$

or

$$\begin{aligned} U &= \frac{1}{1/h_c + \ell_2/k_2 + \ell_3/k_3 + \ell_4/k_4 + 1/h_h} \\ &= \frac{1}{R_1 + R_2 + R_3 + R_4 + R_5} \end{aligned} \tag{4}$$

For the panel shown in figure 11-1, which is made of aluminum, urethane foam, and aluminum, an *R* value for the composite can be estimated with the properties given in table 11-1. It is important that consistent units for k and ℓ be used. An example of the method for calculating an *R* value using equation (4) is shown in table 11-3. It should be cautioned that this calculated *R* value may be too high when the panel has metal ends and joints (parallel layering). Under these circumstances, the walls and roofs of an assembled kiln may have greater heat losses than predicted.

Heat Transfer Concepts

Heat is transferred from one body to another by conduction, convection, and radiation.

Conduction is the energy transfer from a high to a low temperature through a medium (solid, liquid, or gas, alone or in combination).

Convection is a complex combination of heat conduction and mass flow; it is the most important form of heat transfer between solid surfaces and liquids or gases (Kreith 1965). Convection can be subclassified as free or natural convection (the physical displacement of energy by movement of material (gas and liquid) induced by density differences) or forced convection (displacement and mixing induced by fans and pumps). Free and forced convection can take place independently or in combination.

Radiation is energy transfer across transparent spaces by electromagnetic means such as infrared wavelengths. The amount of energy transferred will be controlled in conduction by temperature difference (t_2 - t_1); in convection within a medium by density differences or forced means, or both; and in radiation by the difference in the fourth power of absolute temperature $(T_2^4 - T_1^4)$.

In any system exhibiting energy transfer, any of these mechanisms may occur singly or in combination. For practical considerations of energy losses in dry kiln operation, the overall heat transfer coefficient *U* is sufficient for describing heat losses. Inside the kiln, radiation may be a factor in operating performance. Natural circulation (convection) kilns are no longer of commercial importance.

Identification of Energy Consumed in Wood Drying

Even though each individual dryer will consume different combinations and quantities of energy per unit of water evaporated, it is useful to consider energy consumption for the general case, which will help one to understand the limitations and advantages of different drying systems.

In general, all the possible elements of energy consumption and supply in wood drying that appear in various combinations in specific drying systems can be listed as follows:

1. Latent heat required to evaporate water (also heat of adsorption and possibly heat of fusion)
2. Heat loss from dryer structures by conduction from the high-temperature interior through the walls, ceiling, and floor to lower temperature regions outside

3. Heat loss associated with vent air used to remove water vapor from the dryer (and air loss from leaky dryer structures in excess of necessary venting)
4. Sensible heat (heat capacity) required to heat the lumber and building structure to drying temperature
5. Electrical energy needed for air movement
6. Energy source and delivery system

Each of these items is discussed in the following sections.

Latent Heat of Evaporation

Latent heat is directly and invariably determined by the wood volume, specific gravity, and expected percentage of moisture change (expressed on a dry basis).

$$q_a = \text{Volume} \times \text{Specific gravity} \times \rho_{H_2O} \times \lambda \times (M_o - M_f)/100 \qquad (5)$$

where

q_a is total heat (Btu) required to evaporate water from wood substance,

λ latent heat of vaporization (Btu/lb H_2O) (moisture content >20 percent),

M_o original moisture content (percent), and

M_f final moisture content (percent).

Let

$$q_a = q_f + q_b$$

where

q_f is energy (Btu) needed to evaporate free water per drying run and

q_b is energy (Btu) needed to evaporate bound water per drying run.

For final moisture contents greater than 20 percent,

$$q_b = 0$$
$$q_a = q_f$$

For final moisture contents less than 20 percent, q_b can be calculated from equation (5), substituting

where volume is total green volume charged to the kiln (ft^3), specific gravity is based on ovendry–green volume of wood (lb/ft^3), r_{H_2O} is the density of water (62.4 lb/ft^3), and

$$\lambda' = \lambda + \Delta h_a \qquad (6)$$

(see table 11-1). See table 11-2 for definition of $\bar{\lambda}'$. The variable λ is a function of temperature that can be expressed by the following equation (Keenan et al. 1969):

$$\lambda = 1,075.4 - 0.58(t - 32) \text{ Btu/lb } H_2O$$

where evaporation occurs at temperature t (°F)

Heat Loss From Dryer

The magnitude of the quantity of heat loss from the dryer will depend upon the difference in temperature between the inside and the outside of the dryer, the area of the dryer surfaces, the materials of construction, and the time of dryer operation for any batch run. Heat loss can be expressed as the sum of heat loss through various kiln surfaces at different times in the drying schedule:

$$q = \sum U_i A_i (t_2 - t_1)\theta_i \qquad (7)$$

where

q is heat loss through walls (Btu),

U_i overall heat transfer coefficient of individual dryer structural components (Btu/h/ft^2/°F),

A_i surface area of walls, ceiling, floors, and doors (ft^2),

t_2 dry-bulb temperature (°F),

t_1 exterior or ambient temperature (°F), and

q_i drying time (h).

Since the temperature of the dryer will vary with time, as by schedule, the time q will be broken into time steps: $q_1, q_2, \ldots, q_i$. Also, the U values of walls, ceiling, and floors will differ: $U_1, U_2, \ldots, U_i$. The outside surface temperature t_1 will vary night to day and the ground (floor) temperature will be higher than the outside air, as will the third wall common in tandem installations. The value t_1 will have seasonal variation for any one location and will vary according to the local climate. Wind may be a factor.

Heat Loss Associated With Vent Air

The kiln most used in wood drying is a forced convection dryer wherein air is the means used to supply heat to evaporate water as well as to remove water from the dryer as water vapor-air mixture. For operations below 212 °F, air will always be needed to vent the dryer. The energy required to heat this vent air from an ambient temperature to dryer exhaust temperature represents a big part of the energy required to dry wood; it is the reason why more than 1,000 Btu are needed per pound of water evaporated in convective dryer operation. Because air will hold more water vapor at higher temperatures, less vent air is needed at higher operating temperatures (for equal relative humidity in the vent exhaust). It is an easy task to calculate necessary venting under various conditions of operation. This is more clearly understood by looking at the psychrometric chart in chapter 1, appendix 1-A, figure 1-A-1. For any given temperature (dry bulb) and relative humidity (wet bulb or wet-bulb depression), one can define a very useful quantity, the absolute humidity H (also called the humidity ratio). The units of this term are pounds water per pound dry air. The vent air needs (volume of vent air per pound of water evaporated) can be calculated as follows:

$$V = V_{\mathrm{air}} + V_{\mathrm{H_2O}}$$

where

V is vented moisture air volume at STP (ft^3),

V_{air} vented dry air volume at STP (ft^3), and

$V_{\mathrm{H_2O}}$ vented H_2O vapor volume at STP (ft^3).

(STP is standard temperature and pressure: 32 °F, 1 atm.)

For the following derivation, let the basis be 1 lb of evaporated water, where the following definitions apply:

H_2 is pounds of H_2O per pound dry air in vent air,

H_1 is pounds of H_2O per pound dry air in ambient air,

m_a, is pounds of air needed to vent 1 lb of evaporated water, and

$$m_a = \frac{1}{\Delta H}$$

$$\Delta H = H_2 - H_1$$

$$V_{\mathrm{air}} = \frac{m_{\mathrm{a}}}{\rho_{\mathrm{air}}}$$

$$V_{\mathrm{H_2O}} = \left(\frac{H_2 m_{\mathrm{a}}}{\rho'_{\mathrm{H_2O}}}\right)$$

Then

$$V = V_{\mathrm{air}} + V_{\mathrm{H_2O}} = \frac{1}{\Delta H}\left(\frac{1}{\rho_{\mathrm{air}}} + \frac{H_2}{\rho'_{\mathrm{H_2O}}}\right)$$

where $\rho'_{\mathrm{H_2O}}$ is the density of water vapor (18/359 lb/ft^3 at STP). So

$$V = \frac{12.38 + 19.94H_2}{(H_2 - H_1)} \tag{8}$$

Heat loss in vent air q_{v} (Btu per pound H_2O evaporated) is calculated as

$$\begin{aligned} q_{\mathrm{v}} &= q_{\mathrm{a}} + q_{\mathrm{H_2O}} \\ &= m_{\mathrm{a}} C_{p_{\mathrm{air}}}(t_2 - t_1) + H_1 m_{\mathrm{a}} C_{p_{\mathrm{H_2O}}}(t_2 - t_1) \\ &= (t_2 - t_1)\left(\frac{0.241 + 0.492H_1}{H_2 - H_1}\right) \end{aligned}$$

where C_p is heat capacity (Btu/°F/lb) and $q_{\mathrm{H_2O}}$ is sensible heat of the vapor component.

It is interesting to look at venting rates and energy consumption as a function of dryer temperature and relative humidity. Using equations (8) and (9), we can now calculate V and q_{v} for a dryer operated at two relative humidities, 20 and 80 percent, and different temperature levels (dry bulb), assuming a constant ambient condition of 80 °F, 65 percent relative humidity. The values of H_2 and H_1 can be found in the psychrometric chart (ch. 1, app. 1-A, fig. 1-A-1). The resulting values of V and q_{v} are given in table 11-4.

The following example uses values V and q_{v} from table 11-4. Assume the following:

1. Ambient conditions, 80 °F, 65 percent relative humidity, 50,000 fbm red oak kiln
2. Schedule step 1,100 °F, 80 percent relative humidity (6 °F wet-bulb depression)
3. Dry wood weight (WOD) of 145,000 lb
4. Moisture content per day (DR) of 4 percent

Calculate the following:

1. Vent rate (VR) (ft^3/min, STP)
2. Energy to heat vent air (QR) (Btu/min)
3. Drying rate per minute (DW) (lb H_2O per min)

Example:

$$\begin{aligned}\mathrm{DW} &= \mathrm{DR} \times \mathrm{WOD}/(24 \text{ h/day})(60 \text{ min/h})\\ &= 0.04 \times 145{,}000/24 \times 60\\ &\approx 4.03 \text{ lb/min}\end{aligned}$$

From table 11-4,

$$\begin{aligned}V &= 687 \text{ ft}^3 \text{ (STP)/lb H}_2\text{O}\\ q_v &= 260 \text{ Btu/lb H}_2\text{O}\end{aligned}$$

Thus,

$$\begin{aligned}\mathrm{VR} &= V \times \mathrm{DW}\\ &= 687(4.03) = 2{,}767 \text{ ft}^3 \text{ (STP)}\\ \mathrm{QR} &= q_v \times \mathrm{DW}\\ &= 260(4.03) = 1{,}048 \text{ Btu/min}\end{aligned}$$

Sensible Heat Demand of Wood and Kiln Structures

By definition, sensible heat is that energy required to raise the temperature of either solids, liquids, or gases without phase-change or chemical reaction. In the case of wood drying, the sensible heat is consumed by raising the wood from ambient temperature to the final discharge temperature as it leaves the kiln. The kiln structure and furnishings must be heated from some low level (ambient and completely cooled) or from an intermediate temperature if little time has elapsed between dryer ‘batch operations. Therefore, the sensible heat demand can be stated as

$$q_s = q_{\mathrm{wood}} + q_{\mathrm{kiln}} \tag{10}$$

where q_s is total sensible heat.

