A Guide to Wood Drying, Moisture Content and Dimensional Changes

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CHAPTER 13

A Guide to Wood Drying, Moisture Content and Dimensional Changes

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Contents

In the living tree, wood contains large quantities of water. As green wood dries, most of the water is removed. The moisture remaining in the wood tends to come to equilibrium with the relative humidity of the surrounding air. Correct drying, handling, and storage of wood will minimize moisture content changes that might occur after drying when the wood is in service. If moisture content is controlled within reasonable limits by such methods, major problems from dimensional changes can usually be avoided.

The discussion in this chapter is concerned with moisture content determination, recommended moisture content values, drying methods, methods of calculating dimensional changes, design factors affecting such changes in structures, and moisture content control during transit, storage, and construction. Data on green moisture content, fiber saturation point, shrinkage, and equilibrium moisture content are given with information on other physical properties in Chapter 4.

Wood in service is always undergoing slight changes in moisture content. These changes that result from daily humidity changes are often small and usually of no consequence. Changes that occur because of seasonal variation, although gradual, tend to be of more concern. Protective coatings can retard dimensional changes in wood but do not prevent them. In general, no significant dimensional changes will occur if wood is fabricated or installed at a moisture content corresponding to the average atmospheric conditions to which it will be exposed. When incompletely dried material is used in construction, some minor dimensional changes can be tolerated if the proper design is used.

Determination of Moisture Content

Moisture content is one of the most critical parameters affecting wood and its properties. For most wood products, the amount of moisture in wood is ordinarily expressed as a percentage of wood mass when oven dried. An alternative moisture content approach used for wood fuels is expressed as a percentage of the original mass, which includes the mass of water.

The ASTM (2016) test methods cover calculating moisture content of wood products including engineered wood products and wood-based materials containing resins and other additives. Four methods of determining moisture content are covered in ASTM D4442 (ASTM 2016). Two of these—the oven-drying and the electrical methods—are described here. The oven-drying method, falling under Method A, has been the most universally accepted method for determining moisture content, but it is slow and necessitates cutting the wood. In addition, the oven-drying method may give values slightly greater than true moisture content with woods containing volatile extractives. Regardless, oven-drying method is designed for the full array of activities from research to wood industrial activities, including kiln drying hardwoods where greater precision or accuracy is required (ASTM 2016). Contrarily, the electrical method, falling under Method D, is rapid, does not require cutting the wood, and can be used on wood installed in a structure. This approach allows for simple ways of measuring moisture content. However, considerable care must be taken to use and interpret the results correctly because results tend to be less precise than Method A. Use of the electrical method is generally limited to moisture content values less than 30% or the fiber saturation point (FSP), according to ASTM D4444 (ASTM 2018).

Oven-Drying Method

In the oven-drying method, specimens are taken from representative boards or pieces of a quantity of lumber. With lumber, obtain the specimens at least 500 mm (20 in.) from the end of the pieces because wood gains and loses moisture quickly through the end. They should be free from knots and other irregularities, such as bark and pitch pockets. Specimens from lumber should be full cross sections and 25 mm (1 in.) long. Specimens from larger items may be representative sectors of such sections or subdivided increment borer or auger chip samples. Convenient amounts of chips and particles can be selected at random from larger batches, with care taken to ensure that the sample is representative of the batch. Select veneer samples from four or five locations in a sheet to ensure that the sample average will accurately indicate the average of the sheet.

To prevent drying or reabsorption of moisture, weigh each specimen immediately. If the specimen cannot be weighed immediately, place it in a plastic bag or tightly wrap it in metal foil to protect it from moisture change until it can be weighed. After weighing, place the specimen in an oven heated to 101 to 105 °C (214 to 221 °F), and keep it there until no appreciable weight change occurs in 3-h weighing intervals. A lumber section 25 mm (1 in.) along the grain will reach a constant weight in 12 to 48 h. Smaller specimens will take less time. The constant or oven-dry mass and the (original) mass of the specimen when cut are used to determine the percentage of moisture content (MC) using the formula

$$\text{Moisture content (\%)} = \frac{\text{Mass when cut} - \text{Ovendry mass}}{\text{Ovendry mass}} \times 100 \qquad (13\text{–}1)$$

Electrical Method

The electrical method of determining moisture content of wood uses the relationships between moisture content and measurable electrical properties of wood, such as conductivity (or its inverse, resistivity), dielectric constant, or power-loss factor. These properties vary in a definite and predictable way with changing moisture content, but correlations are not perfect. Therefore, moisture determinations using electrical methods are always subject to some uncertainty (ASTM 2018).

Electric moisture meters are available commercially and are based on each of these properties and identified by the property measured. Conductance-type (or resistance) meters measure moisture content in terms of the direct current conductance of the specimen. Dielectric-type meters are of two types. Those based principally on dielectric constant are called capacitance or capacitive admittance meters; those based on loss factor are called power-loss meters.

The principal advantages of the electrical method compared with the oven-drying method are speed and convenience. Only a few seconds are required for the determination, and the piece of wood being tested is not cut or damaged, except for driving electrode needle points into the wood when using conductance-type meters. Thus, the electrical method is adaptable to rapid sorting of lumber on the basis of moisture content below FSP, measuring the moisture content of wood installed in a building, or establishing the moisture content of a quantity of lumber or other wood items, when used in accordance with ASTM D4444.

For conductance meters, needle electrodes (pins) of various lengths are driven into the wood. The two general types of electrodes are insulated and uninsulated. Uninsulated electrodes will sense the lowest resistance (highest conductance) along their length, thus highest moisture content level. Moisture gradients between the surface and the interior can lead to confusion; therefore, insulating the electrode except the tip is useful to show moisture gradients. They measure moisture content of only the wood at the tips of the electrodes. If the wood is wetter near the center than the surface, which is typical for drying wood, the reading will correspond to the depth of the tip of the insulated electrodes. If a meter reading increases as the electrodes are being driven in, then the moisture gradient is typical. In this case, drive the pins about one-fifth to one-fourth the thickness of the wood to reflect the average moisture content of the entire piece. Dried or partially dried wood sometimes regains moisture in the surface fibers from rewetting, therefore the surface moisture content is greater than that of the interior. An example of this is when dried wood is rained on. In this case, the meter with the uninsulated pins will read the higher moisture content surface, possibly causing a significant deviation from the average moisture content. To guard against this problem, electrodes with insulated shanks should be used.

Dielectric-type meters are fitted with surface contact electrodes designed for the type of specimen material being tested. The electric field from these electrodes penetrates well into the specimen, but with a strength that decreases rapidly with depth of penetration. For this reason, the surface layers of the specimen influence the readings of dielectric (pinless) meters predominantly, and the meter reading may not adequately represent the material near the core if there is a large moisture content gradient.

To obtain accurate moisture content values, use each instrument in accordance with its manufacturer's instructions. The electrodes should be appropriate for the material being tested and properly oriented according to the meter manufacturer's instructions. Take the readings after inserting the electrode. Apply a species correction supplied with the instrument when appropriate. Make temperature corrections if the temperature of the wood differs considerably from the temperature of calibration used by the manufacturer. Approximate corrections for conductance-type (resistance) meters are made by adding or subtracting about 0.5% for each 5.6 °C (10 °F) the wood temperature differs from the calibration temperature. Add the correction factors to the readings for temperatures less than the calibration temperature and subtract from the readings for temperatures greater than the calibration temperature. Temperature corrections for older dielectric meters are rather complex and are best made from published charts (James 1988). Newer dielectric meters perform this temperature calibration internally, although newer dielectric meters require a specific gravity adjustment. This specific gravity adjustment is performed by species selection options on the meter.

Although some meters have scales that go up to 120%, the range of moisture content that can be measured reliably is 4% to about 30% for commercial dielectric meters and about 6% to 30% for resistance meters. The precision of the individual meter readings decreases near the limits of these ranges. Readings greater than 30% must be considered only qualitative. When the meter is properly used on a quantity of lumber dried to a constant moisture content below fiber saturation, the average moisture content from the corrected meter readings should be within 1% of the true average.

Recommended Moisture Content

Install wood at the moisture content levels that the wood will experience in service. This minimizes the seasonal variation in moisture content, and thus dimensional changes, after installation, avoiding problems such as floor buckling or cracks in furniture. The in-service moisture content of exterior wood (siding, wood trim) primarily depends on the outdoor relative humidity and exposure to rain or sun. The in-service moisture content of interior wood primarily depends on indoor relative humidity, which in turn is a complex function of moisture sources, ventilation rate, dehumidification (for example, air conditioning), and outdoor humidity conditions.