For wood being dried, the sensible heat is

$$q_{\mathrm{wood}} = \mathrm{WOD} \times C_{p_\mathrm{M}}\, \Delta t_s$$

where

C_{p_M} is heat capacity of the combined wood and water at moisture content step MC_i and

At, is temperature change between steps in drying schedule,

with

$$C_{p_\mathrm{M}} = C_{p_\mathrm{w}} + C_{p_{\mathrm{H_2O}}}\mathrm{MC}_i$$

where

C_{p_w} is average heat capacity of ovendry wood (C_{p_w} = 0.327 Btu/°F/lb dry wood),

$C_{p_{\mathrm{H_2O}}}$ heat capacity of liquid water ($C_{p_{\mathrm{H_2O}}} = 1.0$), and

MC_i percent moisture content at any step change.

From this equation, one observes that the heat capacity of wet wood is far greater than that of dry wood; for example, at 100 percent moisture content, C_p = 1.327, while at 10 percent, C_p = 0.427 Btu/lb/°F.

For the kiln structure, the sensible heat is

$$\begin{aligned}q_{\mathrm{kiln}} &= C_{p_\mathrm{M}}\, \Delta t\\ \Delta t &= t_2 - t_1\end{aligned}$$

where

t_2 is kiln temperature,

t_1 is beginning kiln temperature, and

$$C_{p_\mathrm{M}} = \sum (C_{p_1 m_1} + C_{p_2 m_2} + \cdots + C_{p_i m_i})$$

$C_{p_i m_i}$ represents the product of the heat capacity and weight of individual kiln components other than drying wood.

Electrical Energy for Air Movement

Electric power is needed for air circulation in most dryer types. For any given kiln, the actual power demand for circulating the air will vary with air velocity, package width, board roughness, and sticker thickness. An increase in velocity and package width and a decrease in sticker thickness all will increase the power demand. For one sticker thickness and package width, a maximum attainable velocity exists that corresponds to the maximum power load. A 1-hp motor at maximum load would dissipate 2,547 Btu/h, or 0.746 kW/h. Electrical energy is converted to thermal energy within the dryer in two ways. If the motors are external to the dryer, then only the work done in air movement is converted to heat by friction (air and bearing friction) minus the work of venting. The heat generated within the motor is lost to the external environment (approximately 10 percent of power input). If the motors are within the dryer compartment, then all the electrical consumption appears as heat.

Steam Generations and Delivery Loss

For indirect fire, steam is the most frequent heat transfer medium from fuel to dryer for heating. (Oil, water, and rarely air are other possible heat transfer media.) The closed system of fuel burner, boiler tubing, and steam delivery to finned tube heating coils (condensate return to the boiler) is the drying system most frequently encountered. The net heat as delivered to the kiln represents a fraction of the total energy available in the fuel (heating value) charged to the boiler. Delivery losses may be incomplete combustion, high fuel moisture content, high stack gas temperatures, steam supply line losses, and boiler heat losses. The delivered energy may be of the order of only 75 percent of the heating value of the fuel used.

Energy Demand in Various Wood Drying Systems

Six distinct energy-consuming factors in drying systems were identified in the previous section. Each of these may be present in different dryers to varying relative and absolute degrees. The various drying systems to be considered, in decreasing frequency of use, are as follows:

1. Forced-air convective drying-most common drying method
2. Air drying followed by kiln drying
3. Predrying followed by kiln drying
4. Dehumidification drying
5. Solar drying (alternately with supplemental energy)
6. Vacuum drying (platen, radiofrequency, and forced air)
7. Platen pressdrying

Forced-Air Drying

Latent Heat of Evaporation

Latent heat demand is unalterably dependent only upon the amount of water evaporated. Thus, the magnitude of the quantity of latent heat is only a function of the initial and final moisture content, species, density, temperature of evaporation, and total volume of wood in the dryer. To reduce fuel use for this purpose, one would have to lower initial moisture content by air drying. The quantity of latent heat may represent 20 to 60 percent of the energy consumed within the drying chamber.

Heat Loss

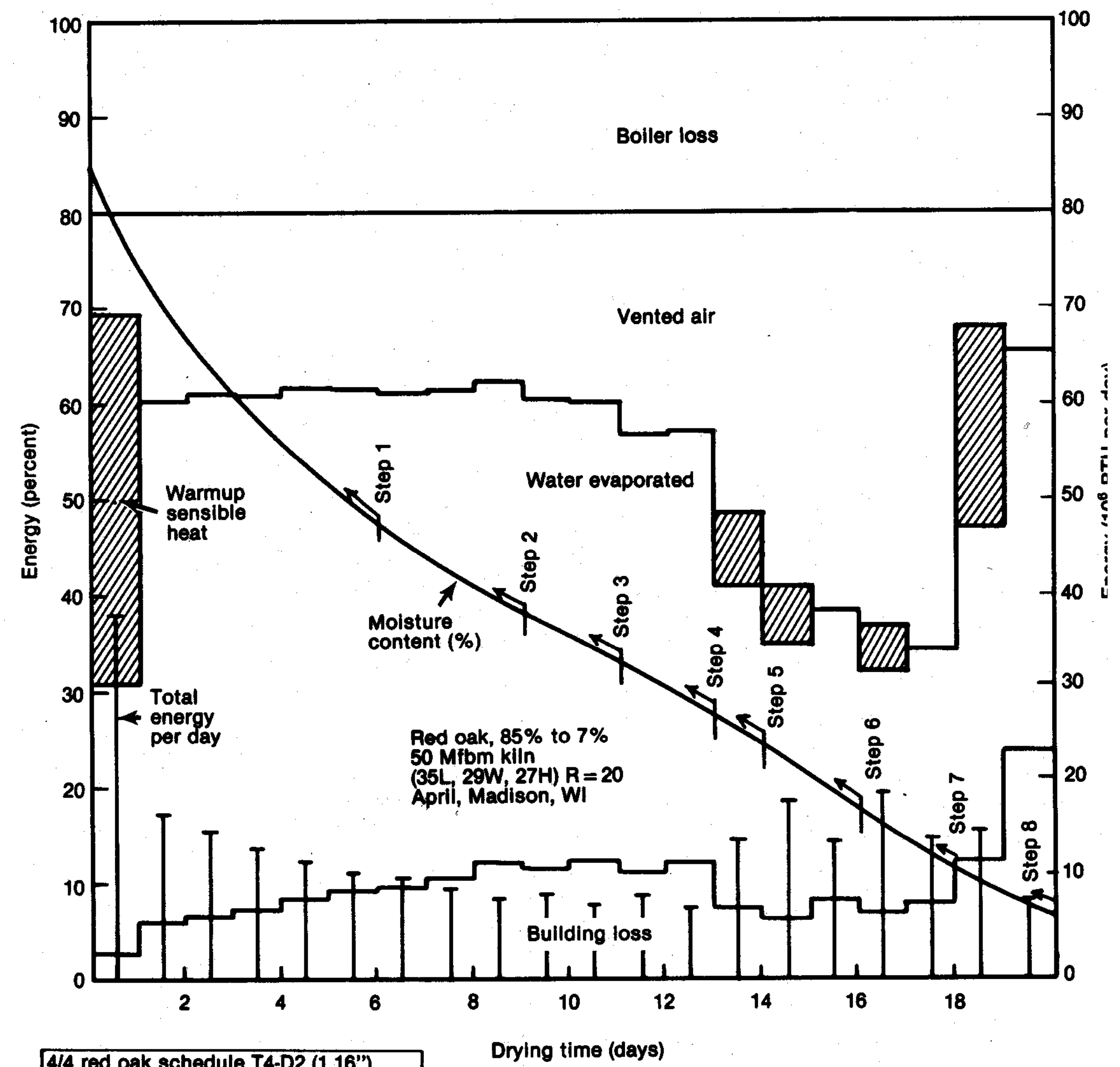
One can reduce heat loss through the kiln walls by selecting equipment with good insulating proper-ties (high *R* values), which remain so under the harsh conditions found in most kilns. Special care must be considered in roof construction and maintenance. Heat loss through the floor can be substantial, and insulation applied during construction will be worth the extra cost. From equation (7) one can see that for given walls, roof, and floor construction, the important factors that increase heat loss are area, temperature difference (inside compared to outside), and time. To a lesser extent, increased air velocity within and outside the dryer will also increase heat loss. Small dryers have a larger heat loss per board foot because of the greater surface area per unit volume (related to wood capacity). The greater the temperature difference, the greater the heat loss; the longer the drying time at a given temperature, the greater the heat loss. While high dryer temperatures will increase the heat loss per unit time, the shorter drying time may actually reduce the total loss.

Vent Air *Loss*

Vent air loss may represent more than 25 percent of the total fuel consumed in the drying system. In equation (9) for heat loss in vent air, note that the important factors in necessary venting are temperature difference between the dryer and makeup air, and the difference in absolute humidity between inside and makeup air. Thus, the most efficient operation of a given system is high absolute humidity in the dryer (vent gases), along with low ambient humidity. Examples are shown in table 11-4. It should not be overlooked that equation (9) assumes that the desired humidity is established by controlled venting-no steam spray humidification. If the dryer is not tight (air leakage) or is overvented because of bad control, steam will be introduced to maintain the humidity, resulting in greater energy demand.

Sensible Heat

When the dryer is cold and charged with cold or even frozen lumber, energy is consumed in heating the wood and kiln structure, in addition to drying and venting. This places the maximum demand on the heat delivery system; this energy demand is shown as a calculated example in figure 11-2 for the case of a red oak hardwood dryer. If the capacity of the heat supply system, such as boiler, is insufficient, the heat-up period will take longer. The current boiler capacity in forced convection kilns is about 30 Btu/fbm/h for hardwoods and 225 Btu/fbm/h for high-temperature drying of softwoods. It is in the nature of the thermodynamics of the dryer operation that the energy required to heat



4/4 red oak schedule T4-D2 (1.16")

Step 1	110°F	4°F	87% RH
Step 2	110°F	5°F	84% RH
Step 3	110°F	8°F	75% RH
Step 4	110°F	14°F	60% RH
Step 5	120°F	30°F	31% RH
Step 6	130°F	45°F	20% RH (modified)
Step 7	140°F	50°F	14% RH
Step 8	180°F	50°F	26% RH

Figure 11-2—Energy partition in kiln drying 4/4 red oak. (ML88 5613)

the wood is actually utilized in evaporating the water (the latent heat of evaporation decreases with increased temperature). The actual sensible heat loss is associated with the final temperature of the dry wood and the kiln structure.

Electrical Energy for Air Movement

Sufficient air movement through a stickered package of lumber is important for optimum drying of wood. The level of airflow (or velocity) needed will depend upon the rate of drying (high or low temperature), width of package, sticker thickness, and hardwood in contrast to softwood operation.

Particularly in hardwoods and thicker stock, the need for high air velocity (for effective heat transfer and removal of evaporated water) is diminished as the average moisture content of the wood drops below 30 percent. Electric power consumption (cost) can be reduced if one can control the air velocity over wide limits. Three fan laws allow us to better understand this phenomenon. These laws are based on constant air density and fan configuration.

1. The total airflow (volume per unit time) is directly proportional to the speed of the fan in revolutions per minute (rpm).
2. The total pressure (head) is proportional to the square of the speed.
3. The power (bhp) is proportional to the cube of the speed.

Thus, if fan speed is reduced by 50 percent, the air velocity will be reduced 50 percent; the pressure head will drop by 75 percent, and the shaft power by 87.5 percent. In actual performance tests under controlled conditions of axial and centrifugal fans of many designs, these three fan laws have been proven correct. The combined motor-shaft-drive system may reduce the power savings as predicted by the third (cubic) fan law. Actually a properly designed electronic speed control fan-motor unit will come close to obeying the cubic law-all other factors being constant. There will always be bearing losses, but for the most part, these are small. With adequate speed control of the motor-drive system, power savings approaching 87.5 percent can be realized with a 50-percent reduction in fan speed. The efficiency of a fan-motor installation, expressed as cubic feet per minute of delivered air per horse power, will vary with actual fan design even though the cubic law still applies.

In the past, velocity could be reduced economically only by using two-speed motors or variable mechanical drives (dc motor controls were possible, but costly). With the advent of solid-state electronic controls, it is now possible to vary the speed of ac induction motors as well as dc motors. For ac induction motors operating at constant voltage, the speed can be changed by varying the frequency and current. This is generally called-a variable frequency drive (VFD) system.

Likewise, for fans with dc drives, the electronic controls can vary the voltage to change the speed. This system is called a silicon-controlled rectifier (SCR) system. The advantage of a VFD over a SCR system is that it can be retrofit into existing drying systems without replacing the motor. However, the operator should be aware that some fan motors are not immediately compatible with this modification, and care must there fore be taken to ensure that the fan works properly. Moreover, the state of the art is such that the solid-state circuits are not as stable at first as they are represented to be. The cost of frequent breakdown and subsequent repair can negate any power savings. Be cause of these disadvantages, the SCR has become the "old workhorse" for continuous speed control.

Energy Source and Delivery System

Forced-air convection dry kilns can be heated indirectly with steam as supplied to heating coils (indirect fire), directly by heated gases (direct fire), or with low-pressure exhaust steam (to coils) from a turbogenerator assembly (co-generation).

Indirect fire.—The most common source of steam for drying is a boiler. The capacity of boilers is frequently rated as boiler horsepower. In terms of Btu, one boiler horsepower is 33,446 Btu/h. For a 50,000-fbm hardwood package dryer, the supply design is about 30 Btu/fbm/h, or 45 boiler hp. For high-temperature southern pine drying, 100,000-fbm capacity, the boilers are sized to at least 225 Btu/fbm/h or more than 675 boiler hp. The choice and availability of fuels for a boiler system affect energy costs. The current and past trends in fuel costs are shown in table 11-5.

The most desirable furnace boiler system would be capable of using multiple fuel types to take advantage of changing fuel markets, but capital costs would be prohibitive. Depending upon completeness of combustion, excess combustion air, stack gas temperature, and fuel moisture content, the net energy delivered to the dryer as steam should be between 70 and 80 percent. The operator should always be vigilant that the boiler system is operating at highest efficiency. For wood-waste fuel, a special concern is the moisture content of the fuel because this affects combustion efficiency and net available energy. Figure 11-3 shows the realized heating values of wood-waste fuels as a function of moisture content (wet basis).

Although indirect fire (steam) is inherently less efficient than direct fire, the advantage of a steam source for equalizing and conditioning cannot be ignored.

Direct **fire.-**As the name implies, direct fire sends the products of combustion from a burner assembly into the dryer chamber. Direct-fired systems inherently use leas fuel than indirect-fired systems. Natural gas burners are particularly efficient for dry kilns when gas supplies are cheap and available. Wood-waste direct-fired burners are also available. Ash flyover into the kiln can occur with this type of burner; burner design and performance need to be scrutinized. In certain improper installations, kiln fires have occurred.

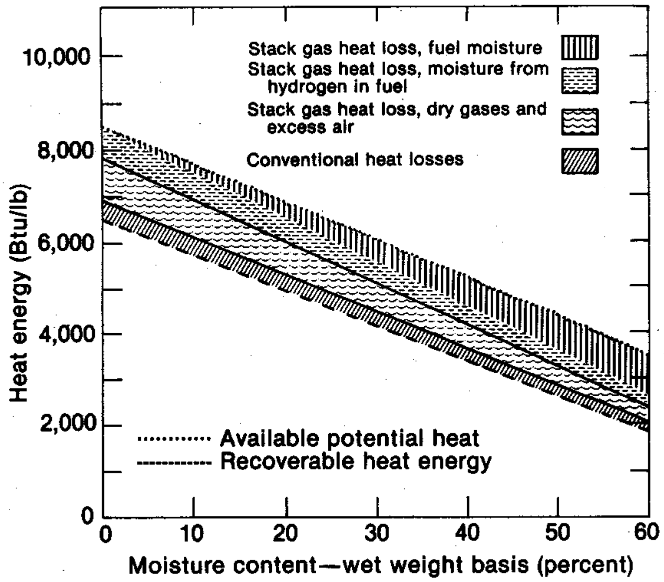


Figure 11-3—Recoverable heat energy, available potential heat, and heat losses for a typical wood fuel per pound of wet fuel at various moisture contents. The fuel has a higher beating value of 8,500 Btu per pound. The higher heat value considers all the water of combustion to be liquid. The combustion heat recovery system is assumed to be operating with 40 percent excess air and a stack gas temperature of 500 °F, fairly typical for an industrial system. A constant conventional heat loss factor of 4 percent and complete combustion are also assumed (Ince 1979). (ML88 5611)

Co-generation.—A growing trend in U.S. industry is co-generation: high-pressure steam is generated in the boiler system, passed through a turbine generator combine for production of electricity, and then exhausted as low-pressure steam for process heating. This system is particularly attractive to firms using large quantities of thermal energy since it can result in 8 to 20 percent savings in energy costs. However, the usefulness of co-generation must be evaluated on a case-by-case basis, taking into account local fuel supply and costs, along with electric power rates.

Air Drying Followed by Kiln Drying

Standard practice, at least in hardwood drying, has been air drying followed by kiln drying. The merits and limitations of air drying are discussed by Rietz (1971). Our concern here is energy savings. If one considers our previous example of a 50,000-fbm kiln as operated in Madison, WI, which dries red oak from different moisture levels, various total energy demands can be calculated for various lumber thicknesses. These calculated estimates are shown in table 11-6. The energy savings are self-evident.

Predrying Followed by Kiln Drying

In recent years, utilization of predryers for controlled "air drying" of hardwoods has increased markedly. The quality of predried wood is high; kiln capacity needs are reduced; and, depending upon the season, kiln location, and construction, energy needs are somewhat reduced compared to those for drying green lumber. Wall insulation, tightness of the building structure, and controlled ventilation are important. The biggest design problem other than structural integrity, however, is air distribution in heated structures holding 1 million fbm of lumber. These dryers operate in the range of 85 to 95 °F. All the elements of increased energy demand are present here.

Dehumidification Drying

Discussions of dehumidification drying appear in chapters 2 and 7. Since the only energy source for drying is electric power, the cost of this method of drying will depend upon local electric rates, which vary greatly in different parts of the United States. With the use of a closed refrigeration cycle, the net energy to evaporate 1 lb of water is much less than 1,000 Btu, but one must carefully understand the manner in which fuel savings are expressed. A system that uses 50 percent less energy is not a bargain, because the energy costs three times as much as other types of fuel; electric power costs are as high as \$20 per 10^6 Btu. Because of the closed heat cycle, a tight kiln is very important. Modern kilns of this design operate at temperatures as high as 160 °F.

Solar Drying

Analysis has shown that caution should be exercised in considering solar energy as a means of lowering fuel costs; it is not a universal solution to energy economy in wood drying. Therefore, no one should leap into investing in such technology without carefully considering engineering criteria as well as the overall operating economics (Tschernitz 1986).

For a passive solar kiln with supplemental energy, the following observations are made:

1. Supplemental energy is necessary to maintain rapid, consistent drying times for all seasons and all locations.
2. The solar surfaces (if the kiln is essentially a greenhouse in design) should be isolated from the dryer during night hours and during periods of low solar influx.
3. The proper choice of solar cover material and kiln wall insulation is critical for enhanced fuel savings.

4. The winter months in the north are not practical for solar drying on any scale.
5. The supplemental energy could be direct-fired gas when available. Wood waste, while cheaper, might require greater capitalization. Electrical energy is too expensive under most circumstances, although capitalization would be low. Use of electrical energy in conjunction with dehumidification is possible (Chen 1982), but capital costs would be high in this case.
6. The choice of collector surfaces in practice is restricted to roof and south wall (or sloping roof only).
7. The solar kiln, operating as a scheduled dryer, requires that conditioning for stress relief must be provided in some manner at the end of the drying cycle.
8. For noncommercial operators who require only limited quantities of dried wood, a small do-it-yourself unit (1-fbm capacity) built with low-cost materials (such as discarded glass and plastic) would be useful even in the northern tier of states for at least 9 months of the year, even without supplemental energy (Bois 1977, Rice 1987).

Vacuum Drying

For many years, vacuum drying has been promoted periodically. The energy used to evaporate the water can be conductive heating (platen), radiation (radiofrequency or infrared), cyclic heating (forced air), or a combination thereof. No vent air is required; some conducted heat losses occur. The cost of energy, primarily electrical, is high and capital costs are also high. Vacuum drying has a special place in the family of drying systems as a fast method for drying thick lumber.

Platen Pressdrying

In platen pressdrying, heat loss from high-temperature presses is high although no vent air is lost. High-pressure steam or oil is required. Energy is not the principal concern in the choice and operation of platen drying equipment. The virtue of this method is speed and the possible improved properties of wood products.

Practical Applications

Energy Partition in a Typical Forced-Air Kiln

If the drying rate of a given wood species can be established as a function of temperature, relative humidity, moisture content, board thickness, and air velocity (which is related to sticker thickness), then it is possible to model the energy consumption at any time in the drying schedule. The results of such computations for a red oak drying system are shown in figure 11-2, where the percentage of each day's energy demands (which varies day to day) attributed to evaporation of water, vent losses, building losses, and boiler losses are plotted as a function of time. The average moisture content of the lumber after each day is also shown, along with total energy demand per day.

This analysis assumes a 50,000-fbm dryer (35 ft long, 29 ft wide, 27 ft high) as operating in Madison, Wisconsin, in the month of April, which approximates the average condition for a total year. The example is for 4/4 red oak, using a slightly modified T4-D2 schedule (ch. 7).

The highest daily energy demand is the first day warmup; as the drying rate decreases, the building energy loss fraction tends to increase; as the dryer temperature is raised and relative humidity drops, the vent energy losses are greater. This pattern will shift winter to summer and location to location. Building energy losses will be higher in the winter; vent losses will increase with very humid ambient conditions. The seasonal change in total energy demand can be illustrated by a series of calculated total energy demands for a small (1,000 fbm) and a large (30,000 lbm) 4/4 red oak dryer as operated in different regions of the United States. In addition, the reduced energy consumption of a large kiln compared to a small one is indicated. These calculated values are shown in table 11-7.