Recommended values for interior wood presented in this chapter are based on measurements in well-ventilated buildings without unusual moisture sources and without air conditioning. In air-conditioned buildings, moisture conditions depend largely on the proper sizing of the air-conditioning equipment. Wood installed in basements or over a crawl space may experience moisture contents greater than the range given. Wood in insulated walls or roofs and attics may experience moisture contents greater or less than the range. Nevertheless, the recommended values for installation provide a useful guideline.

Timbers

Ideally, dry solid timbers to the average moisture content the material will reach in service. Although this optimum is possible with lumber less than 76 mm (3 in.) thick, it is seldom practical to obtain fully dried timbers, thick joists, and planks. When thick solid members are used, some shrinkage of the assembly should be expected. In the case of built-up assemblies, such as roof trusses, it may be necessary to tighten bolts or other fastenings occasionally to maintain full bearing of the connectors as the members shrink.

Lumber

Match the moisture content of lumber as closely as is practical to the equilibrium moisture content (EMC) conditions in service. Table 13–1 shows the EMC conditions in outdoor exposure in various U.S. cities for each month. The EMC data are based on the average relative humidity and temperature data (30 or more years) available from the National Climatic Data Center of the National Oceanic and Atmospheric Administration (Simpson 1998, Mitchell 2018, NOAA 2019). The relative humidity data are the averages of morning and afternoon values. In most cases, these values would be representative of the EMC attained by the wood. However, in some locations, early morning relative humidity may occasionally reach 100%. Under these conditions, condensation may occur on the wood surface, therefore surface fibers will exceed the EMC. The moisture content requirements are more exacting for finished lumber and wood products used inside heated and air-conditioned buildings than those for lumber used outdoors or in unheated buildings. For general areas of the United States, the recommended moisture content values for wood used inside heated buildings are shown in Figure 13–1. Values and tolerances for both interior and exterior uses of wood in various forms are given in Table 13–2. If the average moisture content is within 1% of that recommended and

Table 13–1. Equilibrium moisture content for outside conditions in several U.S. locations through 2010

		Equilibrium moisture content[a] (%)											
State	City	Jan.	Feb.	Mar.	Apr.	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
AK	Juneau	17.3	16.7	14.9	13.9	13.4	14.0	15.6	16.5	18.4	18.5	18.1	18.5
AL	Mobile	13.8	13.6	13.2	13.3	13.2	13.5	14.3	14.3	14.1	13.1	13.4	14.0
AZ	Flagstaff	11.5	11.0	10.2	9.0	8.2	7.0	9.6	11.0	10.1	9.7	10.5	11.5
AZ	Phoenix	8.9	8.3	7.4	6.0	4.9	4.4	6.2	6.8	6.5	6.9	7.8	9.0
AR	Little Rock	13.8	13.2	12.8	12.9	13.7	13.0	13.2	13.0	13.2	13.1	13.3	13.8
CA	Fresno	15.8	13.8	11.9	10.3	8.8	7.9	7.4	7.8	8.5	9.8	12.9	15.8
CA	Los Angeles	9.4	10.2	10.5	10.4	11.0	11.7	11.6	11.2	10.8	10.6	9.8	9.9
CO	Denver	10.1	10.0	8.8	9.1	9.2	8.3	8.0	8.4	8.4	9.1	9.6	10.5
DC	Washington-National	11.9	11.5	11.2	11.0	11.6	11.7	11.7	12.1	12.6	12.6	12.2	12.1
FL	Miami	13.5	13.1	12.7	12.2	12.5	13.7	13.4	13.8	14.4	13.8	13.6	13.5
GA	Atlanta	13.3	12.5	12.2	11.8	12.3	12.7	13.4	13.5	13.5	12.9	12.8	13.2
HI	Honolulu	13.1	12.7	12.3	11.7	11.3	11.1	11.1	11.0	11.4	12.0	12.5	13.0
ID	Boise	14.8	12.9	10.6	9.6	9.2	8.4	6.9	6.9	7.9	9.5	12.7	14.8
IL	Chicago	14.3	14.1	13.4	12.4	12.3	12.3	12.7	13.3	13.3	13.2	13.9	15.1
IN	Indianapolis	15.1	14.5	13.4	12.5	12.6	12.6	13.1	13.6	13.4	13.4	14.4	15.5
IA	Des Moines	14.3	14.2	13.4	12.6	12.5	12.9	13.2	13.6	13.4	12.8	13.8	14.9
KS	Wichita	13.7	13.3	12.6	12.4	13.3	12.7	11.7	11.9	12.5	12.4	13.0	13.8
KY	Louisville	13.8	13.2	12.4	11.6	12.3	12.4	12.6	12.8	13.0	12.9	13.1	14.1
LA	New Orleans	14.6	14.3	13.7	13.9	13.8	14.4	14.8	15.0	14.5	13.8	14.1	14.7
ME	Portland	12.9	12.5	12.4	12.0	12.4	13.1	13.0	13.4	14.1	13.8	13.8	13.4
MA	Boston	12.1	11.7	11.8	11.5	12.0	12.0	11.8	12.4	12.8	12.6	12.5	12.2
MI	Detroit	14.8	14.1	13.2	12.2	12.0	12.2	12.3	13.2	13.5	13.5	14.2	15.1
MN	Minneapolis–St. Paul	14.0	13.8	13.3	11.8	11.7	12.3	12.4	13.1	13.4	13.1	14.2	14.9
MS	Jackson	14.5	14.1	13.5	13.6	13.8	13.8	14.4	14.3	14.1	13.8	14.1	14.7
MO	St. Louis	14.2	13.7	13.0	12.3	12.7	12.5	12.5	12.9	13.1	12.8	13.2	14.3
MT	Missoula	16.5	14.8	12.5	10.9	11.1	11.1	9.3	9.1	10.4	12.5	15.7	17.3
NE	Omaha	14.2	14.2	13.4	12.1	12.7	12.9	13.2	13.8	13.4	12.7	13.5	14.5
NV	Las Vegas	8.3	7.6	6.4	5.3	4.6	3.7	4.4	5.0	5.0	5.7	7.1	8.2
NV	Reno	11.9	10.7	9.3	8.7	8.4	7.8	7.2	7.4	7.9	8.9	10.5	12.1
NM	Albuquerque	9.9	8.8	7.5	6.5	6.3	6.0	7.8	8.5	8.2	8.3	8.8	10.1
NY	New York	12.2	11.9	11.4	11.0	11.5	11.9	11.8	12.4	12.7	12.3	12.5	12.3
NC	Raleigh	12.7	12.2	12.0	11.6	12.5	12.7	13.2	13.9	14.0	13.5	12.8	12.8
ND	Fargo	14.4	14.8	15.2	12.8	11.8	12.9	13.1	13.2	13.4	13.4	14.9	15.3
OH	Cleveland	14.9	14.5	13.7	12.5	12.4	12.5	12.5	13.4	13.6	13.4	13.8	14.8
OK	Oklahoma City	13.2	13.0	12.2	12.1	13.3	13.2	12.0	11.8	12.5	12.3	12.5	13.0
OR	Pendleton	16.0	14.1	11.5	10.6	9.8	9.1	7.2	7.4	8.5	10.9	14.7	16.4
OR	Portland	16.7	14.9	14.0	13.2	12.7	12.1	11.2	11.4	12.2	14.6	16.6	17.2
PA	Philadelphia	12.7	12.0	11.7	11.2	11.7	11.8	11.9	12.3	12.8	12.8	12.6	12.6
SC	Charleston	13.7	13.1	12.2	11.6	12.7	13.3	14.3	14.5	14.3	13.7	13.2	13.8
SD	Sioux Falls	14.1	14.3	14.3	12.6	12.6	13.0	12.9	13.6	13.3	12.9	13.9	14.9
TN	Memphis	13.4	12.9	12.2	12.2	12.7	12.6	12.9	12.8	13.0	12.5	12.8	13.4
TX	Dallas–Ft. Worth	12.7	12.7	11.9	12.5	12.9	12.1	11.3	11.0	12.0	12.2	12.4	12.5
TX	El Paso	8.9	7.7	6.4	5.6	5.5	6.0	8.0	8.5	8.5	8.2	8.3	9.3
UT	Salt Lake City	14.6	13.1	10.6	9.7	9.0	7.8	6.8	7.1	8.1	10.0	12.6	14.9
VA	Richmond	12.7	12.4	11.9	11.3	12.1	12.3	12.6	13.4	13.6	13.4	12.7	12.9
WA	Seattle	16.3	14.9	14.4	13.6	12.9	12.8	12.0	12.4	13.4	15.7	16.6	16.9
WI	Madison	14.4	14.3	13.8	12.8	12.6	12.9	13.2	14.1	14.3	13.8	14.6	15.4
WV	Charleston	13.6	13.1	12.2	11.5	12.7	13.3	14.0	14.3	14.2	13.6	13.0	13.7
WY	Cheyenne	10.1	10.4	10.3	10.2	10.7	10.0	9.5	9.6	9.5	9.7	10.3	10.4
PR	San Juan	13.7	13.2	12.5	12.6	13.3	13.1	13.4	13.5	13.7	13.6	13.9	13.9

[a]EMC values were determined from the average of 30 or more years of relative humidity and temperature data available from the National Climatic Data Center of the National Oceanic and Atmospheric Administration.