Fuel Costs and Delivery Systems

The economic criterion for choosing fuel for drying wood is not simply the fuel with the lowest cost. If that were the case, solar energy would be the first choice, electricity the last. The values shown in table 11-5 are average past and current fuel costs. There is much local variation in fuel costs, particularly electricity, as well as seasonal variation.

To select the best fuel, the most obvious consideration is the uninterrupted availability of fuel supply. The next and perhaps most important consideration is the capital cost of the equipment needed to convert the fuel into useful thermal energy. This is best illustrated in converting solar energy, where collecting the energy and its intermittent delivery are currently too costly for most large-scale commercial wood drying operations.

Thirdly, the efficiency of converting fuel to useful energy must be examined. A low-cost conversion apparatus may consume much larger quantities of fuel and may therefore incur a higher net operating expense. Direct fire (wherein the combustion gases enter the drying chamber) should be considered since a steam boiler and heat transfer coils are not needed. Direct fire is therefore 100 percent efficient, requiring less capital investment.

Decreasing drying time may be a way to compensate for a high-cost fuel such as electricity. For example, rapid drying of the stock in an electrically heated dryer may be economically sound considering both the quantity and value of the product and sharply reduced drying time.

Maintaining High Energy Efficiency in Existing Forced-Air Kilns

The following list (McMillen and Wengert 1978) should be helpful in increasing the efficient use of energy during kiln drying.

1. Use as much air drying or forced-air drying as possible--preferably drying to 25 percent moisture content or less. While this will reduce the cost of energy, lumber degrade costs may offset the energy savings.
2. Do not use steam spray or water spray in the kiln except during conditioning. Let the moisture coming out of the wood build up the humidity to the desired level. Steam may have to be used, however, when very small wet-bulb depressions are required.
3. Repair and caulk all leaks, cracks, and holes in the kiln structure and doors to prevent unnecessary venting and loss of heat. Make sure the doors close tightly, especially at the top. Temporarily plug any leaks around the doors with rags, and order new gaskets, shimming strips, or hangers if necessary. In a track kiln, use sawdust-filled burlap bags to plug leaks around tracks. Adjust and repair the vents so that they close tightly.
4. For brick or cinder block kilns, maintain the moisture vapor-resistant kiln coating in the best possible condition. This will prevent the walls and the roofs from absorbing water. Dry walls conduct less heat to the outside.
5. For outdoor aluminum kilns only, paint the exterior walls and roof a dark color to increase the wall temperature by solar heat and reduce heat loss from the kiln. Check to ensure that weep holes are open, not plugged. Painting would be disastrous on permeable walls like brick or cinder block.
6. In many kilns, more heat is lost through the roof than through the walls, and much of this loss is due to wet insulation. To reduce heat loss, consider installing a new roof or repairing an old one. Add more insulation if necessary. Make sure the interior vapor barrier or coating is intact (see suggestion 4).
7. Install or repair baffling to obtain high, uniform air velocity through the lumber and to prevent short circuiting of the airflow. This pays off in saving energy. Reverse air circulation every 6 h only.
8. Research has shown that in the early stages of drying, high air velocities (more than 600 ft/min) can accelerate drying. In the late stages, low velocities (250 ft/min) are as effective as high velocities and use less energy. Therefore, adjust fan speeds during a run if possible.
9. Calibrate and check the recorder-controller for efficient operation. Kiln conditions should not oscillate between periods of venting and steam spraying, and venting and steaming should not occur at the same time.
10. Check the remainder of the equipment. Are traps working? Do traps eject mostly hot water with little, if any, steam? Do valves close tightly? Are heating coils free of debris? Is valve packing tight? Is there adequate water for the wet bulb?
11. Accurately determine the moisture content of the drying wood. Do not waste energy by overdrying be cause the sample boards do not represent the load. Try to plan the loads so that when they are sufficiently dry, someone will be available to shut off the kiln (and, if possible, to unload, reload, and begin a new run). Do not allow a kiln load of dry lumber to continue to run overnight or through a weekend.
12. Unload and reload the kiln as fast as possible, but avoid doing this until the air temperature has warmed up from the morning low temperature. Do not cool the kiln unnecessarily.
13. In a battery of adjacent kilns, avoid unloading or loading a kiln while the adjacent kiln is at 180 °F or another high temperature.
14. During nonuse periods, close all valves tightly and keep kiln doors closed. Use a small amount of heat, if necessary, to prevent freezing of steamlines and waterlines.
15. Use accelerated schedules where possible. Check chapter 7 for schedules for accelerating schedules with minimum risk. The higher the drying temperature, the more efficient the energy use.
16. If possible, reduce the length of time used for conditioning; some low-density hardwoods can be conditioned in 6 h.

17. Finally, check with the manufacturer of your equipment to determine if steam pressures can be lowered or gas or oil flow rates reduced during periods of constant dry-bulb temperature. For top efficiency, check the burner as well.

Heat Recovery From Vent Air

The use of air-to-air heat exchangers-sometimes called economizers-for partial recovery of energy exhausted from dry kilns has been considered for decades. Cost, efficiency, and design problems made practical application of these units marginal. Rising fuel and boiler costs, along with new designs, again make such recovery systems worth considering. In addition to conventional air-to-air heat exchangers, “heat pipes” (Perry and Chilton 1973) have recently been incorporated into a new design for dry kilns with interesting possibilities.

List of Symbols

A	surface area (ft^2)
C_p	heat capacity (Btu/°F/lb)
C_{p_w}	heat capacity of ovendry wood (Btu/°F/lb dry wood)
DR	moisture content per day (percent)
DW	rying rate per minute (lb H_2O/min);
H_1	pounds water per pound dry air in ambient air
H_2	pounds water per pound dry air in vent air
h_c, h_h	heat transfer coefficient of surface air layers
$\boldsymbol{k}$	thermal conductivity (Btu/h/ft/°F)
ℓ	substance thickness (ft)
M_f	final moisture content (percent)
M_i	intermediate moisture content (percent)
M_o	original moisture content (percent)
m_a	pounds air needed to vent 1 lb evaporated water
MC_i	moisture content at any step change (percent)
Q	energy (Btu/h)
q	heat loss through walls (Btu)
q_a	energy needed to evaporate water in wood (Btu)
q_b	energy needed to evaporate bound water per drying run (Btu)
q_f	energy needed to evaporate free water per drying run (Btu)
q_{kiln}	sensible heat of kiln structure (Btu)
q_s	total sensible heat (Btu)
q_v	energy lost in vent air (Btu)
q_{wood}	sensible heat of wood (Btu)
QR	energy needed to heat vent air (Btu/min)
T	absolute temperature (°R)
t_c	air temperature outside dryer (°F)
t_h	air temperature within dryer (°F)
U	overall heat transfer coefficient (Btu/h/ft^2/°F)
V	vented moist air volume at standard temperature and pressure (ft^3)
V_{air}	vented dry air volume at standard temperature and pressure (ft^3)
V_{H_2O}	vented water vapor volume at standard temperature and pressure (ft^3)
VR	vent rate (ft^3/min)
WOD	dry wood weight (lb)
ΔH	pounds water per pound dry air evaporated ($H_2 - H_1$)
Δh_a	differential heat of wetting (Btu/lb)
Δt	temperature difference (°F)
Δt_s	temperature change between steps (°F)
q	drying time (h)
λ	latent heat of evaporation (Btu/lb)
λ'	$\lambda + \Delta h_a$
r	density (lb/ft^3)
r'_{H_2O}	density of water vapor

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Table 11-1—Heat capacity and other properties of selected materials

Material	Heat capacity (C_p) (Btu/lb/°F)	Thermal conductivity (k) (Btu/h/ft/°F)	Density (p) (lb/ft³)	Specific volume (1/p) (ft³/lb)
Water				
Solid	0.46	1.28	57.2	0.0175
Liquid	1.00	0.375	62.4	0.0160
Gas	0.492	0.0142	[1]0.0373	26.8
Wood	[2]0.327	0.11	35	0.0286
Air	0.241	0.0174	0.081	12.4
Steel	0.11	25	489	0.002
Concrete	0.21	0.47-0.81	130	0.007
Aluminum	0.21	100	170	0.005
Urethane foam		0.02		
Stainless steel	0.11	7	510	0.002
Copper	0.092	220	559	0.001

[1] 14.7 lb/in²: 212 °F.
[2] Dry Wood.
[3] 14.7 lb/in²: 32 °F.

Table 11-2—Differential heat of wetting and latent heat of bound water at 150 °F[1]

Moisture content (percent)	Differential heat of wetting (Δh_a) (Btu/lb)	Latent heat of evaporatio (Btu/lb)[2]	
		λ'	$\overline{\lambda'}$
20	27	1,034	1,034
15	55	1,062	1,048
10	113	1,120	1,072
8	151	1,158	1,094
6	203	1,210	1,117
4	270	1,277	1,144
2	360	1,367	1,1[illegible]5
1	416	1,423	1,2

[1] For moisture contents less than 20 percent.
[2] λ = 1,007 Btu/lb H_2O at 150 °F
$\lambda' = \gamma + \Delta ha$ Btu/lb H_2O removed at M_i
$\overline{\lambda'}$ = Btu/lb H_2O removed in the internal MC of 20 percent to M

Table 11-3—Calculated R value for aluminum panel

Panel[1]	[2]h_i	k_i	P_i	$1/R_i$	R_i
Cold air side (1)	1.5	—	—		0.667
Aluminum layer (2)	—	100	0.0156 (3/16 in)	6,369	0.0002
Urethane foam[3] layer (3)	—	0.02	0.333 (4 in)	0.0606	16.50
Aluminum layer (4)	—	100	0.0156 (3/16 in)	6,369	0.0002
Hot air side (5)	0.6	—	—		0.16666
					[4]R = 17.33

[1] Numbers in parentheses correspond to notation in Figure 11-1.

[2] Gas film heat transfer coefficient, h_i (Btu² ft·h °F).

[3] The thermal conductivity k_i of urethane foams will vary with mode of manufacture.

[4] Reciprocal of R is U = 1/R = 0.058 (Btu/ft²·h °F).

Table 11-4—Vent rates and associated heat losses per pound of water evaporated at various dryer temperatures and relative humidities[1]

Dryer temperature (°F)[2]		Absolute humidity		Vent rate[3] (ft³/lb H_2O evaporated)	Vent heat loss[4] (Btu/lb H_2O evaporated)
^{t}DB	^{t}WB	H_2	$H_2 - H_1$		
DRYER RELATIVE HUMIDITY OF 80 PERCENT					
100	94	0.034	0.019	687	260
120	113	0.066	0.051	269	194
140	132	0.117	0.102	144	145
160	151	0.216	0.201	83	98
180	170	0.430	0.415	50	60
200	190	1.090	1.075	32	28
DRYER RELATIVE HUMIDITY OF 20 PERCENT					
100	70	0.0085	—	—	—
120	82	0.0161	0.0011	11,645	9,020
140	95	0.0250	0.0100	1,288	1,488
160	110	0.045	0.0300	446	661
180	127	0.072	0.0570	242	435
200	135	0.118	0.103	143	289

[1] Ambient temperature (t_1) is 80 °F, relative humidity is 65 percent, and H_1 = 0.015 pound H_2O per pound dry air.

[2] DB is dry-bulb temperature (t_2): tWB is wet-bulb temperature.

[3] Equation (8).

[4] Equation (9).