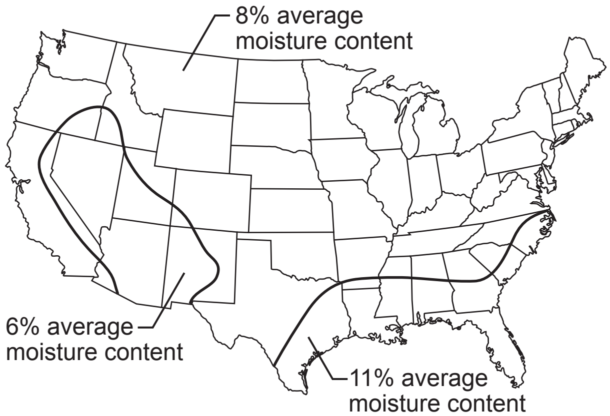

Figure 13–1. Recommended average moisture content for interior use of wood products in various areas of the United States.

all pieces fall within the individual limits, the entire lot is probably satisfactory (Simpson 1998, Glass and others 2014).

General commercial practice is to kiln dry wood for some products, such as flooring and furniture, to a slightly lower moisture content than service conditions demand. This anticipates a moderate increase in moisture content during processing, transportation, and construction. This practice is intended to ensure uniform distribution of moisture among the individual pieces. Common grades of softwood boards and softwood dimension lumber are not normally dried to the moisture content values indicated in Table 13–2. Dry lumber, as defined in the American Softwood Lumber Standard, has a maximum moisture content of 19%. Some industry grading rules provide for an even lower maximum. For example, to be grade marked KD 15, the maximum moisture content permitted is generally 15%.

Glued Wood Products

When veneers are bonded with cold-setting adhesives to make plywood, they absorb comparatively large quantities of moisture. To keep the final moisture content low and to minimize the need for redrying the plywood, the initial moisture content of the veneer should be as low as practical. However, dry veneer is brittle and difficult to handle without damage, so the minimum practical moisture content is about 4%. Freshly glued plywood intended for interior service should be dried to the moisture content values given in Table 13–2.

Hot-pressed plywood and other board products, such as particleboard and hardboard, usually do not have the same moisture content as lumber. The high temperatures used in hot presses cause these products to assume a lower moisture content for a given relative humidity. Because this lower equilibrium moisture content varies widely, depending on the specific type of hot-pressed product, it is recommended that such products be conditioned at 30% to 40% relative humidity for interior use and 65% for exterior use.

Lumber used in the manufacture of large laminated members should be dried to a moisture content slightly less than the moisture content expected in service. This is done so that the moisture adsorbed from the adhesive will not cause the moisture content of the product to exceed the service value. The range of moisture content between laminations assembled into a single member should not exceed 2 percentage points (River 1991).

Although laminated members are often massive and respond rather slowly to changes in environmental conditions, it is desirable to follow the recommendations in Table 13–2 for moisture content at time of installation.

Drying of Wood

Drying is required for wood to be used in most products. Dried lumber has many advantages over green lumber for producers and consumers. Removal of excess water reduces weight, thus reducing shipping and handling costs. Proper drying reduces shrinking and swelling of wood while in use to manageable amounts under all but extreme conditions of relative humidity or rewetting, such as flooding. As wood dries, most of its strength properties increase, as well as its

Table 13–2. Recommended moisture content values for various wood products at time of installation

	Recommended moisture content (%) for areas in the United States					
	Most areas of the United States		Dry southwestern area[a]		Damp, warm coastal area[a]	
Use of wood	Average[b]	Individual pieces	Average[b]	Individual pieces	Average[b]	Individual pieces
Interior: woodwork, flooring, furniture, wood trim	8	6–10	6	4–9	11	8–13
Exterior: siding, wood trim, sheathing, laminated timbers	12	9–14	9	7–12	12	9–14

[a]Major areas are indicated in Figure 13–1.
[b]To obtain a realistic average, test at least 10% of each item. If the quantity of a given item is small, make several tests. For example, in an ordinary dwelling containing 60 floor joists, at least six tests should be made on joists selected at random.

electrical and thermal insulating properties. Properly dried lumber can be cut to precise dimensions and machined more easily and efficiently; wood parts can be 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; and paint, varnish, and other finishes are more effectively applied and maintained. Wood must be relatively dry before gluing or treating with decay-preventing and fire-retardant chemicals.

The key to successful and efficient drying is control of the drying process. Timely application of optimum or at least adequate temperature, relative humidity, and air circulation conditions is critical. Uncontrolled drying leads to drying defects that can adversely affect the serviceability and economics of the product. The usual strategy is to dry as fast as the particular species, thickness, and end-product requirements allow without damaging the wood. Slower drying can be uneconomical and can introduce the risk of stain.

Softwood lumber intended for framing in construction is usually targeted for drying to an average moisture content of 15%, not to exceed 19%. Softwood lumber for many appearance grade uses is dried to a lower moisture content of 10% to 12% and to 7% to 9% for furniture, cabinets, and millwork. Hardwood lumber for framing in construction, although not in common use, should also be dried to an average moisture content of 15%, not to exceed 19% (Simpson and Wang 2001, Ross and Erickson 2005). Hardwood lumber for furniture, flooring, cabinets, and millwork is usually dried to 6% to 8% moisture content.

Lumber drying is usually accomplished by some combination of air drying, accelerated air drying or pre-drying, and kiln drying. Wood species, initial moisture content, lumber thickness, economics, and end use are often the main factors in determining the details of the drying process.

Air Drying

The main purpose of air drying lumber is to evaporate as much of the water as possible before end use or prior to kiln drying. Air drying down to 20% to 25% moisture content prior to kiln drying saves energy costs because kiln (forced) drying tends to consume the most energy of all wood production processes (Comstock 1975, Puettmann and others 2010). In addition, air drying reduces required dry kiln capacity. However, depending on a sawmill's scheduling, air drying may be cut short at a higher moisture content before the wood is sent to the dry kiln. Limitations of air drying are generally associated with uncontrolled drying. The drying rate is very slow during the cold winter months. At other times, hot, dry winds may increase degrade and volume losses as a result of severe surface checking and end splitting. End coating may alleviate end checking and splitting. Warm, humid periods with little air movement may encourage the growth of fungal stains and aggravate chemical stains. Another limitation of air drying is the high cost of carrying a large inventory of high-value lumber for extended periods. Air drying time to 20% to 25% moisture content varies widely, depending on species, thickness, location, and the time of year the lumber is stacked. Some examples of extremes for 25-mm- (1-in.-) thick lumber are 15 to 30 days for some of the low density species, such as pine, spruce, red alder, and soft maple, stacked in favorable locations and favorable times of the year; 200 to 300 days for slow-drying species, such as sinker hemlock and pine, oak, and birch, in northern locations and stacked at unfavorable times of the year. Details of important air-drying considerations, such as lumber stacking and air drying yard layout, are covered in *Air Drying of Lumber: A Guide to Industry Practices* (Rietz and Page 1971).

Accelerated Air Drying and Pre-Drying

The limitations of air drying have led to increased use of technology that reduces drying time and introduces some control into drying (green) wood. Accelerated air drying involves the use of fans to force air through lumber piles in a shed. This protects the lumber from the elements and improves air circulation compared with simple air drying, thus improving quality. Heat is sometimes added to reduce the relative humidity and slightly increase the shed temperature to aid drying. Pre-dryers take this acceleration and control a step further by providing control of both temperature and relative humidity and providing forced air circulation in a completely enclosed compartment. Typical conditions in a pre-dryer are 27 to 38 °C (80 to 100 °F) and 65% to 85% relative humidity.

Kiln Drying

In kiln drying, higher temperatures and faster air circulation are used to significantly increase the drying rate. Specific kiln schedules have been developed to control temperature and relative humidity in accordance with the moisture content and stress situation within the wood, thus minimizing shrinkage-caused defects (Boone and others 1988). Typically, conventional dry kilns use heat from steam boilers primarily fueled by mill residues, such as hog fuel, and some fossil fuel to kiln dry lumber in batches. Recent technology advances have been made in vacuum and progressive (continuous) dry kiln operations (Salin and Wamming 2008, Bond and Espinoza 2016, Espinoza and Bond 2016, Milota and Puettmann 2017).

Drying Mechanism

Water in wood normally moves from high to low zones of moisture content, which means that the surface of the wood must be drier than the interior if moisture is to be removed. Drying can be divided into two phases: movement of water from the interior to the wood surface and evaporation

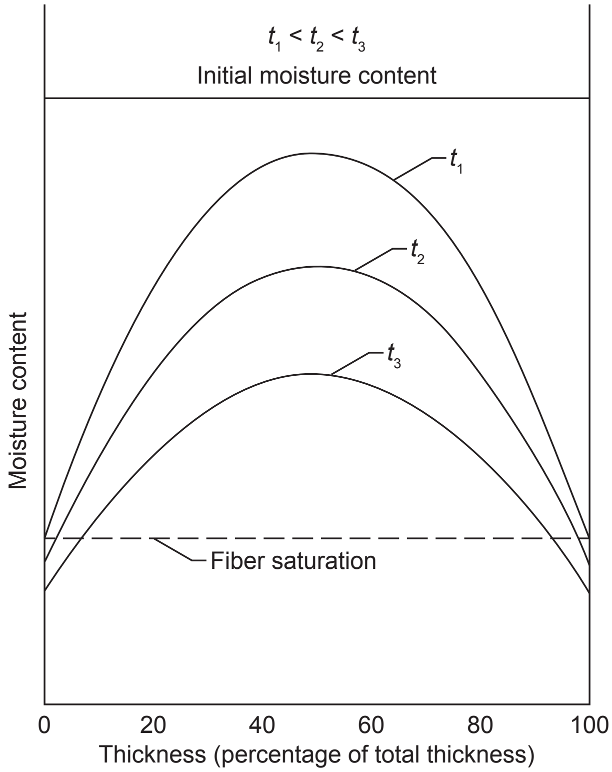

Figure 13–2. Typical moisture gradient in lumber during drying at time increasing from t_1 to t_3.

of water from the surface. The surface fibers 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. 13–2), that is, the difference in moisture content between the inner and outer portions of a board. If air circulation is too slow, a longer time is required for the wood surface to reach moisture equilibrium. This is one reason why air circulation is so important in kiln drying. If air circulation is too slow, the drying rate is also slower than necessary and mold could develop on the surface of lumber. Contrarily, if air circulation is too fast, electrical energy in running the fans is wasted, and in certain species, surface checking and other drying defects can develop if relative humidity and air velocity are not coordinated. Either way, wood quality suffers. Ensuring proper water movement in the wood structure is vital to alleviate these problems.

Water moves through the interior of wood as a liquid or vapor through various air passageways in the cellular structure of the wood, as well as through the wood cell walls. Moisture moves in these passageways in all directions, both across and with the grain. In general, lighter species dry faster than heavier species because the structure of lighter wood contains more openings per unit volume, and moisture moves through air faster than through wood cell walls. Water moves by two main mechanisms: capillary action (liquid) and diffusion of bound water (vapor). Capillary action causes the free water to flow through cell cavities and the small passageways that connect adjacent cell cavities. Diffusion of bound water moves moisture from areas of high concentration to areas of low concentration. Diffusion in the longitudinal direction is about 10 to 15 times faster than radial or tangential diffusion, and radial diffusion is somewhat faster than tangential diffusion. This explains why flatsawn lumber generally dries faster than quartersawn lumber. Although longitudinal diffusion is much faster than diffusion across the grain, it generally is not of practical importance in lumber that is many times longer than it is thick. However, excessive longitudinal diffusion can cause end-checking or splitting without proper care.

Moisture affects heartwood and sapwood differently. Because chemical extractives in heartwood plug up passageways, moisture generally moves more freely in sapwood than in heartwood; thus, sapwood generally dries faster than heartwood. However, given that the heartwood of many species is lower in moisture content than the sapwood, the final (kiln-dried) moisture content for both heartwood and sapwood can be reached just as fast for typical kiln-drying operations.

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. Lower relative humidity increases capillary flow. Low relative humidity also stimulates diffusion by lowering the moisture content at the surface, thereby steepening the moisture gradient and increasing the diffusion rate. The greater 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 shrinkage may occur, resulting in surface and end checking. If the temperature is too high, collapse, honeycomb, or strength reduction can occur.

Drying Stresses

Drying stresses are the main cause of non-stain-related drying defects. Understanding these stresses provides a means for minimizing and recognizing the damage they can cause. The cause of drying stresses is differential shrinkage between the outer part of a board (the shell) and the interior part (the core) that can result in drying defects. Early in drying, the fibers in the shell dry first and begin to shrink. However, the core has not yet begun to dry and shrink; consequently, the core prevents the shell from shrinking fully. Thus, the shell goes into tension and the core into compression (Fig. 13–3). 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 cracks, or checks, occur from this initial stage of drying and 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

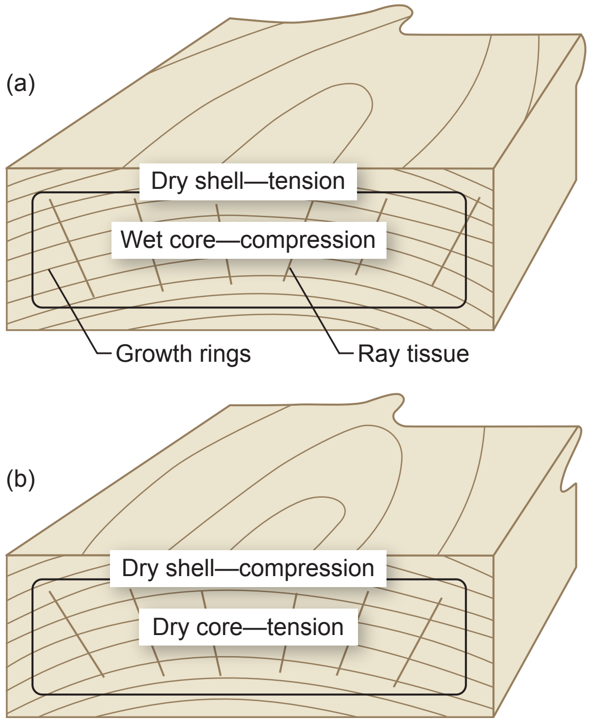

Figure 13–3. End view of board showing development of drying stresses (a) early and (b) later in drying.

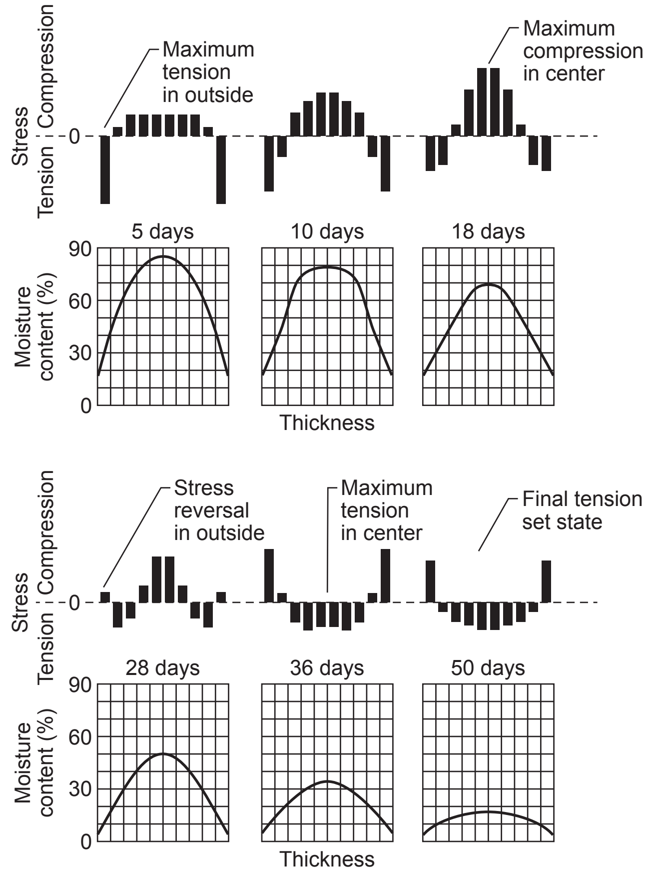

Figure 13–4. Moisture–stress relationship during six stages of kiln drying 50-mm- (2-in.-) thick red oak.

causes the stresses to reverse; the core goes into tension and the shell into compression (Fig. 13–3). The change in the shell and core stresses and in the moisture content level during drying are shown in Figure 13–4. These internal tension stresses may be severe enough to cause internal cracks (honeycomb).

Differential shrinkage caused by differences in radial, tangential, and longitudinal shrinkage is a major cause of warp. The distortions shown in Figure 4–3 (Chap. 4) are due to differential shrinkage. When juvenile or reaction wood is present on one edge or face of a board and normal wood is present on the opposite side, the difference in their longitudinal shrinkage can also cause warp.