Note: For total energy loss in the vent gases, add the latent heat of evaporation of water, λ, to this value, q_v.

Table 11-5—Fuel costs

Fuel type	Industrial fuel costs per 10^6 Btu				Energy per unit supply (Btu)
	1967[1]	1979[2]	1982[3]	1986[4]	
Power (electric)[5]	$1.20-4.40	$11.70	$17.56	$19.35	1 kW (3,414 Btu/h/kW)
Coal	0.16-0.35	1.25	1.66	1.53	10,500 Btu/lb
Oil no. 6	0.25-0.85	3.07-3.40	4.75-5.50	2.99-3.47[6]	138,700 Btu/gal
Natural gas	0.18-0.60	2.80-3.00	3.27-5.21	2.90-4.72	1,030 Btu/ft[3]
Liquid propane (LP)	0.33-0.60	4.50	8.10-11.50[7]	6.17-7.36[7]	92,400 Btu/gal
Wood waste (50 percent moisture content, wet basis)[8]	—	0.50-2.00	0.50-2.00	0.50-2.00	3,400 Btu/lb[9]
Solar	0	0	0	0	1,000-1,900 Btu/day/ft[2] [10]

[1] Data from Chemical Weekly 101.83, October 28, 1967.
[2] Data from Monthly Energy Review, Department of Energy, February 1980.
[3] Data from Monthly Energy Review, Department of Energy, March 1982.
[4] Data from Monthly Energy Review, Department of Energy, November 1986.
[5] 1967, 0.4-1.5¢/kWh; 1986, 6.59¢/kWh.
[6] Oil no. 2.
[7] Local supplier (Madison, WI).
[8] *Forest Service, large local variation in cost.*
[9] Ince 1979.
[10] United States. (Horizontal surface. Add 1,000 for June.)

Table 11-6—Total energy demand for kiln drying air-dried red oak

Lumber Size[1]	Energy demand[2] at various levels of initial moisture content		
	30%	50%	80%
4/4 (1.156)	2.54 (8)	3.92(15)	5.58(20)
5/4 (1.438)	2.69(11)	3.97(20)	5.81(27)
6/4 (1.688)	2.78(13)	4.09(25)	6.09(36)
8/4 (2.250)	3.50(23)	5.02(41)	6.88(56)

[1] Green size.
[2] Energy (10^6 Btu/thousand fbm) required to dry lumber to 7 percent moisture content for the average climate in Madison, WI, by schedule T4-D2 for 4/4 and 5/4 lumber and schedule T3-D1 for 6/4 and 8/4 lumber. Numbers in parentheses indicate drying days.

Table 11-7—Energy demands for a low-temperature drying schedule for 4/4 red oak in three regions of the United State

Kiln size (1,000 fbm)	Package height[2]	Energy demand (10^6 Btu/thousand fbm)			
		Annual average	January	July	Difference
SOUTHWEST (PHOENIX, AZ)					
1	1	5.93	7.92	3.88	4.04
30	2	4.06	4.06	2.45	1.61
SOUTHEAST (ATLANTA, GA)					
1	1	7.34	9.05	5.93	3.12
30	2	4.41	4.64	3.74	0.90
NORTH CENTRAL (INTERNATIONAL FALLS, MN)					
1	1	9.51	13.11	6.42	6.69
30	2	4.67	5.96	3.50	2.46

[1] Without fan energy; 28-day schedule, maximum temperature 120 °F.
[2] Package height in terms of number of packages.

Glossary

This glossary includes generally accepted definitions of a limited number of terms currently used in wood-drying literature. It also includes closely related terms that are not fully defined in their special application to present-day drying in most dictionaries or glossaries.

The following abbreviations are used throughout this manual.

Btu	British thermal unit
COD wt	Calculated ovendry weight
DB	Dry bulb
EMC	Equilibrium moisture content
fbm	Board feet (foot board measure); although it is not used in this manual, MBF is a commonly used term for thousand board feet
FSP	Fiber saturation point
MC	Moisture content
OD wt	Ovendry weight
RH	Relative humidity
sp. gr.	Specific gravity
WB	Wet bulb
WBD	Wet-bulb depression
wt	Weight

The glossary was compiled by R. Sidney Boone, Research Forest Products Technologist.

Absorption, liquid—The taking in or imbibing of a liquid.

Adsorbed water—In context of wood drying, adsorbed water is held in wood substance by hygroscopic or molecular attraction. (Syn: bound water)

Air, entering—Heated air just as it enters the kiln loads of lumber.

Air, fresh—Air brought into the dryer to replace vented air.

Air, laminar—In kiln drying, airflow across the lumber, parallel to the stickers, which is very smooth and layered, with no eddies or swirls; generally considered a condition in which velocity is too low to produce an optimum drying effect.

Air, leaving—Air just after it leaves the kiln loads of lumber. It is usually at a lower temperature than the entering air.

Air, short circuiting of—See Short circuiting of air.

Air, turbulent—In kiln drying, airflow across the lumber, parallel to the stickers, which is not layered and has fluctuations creating definite eddies and swirls; generally considered preferable to laminar flow for optimum drying.

Air binding—The presence of air (generally in pockets) in steam coils and traps, which interferes with the normal flow of steam and condensate.

Air drying—See Drying, air.

Air reversal—Changing the airflow to flow in the opposite direction through a load of drying lumber or products.

Air travel, length of—The distance between the entering- and leaving-air sides of the kiln charge.

Air velocity—The speed at which air moves, generally measured in feet per minute.

Air volume—The total amount of air occupying or moving through a given space, generally measured in cubic feet.

Anemometer—An instrument for measuring air velocity.

Annual growth ring—The growth layer put on a tree each year in temperate climates, or each growing season in other climates; each ring includes springwood and summerwood.

Baffle—A piece of canvas, metal, or wood used for deflecting, checking, or otherwise regulating the flow of air.

Load—A rigid or flexible panel placed to minimize the amount of air short-circuiting over, under, and between the kiln loads of lumber or other wood products.

Balance—An instrument used for measuring mass or weight and often used in weighing moisture content sections and kiln sample boards.

Bark—Outer layer of it tree, which consists of a thin, living inner part and a dry, dead outer part that is generally resistant to moisture movement.

Bastard sawn—Lumber in which the annual growth rings make angles of 30° to 60° with the surface of the piece.

Blue stain—See Stain, blue.

Bolster—A piece of wood, generally a nominal 4 in. in cross section, placed between stickered packages of lumber or other wood products to provide space for the entry and exit of the forks of a lift truck.

Bow—The distortion in a board that deviates from flatness lengthwise but not across its faces.

Boxed heart—The term used when the pith falls entirely within the outer faces of a piece of wood anywhere in its length. Also called boxed pith.

Bright—A term applied to wood that is free from discolorations.

British thermal unit (Btu)—The amount of heat necessary to raise 1 lb of water 1 °F in temperature.

Bulb—The temperature-sensitive part of a thermostatic control system.

Control—The sensing part of the controlling system, located in the kiln, which contains a temperature-sensitive liquid, gas, or electronic sensor.

Controlling dry—The bulb that controls the dry-bulb temperature.

Controlling wet—A bulb, kept completely covered at all times with a clean, water-saturated wick or porous sleeve, which automatically controls the wet-bulb temperature.

Double-end control—Control bulbs, usually located in each longitudinal half of the kiln, which control kiln temperatures for their respective zone, independent of each other.

Dual control—Two bulbs of a Y-shaped control system. They are usually located on each kiln wall directly opposite each other and control the temperature of the entering air regardless of the direction of air movement.

Recorder—The temperature-sensitive part of a system that records but does not control kiln conditions.

Recorder-controller—A bulb attached by means of a capillary tube to a recording-controlling instrument.

Zone control—A bulb or sensor that controls the temperature within a zone.

Bypass pipe or duct—A pipe or chamber that permits air, steam, or water to be diverted from their regular channels.

Cam—A rotating plate so cut that the edges act as a guide for a pin rolling along the edge. In drying control instruments, the pin is employed to control temperatures and/or moisture conditions in the drying chamber.

Cambium—The one-cell-thick layer of tissue between the bark and wood that repeatedly subdivides to form new wood and bark cells.

Capacitance, electrical—The property of an electrical conductor or configuration of conductors that allows it to store potential energy in the form of an electrical field.

Capillary action—The combination of solid-liquid adhesion and surface tension by which a liquid is elevated in a vertical tube or moved through a cellular structure.

Casehardening—A condition of stress and set in wood in which the outer fibers are under compressive stress and the inner fibers under tensile stress, the stresses persisting when the wood is uniformly dry.

Casehardening, reverse—A final stress and set condition (in lumber and other wood items) in which the outer fibers are under a tensile stress and the inner fibers are under a compressive stress as a result of overconditioning.

Cell—A general term for the minute units of wood structure, including wood fibers, vessel segments, and other elements of diverse structure and function, having distinct cell walls and cell cavities.

Charge—See Kiln charge.

Chart, recorder—A sheet, usually circular, on which a graphic record of kiln temperatures is transcribed.

Check—A lengthwise separation of the wood that usually extends across the rings of annual growth and parallel to the wood rays. Checks result from drying stresses.

Surface—A check starting on a wide-grain surface and extending into the interior of a board.

End—A check starting on an end-grain surface and extending along the length of a board.

Internal—Checks originating in the interior of a piece of wood or extensions of surface and end checks.

Circulation, air—The movement of air within a kiln by either natural or mechanical means.

Direction of—The direction of movement of air through the kiln charge, expressed as longitudinal, transverse, or vertical.

Forced—The movement of air within a kiln by mechanical means.

Longitudinal—Air movement through the kiln charge to be expressed as front to rear or rear to front.

Natural—The movement of air within a kiln by natural means. Reversible. Capable of change in the direction of air movement.

Transverse—Air movement through the kiln charge from wall to wall to be expressed as right to left or left to right.

Vertical—Air movement through the kiln charge from top to bottom or bottom to top.

Co-generation—The simultaneous generation of electricity and low-pressure steam for on-site use, such as in drying.

Coil header (or manifold)—A pipe fitting to which a number of pipes are connected on one side.

Coil, intermittent operation of—The alternate opening and closing of the valve that controls steam flow into the coil.

Coil, pipe—One or more runs of pipes, the function of which is to heat the air in the kiln.

Booster—A supplementary coil, usually located between tracks of a multiple-track kiln, used to add heat to air that has already moved across a trackload of lumber.

Ceiling—A coil placed near the kiln ceiling to warm the ceiling and roof, thus preventing moisture condensation.

Double-end—Coils usually extending half the length of the kiln from both ends and usually operating as separate units.

Multiple-return-bend header—A coil usually with the discharge header located below the supply header, the pipes running back and forth with a 180° elbow at the bends.

Plain header (horizontal or vertical)—A coil consisting of a supply and discharge header at opposite ends with the pipes running from one to the other.

Single-return-bend header (horizontal or vertical)—A coil with the discharge header usually located under or on the side of the supply header, the pipes running from the supply header to a 180° bend and back to the discharge header.

Coil radiating surface—The entire uninsulated surface area of a heating coil.

Collapse—The severe distortion or flattening of single cells or rows of cells in wood during drying, often evidenced by a caved-in or corrugated appearance of the surface of the piece.