Dry Kilns

Most dry kilns are thermally insulated compartments designed for a batch process in which the kiln is completely loaded 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 can be controlled over a wide range. As the wood dries, kiln temperature and relative humidity change based on a schedule that takes into account the moisture content or the drying rate, or both, of the lumber. All dry kilns use some type of forced-air circulation, with air moving through the lumber perpendicular to the length of the lumber and parallel to the spacers (stickers) that separate each layer of lumber in a stack. This forced-air circulation allows for uniform air flow in the dry kiln.

Five general types of kilns are in common use. One is the track-loaded type (Fig. 13–5), in which lumber is stacked on kiln trucks that are rolled in and out of the kiln on tracks. Most softwood lumber in the United States is dried in this kiln type. Another major type is the package-loaded kiln (Fig. 13–6), in which individual stacks of lumber are fork-lifted into place in the kiln. Package-loaded kilns are commonly used for drying hardwood lumber. Indirect-steam heat is common for these two types, although softwood lumber kilns are sometimes directly heated using combustion gases from burning fuel. A third common type of kiln, usually package loaded, is the dehumidification kiln. Instead of venting humid air to remove water, as the other two types of kilns do, water is removed by condensation on cold dehumidifier coils (Fig. 13–7). The last two types, vacuum and progressive (continuous flow) are more common in the Scandinavian countries but are becoming more prevalent in the Unites States. Drying by vacuum kilns occurs below atmospheric pressure, enabling lumber to dry at lower temperatures (Espinoza and Bond 2016). Progressive dry kilns provide cross-sectional circulation and multizone control, which reduce energy consumption and

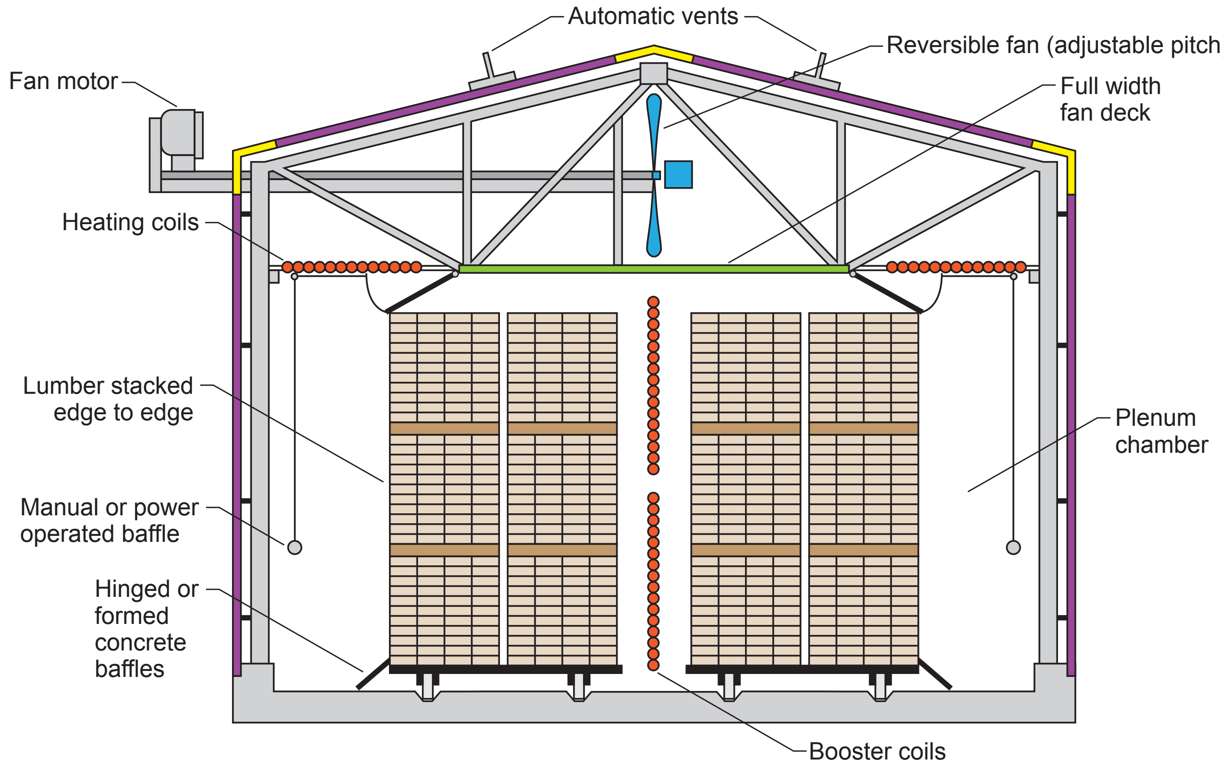

Figure 13–5. Lineshaft, double-track, compartment kiln with alternately opposing fans. Vents are over fan shaft between fans. Vent on high pressure side of fans becomes fresh air inlet when direction of circulation is reversed.

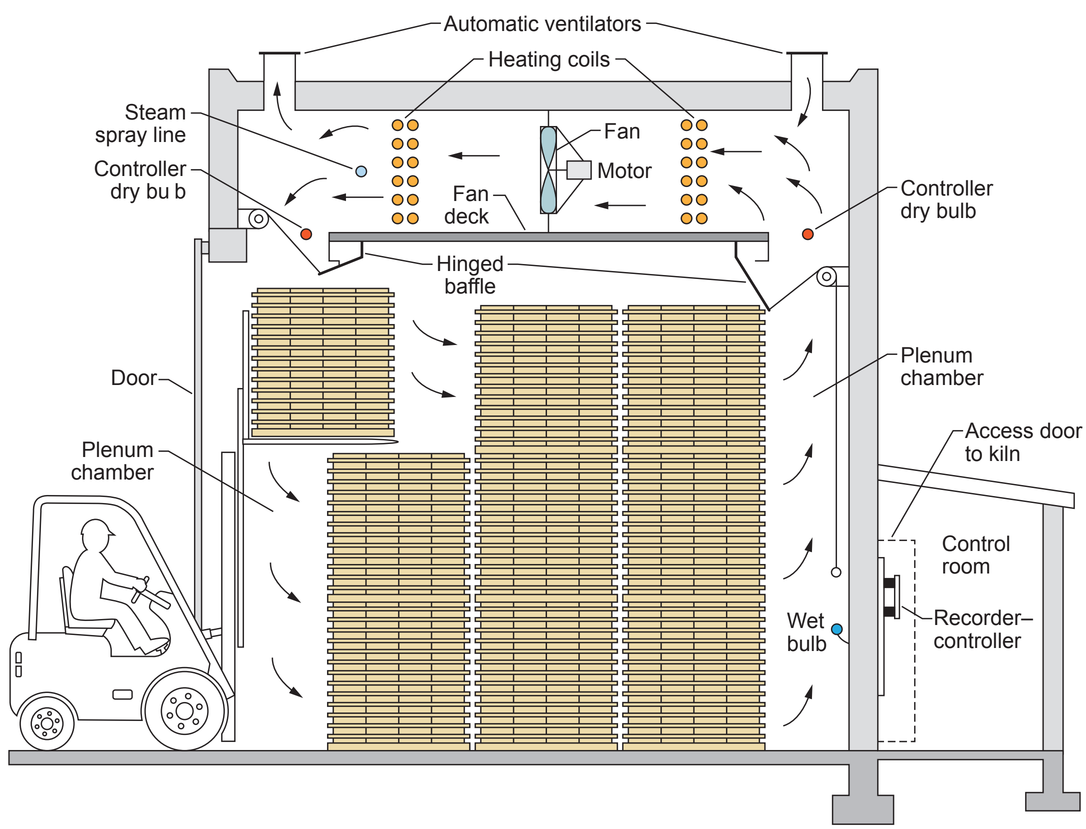

Figure 13–6. Package-loaded kiln with fans connected directly to motors.