Compression failure—Rupture of the wood structure resulting from excessive compression along the grain. It may develop as a result of bending in the living tree or during felling. In surfaced lumber, compression failures appear as fine wrinkles across the face of the piece.

Compression wood—Abnormal wood formed on the lower side of branches and inclined trunks of softwood trees. It has relatively wide, eccentric growth rings with little or no demarcation between springwood and summerwood and more than normal amounts of summerwood. Compression wood shrinks more than normal wood longitudinally, causing bow, crook, and twist.

Condensate—Water formed by the cooling of steam.

Conditioning—See Stresses, relief of.

Conditioning treatment—A controlled high temperature-high relative humidity condition used in a dry kiln after the final stage of drying to bring about a uniform moisture distribution in the boards and to relieve drying stresses.

Conduction, heat—Transmission of heat through or by means of a conductor.

Controller—An instrument that automatically controls kiln temperatures.

Convection, heat—Transfer of heat from heating coils to lumber by means of air.

Course, lumber—A single layer of lumber.

Crib—A stickered kiln truckload of lumber usually stacked onto kiln trucks and kiln bunks to make a load 6 to 10 ft wide, 10 to 16 ft high, and as long as the lumber being stacked.

Crook—A distortion of a board in which the edges deviate from a straight line from end to end of the board.

Cup—A distortion of a board in which there is deviation from flatness across the width of the board.

Cycle, heating—The time intervening between successive openings of a control valve.

Cycle, temperature—The time between the maximum and minimum temperatures during a heating cycle.

Decay—The decomposition of wood substance by fungi.

Advanced (or typical)—The older stage of decay in which the destruction is readily recognized because the wood has become punky, soft and spongy, stringy, ringshaked, pitted, or crumbly. Decided discoloration or bleaching of the rotted wood is often apparent.

Incipient—The early stage of decay that has not proceeded far enough to soften or otherwise perceptibly impair the hardness of the wood. It is usually accompanied by a slight discoloration or bleaching of the wood.

Defects, drying—Any irregularity occurring in or on wood, as a result of drying, that may lower its strength, durability, or utility value.

Degrade, kiln—A drop in lumber grade that results from kiln drying.

Dehumidification kiln—See Kiln, dehumidification.

Density—The weight of a body per unit volume.

Depression, wet-bulb—The difference between the dry- and wet-bulb temperatures.

Desorption—The loss of adsorbed (hygroscopic) moisture from wood to the surrounding air.

Desuperheater—A device for removing from steam the heat in excess of that required for saturation at a given pressure. In kiln drying, atomized water injection is often used to eliminate the superheat from the steam employed for humidification.

Dew point—The temperature at which steam or water vapor begins to condense.

Diamonding—A form of warp in which the cross section assumes a diamond shape.

Diffuse-porous wood—A hardwood in which the pores tend to be uniform in size and distribution throughout each annual ring or to decrease in size slightly and gradually toward the outer border of the ring.

Diffusion—Spontaneous movement of heat, moisture, or gas throughout a body or space. Movement is from high to low points of temperature or concentration.

Direct fired—A method of heating a dry kiln where the hot gases produced by burning gas, oil, or wood waste are discharged directly into the kiln atmosphere.

Dry-bulb temperature—The temperature of the air indicated by any type of thermometer not affected by the water vapor content or relative humidity of the air.

Drying, air—Process of drying lumber by natural conditions in a yard or in an open unheated shed.

Drying, precision kiln—Process of drying wood in which controlled procedures are followed in order to obtain a stress-free product that has a desired moisture content and has suffered a minimum loss in strength.

Drying in transit—The partial or complete kiln drying of lumber by a drying facility located between the shipping and fabrication points.

Drying rate—The amount of moisture lost from the lumber per unit of time.

Duct, air—A rectangular, square, or circular passageway to conduct air.

Electrodes—In testing wood for moisture content, devices made of an electrical-conducting material for connecting wood into the electric circuit of an electric moisture meter. In high-frequency heating, metal plates used to apply the electric field to the material being heated.

Insulated—In testing wood for moisture content, special electrodes for use with resistance-type electric moisture meters that are coated with an insulating material to limit or control the point of contact between the electrode and the wood.

End check—See Check, end.

End coating—A coating of moisture-resistant material applied to the end-grain surface to retard end drying of green wood or to minimize moisture changes in dried wood.

Equalization—Bringing the pieces of lumber in a kiln charge to nearly uniform moisture content. See Treatment, equalization.

Equilibrium moisture content—The moisture content at which wood neither gains nor loses moisture when surrounded by air at a given relative humidity and temperature.

Evaporation—The change from the liquid to the vapor form.

Extractives—Substances in wood that are not an integral part of the cellular structure and can be removed by solution in hot or cold water, ether, benzene, or other solvents that do not react chemically with wood substance.

Fan

Centrifugal fan—A device for moving air by means of a rotating wheel or impeller, which gives a centrifugal action to the air being moved. Frequently used for pressure venting.

Deck fan—Fan mounted with fan impeller horizontally oriented in a horizontal panel opening, such as a floor or ceiling opening.

Disk or propeller fan—An axial-flow fan with the air flowing through the impeller parallel to the shaft upon which the impeller is mounted. The impeller blade is designed to deliver about the same volume of air in either direction of rotation.

Pitch—The angle a fan blade is set with respect to the axis of the propeller fan shaft.

Shroud—Flanges around the wall opening for a disk fan impeller that give support to the wall and provide protection for the impeller and personnel.

Fiber, wood—A comparatively long (≤1/25 to 1/3 in), narrow, tapering hardwood cell closed at both ends.

Fiber saturation point—The stage in the drying or wetting of wood at which the cell walls are saturated with water and the cell cavities are free from water. It normally applies to an individual cell or group of cells, not to whole boards. It is usually taken as approximately 30 percent moisture content, based on the weight of ovendried wood.

Flat-sawed—Lumber sawed in a plane approximately perpendicular to a radius of the log. See Grain.

Flitch—A portion of a log sawed on two or more sides and intended for remanufacture, as into lumber or veneer.

Fluctuation, steam pressure—Variation of steam **pressure.**

Flue, vertical—A vertical space, usually 6 in or less in width and extending the length and height of a kiln truckload or package of lumber.

Grain—The general direction of the fibers in wood or lumber. When used with qualifying adjectives, it has special meanings concerning the direction of the fibers or the direction or size of the growth rings. Specific terms for fiber and growth ring direction are as follows:

Cross grain—Grain deviating from a line parallel to the sides of the piece.

Diagonal grain—A form of cross grain resulting from sawing at an angle with the bark of the log.

Interlocked grain—A form of spiral grain in which the fiber direction gradually alternates from right-hand to left-hand spiral and back again in adjacent groups of annual rings.

Spiral grain—A form of cross grain that results during the growth of the tree; the fibers take a spiral course about the trunk instead of the normal vertical course.

Straight grain—Grain parallel to the sides of the piece.

Coarse grain—wood in which the growth rings are wide or have major differences in density and color between springwood and summerwood.

Edge grain (or vertical grain)—The grain in lumber produced by quartersawing so that ‘the edges of the growth rings are exposed on the widest faces of the piece, and the rings form angles of 45° to 90° with the widest faces.

Fine grain—Wood in which the growth rings are narrow and inconspicuous.

Flat grain—The grain in lumber produced by flat sawing so that the tangential faces of the growth rings are exposed on the widest faces of the piece and the rings form angles of less than 45° with the widest faces.

Green lumber (or grass green)—Lumber cut from freshly felled trees.

Growth rate—The rate at which a tree has laid on wood, measured radially in the tree trunk or in the radial direction in lumber. The unit of measure in use is the number of annual growth rings per inch.

Hardwoods—Woods produced by one of the botanical groups of trees that have broad leaves in contrast to the needles or scalelike leaves of the conifers or softwoods. The term has no reference to the actual hardness of the wood.

Heartwood—The wood extending from the pith to the sapwood, the cells of which no longer participate in the life processes of the tree. Heartwood may be infiltrated with gums, resins, and other materials that usually make it darker and more decay resistant than sapwood.

Heat

Conduction—The transfer of heat within a material or from one material to another in contact with it.

Consumption—In kiln drying, the total heat required to heat the wood and the kiln structure and to evaporate the water from the wood, as well as heat losses, including venting.

Convection—The transfer of heat to or from a material by reason of the mass movement of a fluid or gas in contact with it. In kiln drying wood, air is generally used as the medium of exchange.

Exchanger—Normally a device for transferring heat from one fluid or gas to another without allowing them to mix. Examples: fin pipes, radiators.

Latent heat of evaporation—The heat required to change water into steam without a temperature change and at constant pressure; for example, water at 212°F and at atmospheric pressure changes to steam at the same temperature by adding 970.3 Btu/lb.

Loss—The amount of heat lost by transmission through the building walls, roof, doors, floor, and vents.

Radiation—The transfer of heat by waves through space by reason of a temperature difference existing between two bodies. In common terminology in kiln drying, all forms of heat transfer are often lumped into one term--radiation of heat.

Sensible heat—n kiln drying, the amount of heat required to raise the kiln and lumber to drying temperature. (Syn: enthalpy)

Total heat—The latent heat of the water vapor in the air-water vapor mixture plus the sensible heat of the mixture.

Transfer coefficient—An experimentally derived number for a particular system that quantifies the rate of heat exchange between two zones.

High-temperature drying—Use of dry-bulb temperatures of 212°F or more.

Honeycombing—Checks, often not visible on the surface, that occur in the interior of a piece of wood, usually along the wood rays. See Ring failure.

Humidity, absolute—The weight of water vapor per unit volume of space.

Humidity, relative—Ratio of the amount of water vapor present in the air to that which the air would hold at saturation at the same temperature. It is usually considered on the basis of the weight of the vapor, but for accuracy it should be considered on the basis of vapor pressures.

Hygrometer—An instrument for measuring relative humidity, often consisting of dry-bulb and wet-bulb thermometers.

Hygroscopicity—The property of a substance that permits it to adsorb and retain moisture.

Hysteresis— The tendency of wood exposed to any specified temperature and relative humidity conditions to reach equilibrium at a lower moisture content when absorbing moisture from a drier condition than when losing moisture from a wetter condition.

Implosion— The caving in of kiln doors and/or walls because of a sudden marked decrease in pressure below atmospheric within the kiln. Normally occurs at kiln startup with very cold lumber or when restarting after fan failure early in a run.

Indirect fired—A method of heating a dry kiln where a hot fluid (steam, water, or oil) flows into the kiln in pipes and gives off its heat to the kiln atmosphere through a suitable radiating surface.

Infiltration, cold air—The uncontrolled and inadvertent entry of cold air into the dryer through cracks in the walls and ceiling, or leaky doors, or openings other than the fresh-air intake.

Juvenile wood—The initial wood formed adjacent to the pith, characterized often by lower specific gravity, lower strength, higher longitudinal shrinkage, and different microstructure than mature wood.

Kiln—A heated chamber for drying lumber, veneer, and other wood products in which temperature and relative humidity are controlled.

Automatically controlled—A dry kiln in which drying conditions are controlled by the action of thermostats.

Compartment—A dry kiln in which the total charge of lumber is dried as a single unit. At any given time, the temperature and relative humidity are uniform throughout the kiln.