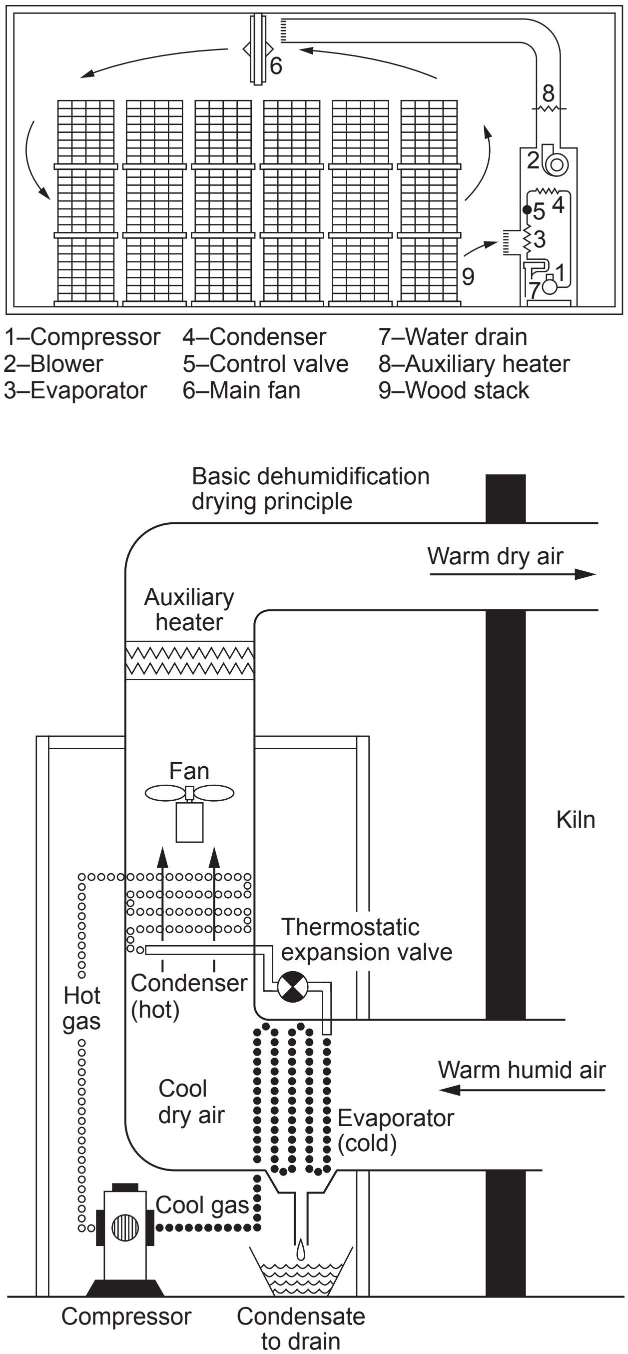

Figure 13–7. A typical dehumidification kiln (top) and dehumidification drying system (bottom).

increase productivity over conventional batch kilns (Salin and Wamming 2008, Elustondo 2014)

Kiln Schedules

A kiln schedule is a carefully developed compromise between the need to dry lumber as fast as possible for economic efficiency and the need to avoid severe drying conditions that will lead to drying defects. A kiln schedule is a series of temperatures and relative humidities that are applied at various stages of drying (Boone and others 1988).

In most schedules, the temperature is gradually increased and the relative humidity decreased, thus lowering the EMC. The schedule for Southern Pine structural lumber is an exception to this general rule. This is lumber usually dried at a constant temperature and relative humidity. Temperatures are chosen to balance the highest drying rate with the avoidance of objectionable drying defects. The stresses that develop during drying are the limiting factor in determining the kiln schedule. The schedule 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 the 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 increase 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 (Culpepper 1990).

Drying schedules vary by species, thickness, grade, moisture content, and end use of lumber. The two general types of kiln schedules are moisture content schedules and time-based schedules. Most hardwood lumber is dried by moisture content schedules. This means that the temperature and relative humidity conditions are changed according to the percentage moisture content of the lumber during drying.

A typical MC-based hardwood schedule might begin at 49 °C (120 °F) and 80% relative humidity when the lumber is green. By the time the lumber has reached 15% moisture content, the temperature is as high as 82 °C (180 °F). A typical hardwood drying schedule is shown in Table 13–3. Some method of monitoring moisture content during drying is required for schedules based on moisture content. One common method is the use of kiln samples that are periodically weighed, usually manually but potentially remotely with load cells.

Alternatively, embedded electrodes in sample boards sense the change in electrical conductivity with moisture content. This system is limited to moisture content values less than 30% (Simpson 1991, Denig and others 2000).

Softwood kiln schedules generally differ from hardwood schedules in that changes in kiln temperature and relative humidity are made at predetermined times rather than moisture content levels. Examples of time-based schedules, both conventional temperature (<100 °C (<212 °F)) and high temperature (>110 °C (>230 °F)), are given in Table 13–3. Some hardwoods used as structural lumber

Table 13–3. Typical dry kiln schedules for lumber

Moisture-content-based schedule for 25-mm (1-in.) (4/4) black walnut, dried to 7% moisture content

Moisture content (%)	Temperature (°C (°F))		Relative humidity (%)	Equilibrium moisture content (%)
	Dry-bulb	Wet-bulb		
Above 50	49.0 (120)	45.0 (113)	80	14.4
50 to 40	49.0 (120)	43.5 (110)	72	12.1
40 to 35	49.0 (120)	40.5 (105)	60	9.6
35 to 30	49.0 (120)	35.0 (95)	40	6.5
30 to 25	54.5 (130)	32.0 (90)	22	4.0
25 to 20	60.0 (140)	32.0 (90)	15	2.9
20 to 15	65.5 (150)	37.5 (100)	18	3.2
15 to 7	82.2 (180)	54.4 (130)	27	3.7
Equalize	82.2 (180)	58.3 (137)	30	3.8
Condition	82.2 (180)	76.7 (170)	79	11.1

Time-based schedule for 25- to 50-mm (1- to 2-in.) (4/4 to 8/4) Douglas-fir, upper grades, dried to 12% moisture content

Time (h)	Temperature (°C (°F))		Relative humidity (%)	Equilibrium moisture content (%)
	Dry-bulb	Wet-bulb		
0 to 12	76.5 (170)	73.5 (164)	86	14.1
12 to 24	76.5 (170)	71.0 (160)	78	11.4
24 to 48	79.5 (175)	71.0 (160)	69	9.1
48 to 72	82.2 (180)	71.0 (160)	62	7.7
72 to 96 or until dry	82.2 (180)	60.0 (140)	36	4.5

High-temperature schedule for 50- by 100-mm to 50- by 250-mm (2- by 4-in. to 2- by 10-in.) Southern Pine, dried to 15% moisture content

Time (h)	Temperature (°C (°F))		Relative humidity (%)	Equilibrium moisture content (%)
	Dry-bulb	Wet-bulb		
0 until dry	116 (240)	82.2 (180)	29	2.5

Time-based schedule for 50- by 150-mm (2- by 6-in.) sugar maple, dried to 15% moisture content in 5 days

Time (h)	Temperature (°C (°F))		Relative humidity (%)	Equilibrium moisture content (%)
	Dry-bulb	Wet-bulb		
0 to 24	71.0 (160)	67.2 (153)	84	14.1
24 to 48	71.0 (160)	65.6 (150)	78	12.1
48 to 60	71.0 (160)	62.8 (145)	69	10.1
60 to 72	71.0 (160)	57.2 (135)	52	7.4
72 to 84	76.7 (170)	54.4 (130)	35	4.9
84 to 115	82.2 (180)	54.4 (130)	27	3.7

also use a time-based schedule, as shown in Table 13–3 (Simpson and Wang 2001, Ross and Erickson 2005).

Drying Defects

Most drying defects or problems that develop in wood products during drying can be classified as fracture or distortion, warp, or 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 and undesirable color or surface texture. Drying temperature is the most important processing factor because it can be responsible for defects in each category.

Fracture or Distortion

Surface checks occur early in drying when the shell of a board is stressed in tension enough to fracture the wood. These checks occur most often on the face of flatsawn boards and are illustrated in Figure 13–8. End checks (Fig. 13–9) are similar to surface checks but appear on the ends of boards and logs. End checks occur because the rapid

Figure 13–8. Surface checking on white oak 5/4 lumber.

Figure 13–9. End checking in red pine logs.

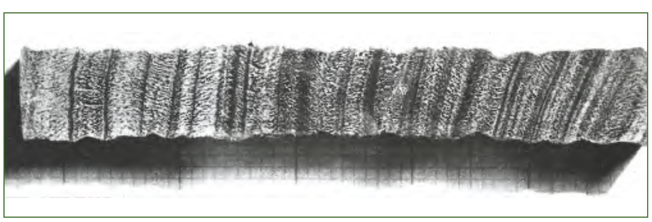

Figure 13–10. Severe collapse in western redcedar.

Figure 13–11. Red cedar timber end shows honeycomb (top). Surface of the timber shows no honeycomb (bottom).