Conventional-temperature—A kiln for drying lumber and other wood products typically operated in the range of 110 to 180°F.

Dehumidification—A type of kiln in which the moisture removed from the lumber, or other wood product, is condensed out of the circulating air, which is reheated instead of being exhausted to the atmosphere.

Elevated-temperature—A kiln for drying lumber and other wood products typically operated in the range of 110 to 211°F.

Forced-circulation—A dry kiln in which the air is circulated by mechanical means.

High-temperature—A kiln for drying lumber and other wood products operated at temperatures above 212°F.

Low-temperature—A kiln for drying lumber or other wood products typically operated in the range of 85 and 120°F.

Manually controlled—A dry kiln in which drying conditions are controlled by the manual operation of valves and ventilators.

Multiple-track—A dry kiln equipped with two or more tracks.

Natural-circulation—A dry kiln in which air circulation depends on the power of gravity and the varying density of air with changes in its temperature and moisture content.

Package-loaded—A trackless compartment kiln for drying packages of stickered lumber or other wood products. The dryer usually has large doors that can be opened so that the kiln charge can be placed in or removed from the dryer by forklift trucks.

Progressive—A dry kiln in which the total charge of lumber is not dried as a single unit hut as several units, such as kiln truckloads, that move progressively through the kiln. The temperature is lower and the relative humidity higher at the entering end (green end) than at the discharge end (dry end).

Reversible-circulation—A dry kiln in which the direction of air circulation can be reversed at desired intervals.

Side-loaded—See Package-loaded.

Single-track—A dry kiln equipped with one track.

Track-loaded—A compartment kiln for drying stickered lumber that is stacked on kiln trucks, which are rolled into and out of the kiln on tracks.

Vacuum—A compartment kiln in which lumber is dried at less than atmospheric pressure either continuously or intermittently during the drying cycle.

Kiln charge—The total amount of lumber or wood items in a dry kiln.

Kiln charge, mixed—Same as kiln charge but composed of more than one species or thickness of lumber or wood items.

Kiln drying—Process of drying lumber in a dry kiln.

Kiln leakage—The undesirable loss of heat and vapor from a kiln through badly fitted doors and ventilators or through cracks in the walls and roof.

Kiln run—The term applied to the drying of a single charge of lumber.

Kiln sample—A section 30 in or more in length cut from a sample board and placed in the kiln charge so that it can be removed for examination, weighing, and testing.

Controlling—Some of the wettest samples used to control the drying. The number depends on the total number of samples used and the composition of the kiln charge.

Driest—The kiln sample with the lowest moisture content.

Fastest drying—The kiln sample that loses the largest amount of moisture in a given period.

Pocket—A space provided for the kiln sample in the kiln packages of lumber.

Slowest drying—The kiln sample that loses the least amount of moisture *in* a given period.

Weight, current—The weight of a kiln sample at given times during the drying process.

Weight, final—The weight of a kiln sample after the completion of drying.

Weight, green (initial, original)—The weight of a kiln sample prior to kiln drying regardless of its moisture content.

Wettest—The kiln sample with the greatest amount of moisture.

Knot—That part of a branch that has become overgrown by the body of a tree. The shape of the knot depends on the angle at which the branch is cut.

Laminar air—See Air, laminar.

Loading, cross-piled—Lumber piled on kiln trucks and placed in a dry kiln with the long axis of the load perpendicular to the length of the kiln.

Loading, end-piled—Lumber piled on kiln trucks and placed in a dry kiln with the long axis of the load parallel to the length of the kiln.

Longitudinal—Generally, the direction along the length of the grain of wood. A longitudinal section may be a plane either tangential or radial to the growth rings.

Lumber, kiln-dried—Lumber that has been dried in a dry kiln to a specified moisture condition.

Lumber, shipping-dry—Lumber and other wood products that have been air or kiln dried to a sufficiently low moisture content to prevent stain, mold, and decay in transit; generally taken to be 25 percent moisture content or less.

Lumber storage room—A room maintained within specified equilibrium moisture content limits so that lumber stored in it will not gain or lose moisture beyond fixed limits.

Makeup air—Ambient air that replaces vent air used to exhaust water vapor being released within the dryer.

Meter, moisture—An instrument used for rapid determination of the moisture content in wood by electrical means.

Mineral streak—An olive to greenish-black or brown discoloration of undetermined cause in hardwoods, particularly hard maples; commonly associated with bird pecks and other injuries; occurs in streaks usually containing accumulations of mineral matter.

Moisture content of wood—Weight of the water contained in the wood, expressed as a percentage of the weight of the ovendried wood.

Average—The percentage of moisture content of a single piece of wood or the sum of the moisture contents of a number of pieces divided by their number.

Core—The moisture content of the inside part of a moisture section remaining after a shell one-fourth the thickness of the section has been removed.

Determination of—The testing of lumber to determine the amount of moisture present. This is usually expressed in terms of percent of the ovendry weight.

Find—The moisture content of the wood at the end of kiln drying.

Green—The moisture content of wood in the living tree or freshly sawn wood.

Initial—The moisture content of the wood at the start of kiln drying.

Shell—The moisture content of the outer one-fourth of the thickness of a moisture section.

Moisture distribution—The variation of moisture content throughout a piece of wood, usually from face to face but sometimes from end to end or from edge to edge.

Moisture gradient—A condition during drying in which the moisture content uniformly decreases from the inside toward the surface of a piece of wood. Also a term used specifically to denote the slope of the moisture content distribution curve.

Moisture gradient, reverse—A condition following moisture regain in which the moisture content is higher at the surface than inside the wood.

Moisture meter—See Meter, moisture.

Moisture range—The difference in moisture content between the driest and wettest boards or samples.

Moisture section—A cross section, 1 in. in length along the grain, cut from a kiln or random sample and used to determine moisture content.

Initial weight of—The weight of a moisture section immediately after being cut from a kiln sample or board.

Ovendry weight of—The weight of a moisture section after being ovendried to a constant weight.

Mold—A fungal growth on lumber taking place mainly at or near the surface and, therefore, not typically resulting in deep discolorations. Growths are usually ash green to deep green in color, although black is common.

Old growth—Timber in or from a mature, naturally established forest. When the trees have grown during most if not all of their individual lives in active competition with their companions for sunlight and moisture, the timber is usually straight and relatively free of knots.

Ovendry—A term applied to wood dried to constant weight in an oven maintained at temperatures of from 214 to 221°F.

Pervious wood—A wood through which moisture moves readily.

Piling

Box—The flat piling of random-length boards on kiln trucks so that the ends of the completed load are in vertical alignment. The longest boards are placed on the outside of the load, and the shorter boards are alternately placed with one end even with one end of the load or the other.

Edge—Piling lumber so that the broad face of the board is vertical.

Flat—Piling lumber so that the broad face of the board is horizontal.

Pipe

Condensate—The pipe on the downstream side of heating coils and steam traps that carries condensate back to the boiler.

Feed—Usually the pipe conducting steam from the control valve to the heating coils.

Fin—A heating pipe with many finlike projections that increase the radiation surface.

Plain—A heating pipe with a smooth outer surface.

Steam-spray—A pipe with numerous holes or nozzles through which steam is ejected to increase the relative humidity in the kiln.

Pit—A relatively unthickened part of a wood cell wall where a thin membrane may permit liquids to readily pass from one cell to another. A “bordered” pit has an overhanging rim that is not present in a “simple” pit.

Pitch—The mixture of rosin and turpentine or other volatiles produced in the resin canals of pines and other conifers. Term also applied to mixtures of nonvolatile liquids or noncrystalline solids and volatile oils in other species.

Pocket—An opening, extending parallel to the growth rings, that contains or has contained pitch.

Streak—A well-defined streaky accumulation of pitch in the wood of certain softwoods.

Pith—The small, soft core occurring in the structural center of a tree trunk, branch, twig, or log.

Plainsawed—Another term for flat-sawed or flat-grained lumber.

Platen pressdrying—Contact heating of wood between heated metal plates to affect drying while under restraint.

Plenum chamber—The space between the lumber stack and kiln wall for air circulation on the pressure side of a fan or blower in which the air is maintained under pressure.

Pore—The cross section of a specialized hardwood cell known as a vessel. See Vessels.

Predryer—A type of low-temperature dryer. Stickered loads or unit packages of lumber or other wood products are placed in a large building provided with fans, heating system, and vents such that air of a given temperature and humidity can be circulated through the lumber.

Pressdrying, platen—See Platen pressdrying.

Psychrometer—An instrument with both wet-bulb and dry-bulb thermometers for determining the amount of water vapor in the atmosphere.

Psychrometric char—A table or graph used to relate the absolute humidity, relative humidity, and dry- and wet-bulb temperatures.

Quartersawed—Lumber sawed so the wide faces are approximately at right angles to the annual growth rings. See Grain.

Radial—Coincident with or generally parallel to a radius of the tree from the pith to the bark. A radial section is a lengthwise section in a plane that passes through the pith.

Radiation—A term often used in kiln drying to describe heat transfer from heating coils to lumber. In this common use, it is understood to include both convection and radiation heat transfer, although the former is the most important in kilns.

Balanced—Construction and arrangement so as to ensure equal radiating surface and uniform temperatures throughout the kiln.

Excessive—A greater amount of radiation than required.

Flexible—The arrangement of the heating system into small coils equipped with hand valves that, when opened or closed, permit rapid adjustment of the radiating surface to meet the required needs.

Raised grain—A roughened condition of the surface of dressed lumber in which the hard summerwood is raised above the softer springwood but not torn loose from it.

Rays, wood—Strips of cells extending radially within a tree and varying in height from a few cells in some species to 4 in or more in oak. The rays primarily serve to store food and transport it horizontally in the tree.

Redry—A process in which material that has been dried but is at a moisture content level higher than desired is returned to the dryer.

Refractory—In wood, implies difficulty in processing or manufacturing by ordinary methods, difficulty in drying, resistance to the penetration of preservatives, or difficulty in machining.

Relative humidity—See Humidity, relative.

Resin canal (or duct)—Intercellular passages that contain and transmit resinous materials. They extend vertically or radially in a tree.

Ring, annual growth—See Annual growth ring.

Ring failure (or separation)—A separation of the wood during drying. Occurs along the grain and parallel to the annual rings, either within or between rings; called honeycomb and ring check in some localities. See Shake.

Ring-porous wood—Wood in which the pores of the earlywood (springwood) are distinctly larger than those of the latewood (summerwood) and form a well-defined zone or growth ring.

Sample—See Kiln sample.

Sample board—A board from which one or more kiln samples will be cut, or a board taken from a kiln truckload during drying for the purpose of cutting a moisture section.

Sap—The moisture in green wood, which contains nutrients and other extractives in solution.

Sap stain—See Stain, blue.

Sapwood—The layer of wood near the outside of the log that is actively involved in the life processes of the tree. Usually lighter in color than the heartwood.

Sapwood stain—See Stain, blue.

Seasoning—Removal of moisture from green wood, and in some cases relief of stresses, in order to improve its serviceability. (Syn: drying)

Second growth—Timber that has grown after the removal, whether by cutting, fire, wind, or other agency, of all or a large part of the previous stand.

Sensible heat—See Heat, sensible.

Set—A localized semipermanent deformation in wood caused by internal tensile or compressive stresses.