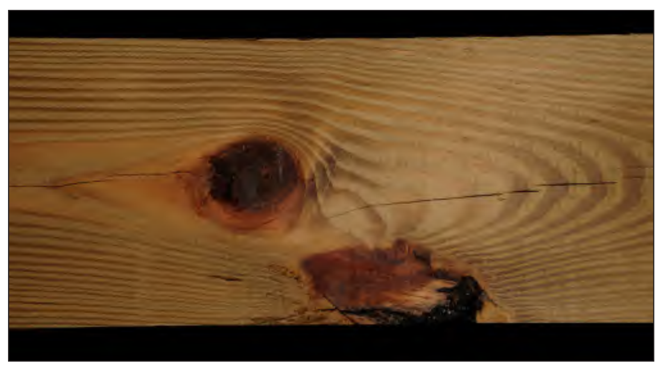

Figure 13–12. Large knot in treated Southern Pine.

longitudinal movement of moisture causes the end to dry very quickly and develop high stresses, therefore fracturing. End coatings, on either the log or freshly sawn (green) lumber, are an effective preventative measure. Collapse is a distortion, flattening, or crushing of wood cells. In severe cases (Fig. 13–10), collapse usually shows up as grooves or corrugations, a washboarding effect. Less severe collapse shows up as excessive thickness shrinkage and may not be a serious problem. Honeycomb (Fig. 13–11) is an internal crack that occurs in the later stages of kiln drying when the core of a board is in tension. This internal defect is caused when the core is still at a relatively high moisture content

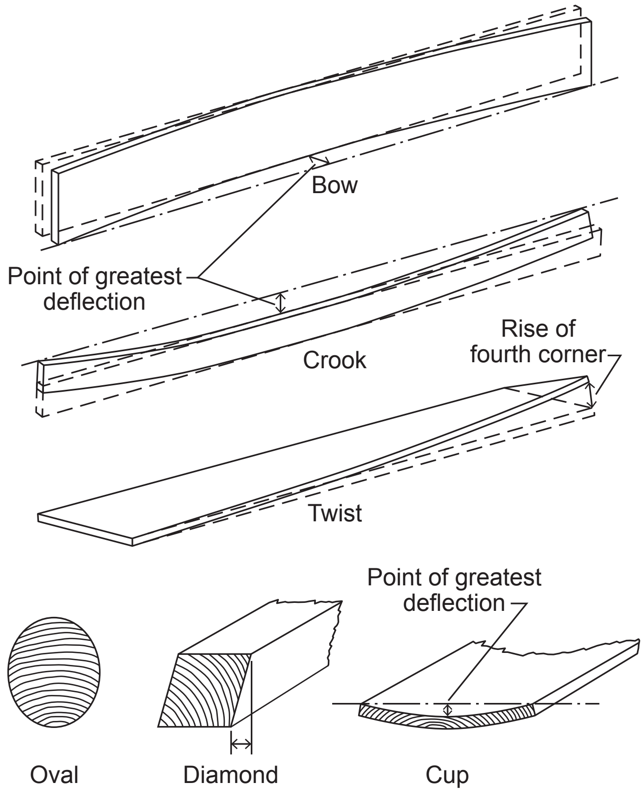

Figure 13–13. Various types of warp that can develop in boards during drying.

and drying temperatures are too high for too long during this critical drying period. It may go unnoticed until the lumber is machined. Nondestructive testing methods, using speed of sound, have been found to be effective in detecting the presence of these cracks in dried lumber. Knots may loosen during drying because of the unequal shrinkage between the knot and the surrounding wood (Fig. 13–12).

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. Warp can be traced to two causes: (a) differences between radial, tangential, and longitudinal shrinkage in the piece as it dries or (b) growth stresses. Warp is aggravated by irregular or distorted grain and the presence of abnormal types of wood, such as juvenile and reaction wood. The six major types of warp are bow, crook, twist, oval, diamond, and cup (Fig. 13–13).

Discoloration

Discoloration impairs the use of dried wood products, particularly when the end use requires a clear, natural finish. Discolorations (or stain) happens in both sapwood and heartwood. Unwanted discoloration can develop in the tree, during storage of logs and green lumber, or during drying. The two general types of discoloration are chemical (nonmicrobial) and fungal (microbial).

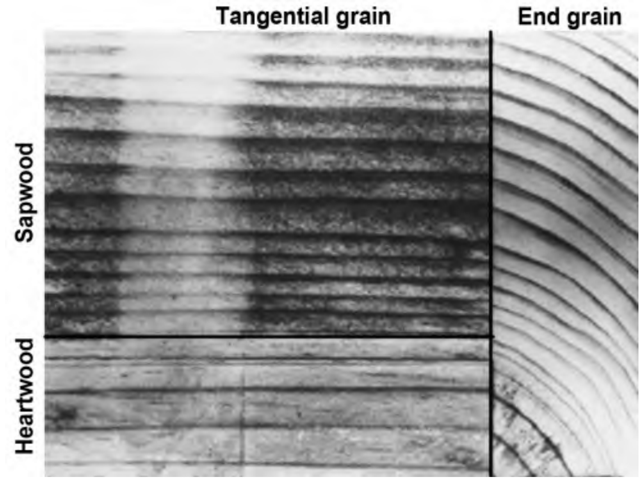

Figure 13–14. Brown sapwood stain in Southern Pine lumber.

Figure 13–15. Soft maple sapwood boards (surface, end, edge) showing patches of oxidative stain.

Chemical discoloration is the result of oxidative and enzymatic reactions with chemical compounds in wood. Discolorations range from pinkish, bluish, and yellowish hues through gray and reddish brown to dark brown shades. Brown stain in pines and darkening in many hardwoods is a common problem when drying temperatures are too high (Fig. 13–14). Hardwoods are prone to chemical discoloration, but it may also affect softwoods. A deep grayish brown chemical discoloration can occur in many hardwood species, including soft maple, if initial drying is too slow or if initial kiln temperature is too high (Fig. 13–15) (Denig and others 2000, Wiemann and others 2009).

Microbial stains are caused by various micro-organisms, such as blue-stain fungi, mold, or bacteria, and are most often caused by fungi that grow in the sapwood (Fig. 13–16). Blue stain is the most common fungal stain (Uzunovic and others 2008). Blue-stain fungi do not cause decay of the sapwood, and blue-stain fungi generally do not grow in heartwood. Heartwood does not contain the needed food substances for blue-stain fungi (Knaebe 2002). Blue stain (which is not a mold) can develop if initial drying is too slow and occurs often during the summer months when lumber is exposed to air before kiln drying. Blue stain has virtually no effect on the wood's physical properties

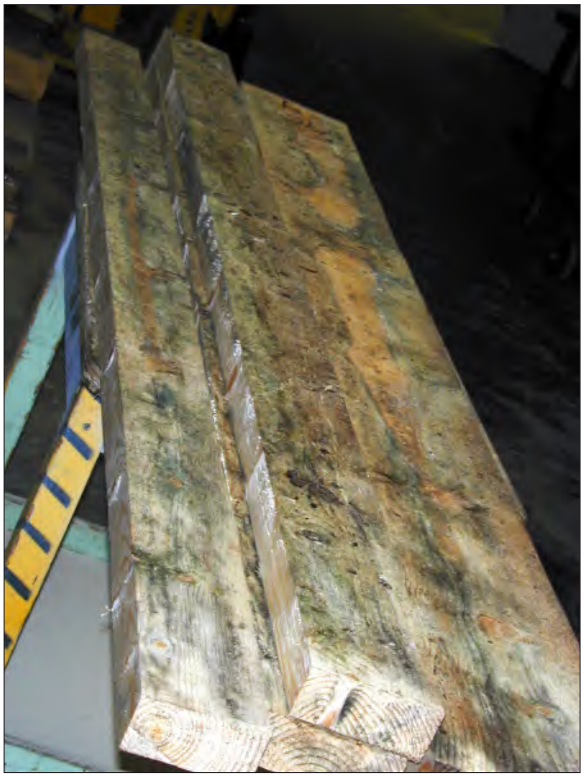

Figure 13–16. Sap stain in ponderosa pine. Color ranges from bluish gray to black.

Figure 13–17. Sticker stain in sapwood of sugar maple after planing.

(Knaebe 2002, FPL 1941). Another common type of stain develops under stickers (Fig. 13–17). This stain results from contact of the sticker with the board. Sticker stains (sometimes called shadow) are imprints of the sticker that are darker or lighter than the wood between the stickers and can be caused by either chemical or fungal action, or both.

Moisture Content of Dried Lumber

Although widely used, the trade terms “shipping dry,” “air dry,” and “kiln dry” may not have identical meanings as to moisture content in different producing regions. Despite wide variations in the use of these terms, they are sometimes used to describe dried lumber. The following statements, which are not exact definitions, outline these categories.

Shipping Dry

Shipping dry means lumber that has been partially dried to prevent stain or mold during brief periods of transit; ideally the outer 3.2 mm (1/8 in.) is dried to 25% or less moisture content (McMillen 1978).