Compression—Set, occurring during compression, that tends to give the wood a smaller than normal dimension after drying. Usually found in the interior of wood items during the last stage of drying but sometimes in the outer layers after overconditioning or rewetting. Also caused by external restraint during rewetting of dried wood.

Tension—Set, occurring during tension, that tends to give the wood a larger than normal dimension after drying. Usually occurring in the outer layers during the first stages. Also caused by external restraint during drying of wet wood.

Shake—A separation along the grain, the greater part of which occurs between and within growth rings. Found in stumps and ends of freshly cut logs and green lumber. See Ring failure.

Short circuiting of air—The movement of air through other than desired channels. Usually results when a kiln charge is improperly loaded and/or baffled.

Shrinkage—The contraction of wood caused by drying the material below the fiber saturation point.

Longitudinal—Shrinkage along the grain.

Radial—Shrinkage across the grain, in a radial direction.

Tangential—Shrinkage across the grain, in a tangential direction.

Sinker—A log that sinks or has low buoyancy in water.

Sinker stock—Green lumber or other green sawmill products that will not float in water. Sinker stock may be sawn from sinker logs that were water-logged during ponding or from freshly cut logs containing wetwood. The green moisture content is abnormally high, and the lumber tends to dry slowly and is prone to develop checks and honeycomb.

Softwood—Wood produced by one of the botanical groups of trees that, in most species, have needle or scalelike leaves.

sorter

Drop—A mechanical lumber-sorting device that sorts lumber for thickness, width, and length by dropping them into separate compartments accordingly.

Edge—A mechanical lumber-sorting device consisting of grooves or slots in which the lumber is placed on edge. Lines of live rolls, arranged under the slots, carry the lumber to the desired bin or compartment.

Tray—A mechanical lumber-sorting device consisting of a series of trays one above the other into which the lumber is ejected by either mechanical or electrical signaling devices.

Specific gravity—The ratio of the ovendry weight of a piece of wood to the weight of an equal volume of water (39°F). In drying, specific gravity values are usually based on the volume of the green wood.

Split—A lengthwise separation of the wood, caused by the tearing apart of the wood parallel to the wood rays.

Spray line—A plain pipe of varying sizes and lengths that is drilled with holes of various sizes and spacing through which steam is injected into the kiln.

Springwood (earlywood)—The part of the annual growth ring that is formed during the early part of the season's growth. It is usually less dense and mechanically weaker than summerwood.

Stain—A discoloration in wood that may be caused by such diverse agencies as micro-organisms, metal, or chemicals. The term also applies to materials used to impart color to wood.

Blue (sap stain, sapwood stain)—A bluish or grayish discoloration of the sapwood caused by the growth of certain dark-colored fungi on the surface and in the interior of the wood, made possible by the same conditions that favor the growth of other fungi.

Chemical—A general term including all stains that are due to color changes of the chemicals normally present in the wood, such as pinking of hickory and browning of some softwoods, particularly the pines.

Chemical, brown—A chemical discoloration of wood, which can occur during the air drying or kiln drying of several softwood species, caused by the concentration and modification of extractives.

Iron-tannate—A bluish-black surface stain on oak and other tannin-bearing woods following contact of the wet wood with iron, or with water in which iron is dissolved.

Mineral—An olive to greenish-black or brown discoloration in hardwoods, particularly maple, caused by bird peck or other injury and found either in mass discoloration or mineral streaks. The mineral associated with such streaks is frequently calcium oxalate, which has a tendency to dull machining knives.

Sticker—A gray to blue or brown chemical stain occurring on and beneath the surface of boards where they are in contact with stickers (also fungal sap stain when found only in the sticker area).

Water—A yellowish to blackish surface discoloration caused by water that dripped onto the wood during drying.

Weather—A very thin grayish-brown surface discoloration on lumber exposed for a long time to the weather.

Steam—The vapor into which water is converted when heated.

Exhaust—Steam that has already passed through a steam engine or machine.

Flash—The reevaporation of hot water produced by excess heat when the water is discharged to a lower pressure.

Live—Steam obtained directly from the boiler.

Superheated—Steam at a temperature higher than the saturation temperature corresponding to the pressure.

Steam binding—The presence of steam in the drain line between the heating coil and trap, which temporarily prevents the drainage of condensate and air from the coil.

Sticker— A wooden strip placed between the courses of lumber in a kiln load and at right angles to the long axis of the boards to permit air circulation.

Alignment—The placing of stickers in a pile, package, or truckload of lumber so that they form vertical tiers.

Spacing—The distance between stickers measured from center to center.

Stress, drying—An internal force, exerted by either of two adjacent parts of a piece of wood upon the other during drying, caused by uneven drying and shrinkage, and influenced by set.

Tensile—Stress in the outer layers of wood during the early stages of drying when the layers are trying to shrink but are restrained by the still-wet interior region; also, the stress in the interior layers later in drying as they try to shrink and are restrained by the set outer shell.

Compressive—Stress found in the interior region of wood during the early stages of drying, caused by the shrinking of the outer shell; also, stress in the outer layers later in drying caused by the shrinking of the interior.

Stress free—Containing no drying stresses.

Stress section—A cross section of a sample that is cut into prongs of equal thicknesses, from face to face.

Stresses, relief of—The result of a conditioning treatment, following the final stage of drying, which causes a redistribution of moisture and a relief of the sets.

Stresses, reversal of—The normal change from tension in the surface and compression in the center to compression in the surface and tension in the center.

Summerwood (latewood)—The part of the annual growth ring that is formed during the latter part of the growing season. It is usually denser and mechanically stronger than springwood.

Surface check—See Check, surface.

Tangential— Coincident with or generally parallel to a. tangent at the circumference of a tree or log, or growth rings. A tangential section is a longitudinal section through a tree perpendicular to a radius.

Temperature— Degree of hotness or coldness.

Cold zone—The lowest entering-air dry-bulb temperature in the kiln.

Drop across the load—The reduction in the dry-bulb temperature of the air as it flows through the load and is cooled by evaporating moisture from the load of lumber.

Dry-bulb—The temperature of the kiln air.

Hot zone—The highest entering-air dry-bulb temperature in the kiln.

Longitudinal variation of—The range of entering-air dry-bulb temperatures in a kiln measured along the kiln length.

Wet-bulb—The temperatures indicated by any temperature measuring device, the sensitive element of which is covered by a smooth, clean, soft, water-saturated cloth (wet-bulb wick or porous sleeve).

Temperature gradient, longitudinal—A term used to denote longitudinal temperature differences within a dry kiln.

Tension wood—A type of wood found in leaning trees of some hardwood species, characterized by the presence of fibers technically known as “gelatinous” and by excessive longitudinal shrinkage. Tension wood fibers tend to “pull out” on sawed and planed surfaces, giving so-called fuzzy grain. Tension wood causes crook and bow and may collapse. Because of slower than normal drying, tension wood zones may remain wet when the surrounding wood is dry.

Texture—A term referring to the size of wood cells. Thus, “fine-textured” wood has small cells and “coarse-textured,” large cells. Where all the cells of a softwood or all the pores of a hardwood are approximately the same size, as seen on the cross section, the wood can be called “uniform textured.” The term is sometimes erroneously used in combination with soft or hard.

Thermocouple— A temperature-sensing device made by soldering or fusing two dissimilar metal wires together and connecting the wires to a potentiometer or similar device, thereby determining the temperature at the junction. Copper-constantan thermocouples are usually used in dry kiln work.

Tracheids—The elongated cells that make up the greater part of the wood of the softwoods; frequently referred to as fibers.

Transverse—The directions in wood at right angles to the wood fibers or across the grain, including radial and tangential directions. A transverse or cross section is a section through a tree or timber at right angles to the pith. It has an end-grain surface.

Trap, steam—A device that discharges air and condensate from steam-heating coils but limits the passage of steam.

Treatment, equalization—A controlled temperature and relative humidity condition used in a dry kiln at the end of drying to stop the drying of the driest boards while allowing the wettest boards to continue drying, thus reducing the moisture range between boards.

Treatment, steaming—Spraying steam directly into the kiln to attain a condition at or near saturation in the initial stages of kiln drying to retard the growth of mold. Also used to increase the rate of heating cold lumber. Sometimes used needlessly during other stages of drying to restore surface moisture, and often used without proper control to partially relieve stresses at the end of drying.

Twist—A form of warp caused by the turning or winding of the edges of a board so that the four corners of any face are no longer in the same plane.

Tyloses—Extensions of parenchyma cells into the pores or vessels of some hardwoods, notably white oak and black locust, prior to or during heartwood formtion. They tend to prevent or greatly retard moisture movement through the vessels.

Vacuum kiln—See Kiln, vacuum.

Vapor barrier—A material with a high resistance to vapor movement, such as asphalt-impregnated paper, that is used in combination with insulation to control condensation.

Vapor pressure—The pressure exerted by a vapor when the rates of condensation and evaporation are in equilibrium between the liquid and vapor state.

Ventilator (or vent)—An opening in the kiln roof or wall, or in the blower duct work, that can be opened or closed in order to maintain the desired relative humidity condition within the kiln.

Automatic control—A ventilator that is opened or closed by a thermostat.

Linkage—The adjustable, pivoted rods connecting the vent cover to an air valve or to a hand-operated level, which facilitate the opening and closing of the vents.

Manual control—A ventilator that is opened or closed by hand.

Vessels—Wood cells in hardwoods of comparatively large diameter that have open ends and are set one above the other so as to form continuous tubes. The openings of the vessels on the surface of a piece of wood are usually referred to as pores.

Virgin growth—The original growth of mature trees.

Wane—Presence of bark or the lack of wood from any cause on the edge or corner of a piece.

Warp—Any variation from a true or plane surface. Warp includes cup, bow, crook, twist, and diamonding, or any combination thereof.

Water, bound (adsorbed, hygroscopic)—Moisture that is bound by adsorption forces within the cell wall; that is, the water in wood below the fiber saturation point.

Water, free—Moisture that is held in the cell cavities of the wood, not bound in the cell wall.

Water box—A water container that is mounted under the wet bulb and supplies water to the wick.

Water pocket—An area of unusually high moisture content in lumber; pockets are of various sizes and shapes. Also called wet pocket.

Waterlogging—The presence of water in steam coils, which interferes with the normal flow of steam and seriously affects the heating efficiency of the coil.

Wet-bulb temperature.—See Temperature.

Wetwood—Green wood with an abnormally high moisture content that generally results from infections in living trees by anaerobic bacteria, but may also result from water logging during log ponding. Wetwood can occur in both softwoods and hardwoods; the green lumber is usually difficult to dry without defects. Although difficult to recognize, wetwood is often characterized by a translucent, water-soaked appearance and a sour or rancid odor.

Wood—The hard material between the pith and the bark in the stems and branches of trees, made up of a variety of organized hollow cells and consisting chemically of cellulose, hemicelluloses, lignin, and extractives.

Wood, reaction—In wood anatomy, wood with more or less distinctive anatomical characteristics, formed in parts of leaning or crooked stems and in branches. Reaction wood consists of tension wood in hardwoods and compression wood in softwoods.

Wood, refractory—See Refractory.

Wood, ring-porous—See Ring-porous wood.

Wood substance—The extractive-free solid material of which the cell walls of ovendried wood are composed. Wood substance has essentially the same specific gravity in all species.

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