Air Dry

Air dry means lumber dried by exposure to the air outdoors or in a shed or by forced circulation of air that has not been heated above 49 °C (120 °F). Commercial air-dry stock generally has an average moisture content low enough for rapid kiln drying or rough construction use. Moisture content is generally in the range of 20% to 25% for dense hardwoods and 15% to 20% for softwoods and low-density hardwoods. Extended exposure can bring standard 19- and 38-mm (nominal 1- and 2-in.) lumber within one or two percentage points of the average exterior EMC of the region. For much of the United States, the minimum moisture content of thoroughly air-dried lumber is 12% to 15% (Table 13–1).

Kiln Dry

Kiln dry means lumber that has been dried in a kiln or by some special drying method to an average moisture content specified or understood to be suitable for a certain use. The average moisture content should have upper and lower tolerance limits, and all values should fall within these limits. If the moisture contents fall outside these limits, use the dry kiln to equalize the lumber until the moisture is inside these limits. Kiln-dried softwood dimension lumber generally has an average moisture content of 19% or less; the average moisture content for many other softwood uses is 10% to 20%. Hardwood and softwood lumber for furniture, cabinetry, and millwork usually has a final moisture content of 6% to 8% and can be specified to be free of drying stresses. Drying stresses built up during the drying cycle can be relieved by conditioning inside the dry kiln. The importance of suitable moisture content values is recognized, and provisions covering them are now incorporated in some softwood standards as grading rules. Moisture content values in the general grading rules may or may not be suitable for a specific use; if not, a special moisture content specification should be made (USDC 2020).

Moisture Control during Long-Term Transit and Storage

Lumber and other wood items may change in moisture content and dimension while awaiting shipment, during fabrication, in transit, and in storage.

When standard 19-mm (nominal 1-in.) dry softwood lumber is shipped in tightly closed boxcars, shipping containers, or trucks or in packages with complete and intact wrappers, average moisture content changes for a package can generally be held to 0.2% or less per month. In holds or between decks of ships, dry material usually adsorbs about 1.5% moisture during normal shipping periods. If green material is included in the cargo, the moisture regain of the dry lumber may be doubled. On the top deck, if unprotected from the elements, the moisture regain can be as much as 7%.

When standard 19-mm (nominal 1-in.) hardwood lumber, kiln dried to 8% or less, is piled solid under a good pile roof in a yard in warm, humid weather, average moisture content of a pile can increase at the rate of about 2% per month during the first 45 days. A moisture uptake rate of about 1% per month can then be sustained throughout a humid season.

Comparable initial and sustaining moisture uptake rates are about 1% per month in open (roofed) sheds and 0.3% per month in closed sheds. Stock piled for a year in an open shed in a western location increased 2.7% on the inside of solid piles and 3.5% on the outside of the piles. Protect all manufactured stock from precipitation and spray because liquid water on a solid pile tends to be absorbed by the wood instead of evaporating. The extent to which additional control of the storage environment is required depends upon the final use of the wood and the corresponding moisture content recommendations. It is important to determine the moisture content of all stock when received. If moisture content is not as specified or required, stickered storage in an appropriate condition could ultimately bring the stock within the desired moisture content range. If a large degree of moisture change is required, the stock must be redried (Rietz 1978).

Structural Lumber and Panel Products

It is good practice to open-pile green or partially dried lumber and timbers using stickers and protect from sunshine and precipitation by a tight roof. Framing lumber and structural panels with 20% or less moisture content can be solid-piled (no stickers) in a shed that has good protection against sunshine and direct or wind-driven precipitation. However, a better practice for stock with greater than 12% moisture content is the use of stickered piling to bring moisture content more in line with the moisture content in use.

Whenever possible for dry lumber, pile it solid in the open for only relatively short periods with a minimum pile cover of waterproofed paper. Because keeping rain out completely is difficult, storing solid-piled lumber in the open for long periods is not recommended. If framing lumber must be stored in the open for a long time, pile on stickers with good base support and cover the piles. Re-piling using stickers for solid-piled material that has become wet again is good practice.

Finish and Factory Lumber

Keep kiln-dried items such as exterior finish, siding, and exterior millwork in a closed, unheated shed. Place material on supports raised above the floor, at least 150 mm (6 in.) high if the floor is paved or 300 mm (12 in.) if not paved. Interior trim, flooring, cabinet work, and lumber for processing into furniture should be stored in a room or closed shed where relative humidity is controlled. In addition, store kiln-dried and machined hardwood dimension or softwood cut stock under controlled humidity conditions.

Dried and machined hardwood dimension or softwood lumber intended for remanufacture should also be stored under controlled humidity conditions. Under uncontrolled conditions, the ends of such stock may attain a higher moisture content than the rest of the stock. Then, when the stock is straight-line ripped or jointed before edge gluing, subsequent shrinkage will cause splitting or open glue joints at the ends of panels. The simplest way to reduce relative humidity in storage areas of all sizes is to heat the closed space to a temperature slightly higher than that of the outside air. Dehumidifiers can be used in small, well-enclosed spaces as needed.

If the heating method is used, and there is no source of moisture except that contained in the air, the equilibrium moisture content can be maintained by increasing the temperature of the storage area greater than the outside temperature by the amounts shown in Table 13–4. When a dehumidifier is used, monitor or control, if needed, the average temperature in the storage space. Select the proper relative humidity in Table 4–2 (Chap. 4) to give the desired average moisture content. Wood in a factory awaiting or following manufacture can become too dry if the area is heated to 21 °C (70 °F) or greater when the outdoor temperature is low. This often occurs in the northern United States during the winter. Under such circumstances, exposed ends and surfaces of boards or cut pieces will tend to dry to the low equilibrium moisture content condition, causing shrinkage and warp. In addition, an equilibrium moisture content of 4% or more below the moisture content of the core of freshly crosscut boards can cause end checking. Simple remedies are to cover piles of partially manufactured items with plastic film and lower the shop temperature during non-work hours. Increased control can be obtained in critical shop and storage areas by humidification. In warm

Table 13–4. Increase in storage area temperature above outside temperature to maintain the desired wood moisture content

Outside relative humidity (%)	Temperature differential (°C (°F)) for desired wood moisture content						
	6%	7%	8%	9%	10%	11%	12%
90	18.3 (33)	16.1 (29)	12.8 (23)	10.0 (18)	8.3 (15)	6.1 (11)	5.0 (9)
80	16.7 (30)	13.9 (25)	10.5 (19)	7.8 (14)	6.1 (11)	4.4 (8)	3.3 (6)
70	13.9 (25)	11.1 (20)	8.3 (15)	5.6 (10)	3.9 (7)	2.2 (4)	1.7 (3)
60	11.1 (20)	8.3 (15)	5.0 (9)	3.3 (6)	1.7 (3)	—	—
50	8.3 (15)	5.6 (10)	2.8 (5)	0.6 (1)	—	—	—

weather, use of air conditioning is suggested for maintaining optimal EMC because it controls both temperature and relative humidity (FPL 1972).

Dimensional Changes in Wood

Dry wood undergoes small changes in dimension with normal changes in relative humidity. More humid air will cause slight swelling, and drier air will cause slight shrinkage. These changes are considerably smaller than those involved with shrinkage from the green condition. Equation (13–3) can be used to approximate dimensional changes caused by shrinking and swelling by using the total shrinkage coefficient from green to oven-dry. However, the equation assumes that the shrinkage–moisture content relationship is linear (Comstock 1965). Figure 4–4 (Chap. 4) shows that this is not the case, so some error is introduced (Wilson 1932, Markwardt and Wilson 1935, Kynoch and Norton 1938, MacLean 1958). The error is in the direction of underestimating dimensional change, by about 5% of the true change. Many changes of moisture content in use are over the small moisture content range of 6% to 14%, where the shrinkage–moisture content relationship is linear (Chap. 4, Fig.4–4). Therefore, a set of dimensional change coefficients (DCCs) using Equation (13-2) based on the linear portion of the shrinkage–moisture content curve were developed (Table 13–5):

The DCC for the tangential direction (based on dimension at 10% MC) is calculated as

$$C_T = \frac{1}{\left(\mathrm{FSP} \times 100/S_T\right) - \mathrm{FSP} + M_I} \qquad (13\text{–}2)$$

where S_T is tangential shrinkage (%) from green to ovendry (based on dimension at green condition) from Table 4–3 (Chap. 4), C_T is DCC tangential direction (for radial direction, use CR), FSP is fiber saturation point (assumed at 30% MC unless noted otherwise), and M_I is 10% MC. The corresponding equation can be used for the radial direction.

Estimating approximate changes in dimension utilizes these DCCs, from Table 13–5, when moisture content remains within the range of normal use (Comstock 1965). (Dimensional changes are further discussed in Chaps. 4 and 7.) Results from Equations (4–7) and (13–2) are not inherently comparable because the equations express dimensional changes from different MC starting points (green and 10% MC, respectively).

Estimation Using Dimensional Change Coefficient

The change in dimension within the moisture content limits of 6% to 14% can be estimated satisfactorily by using a dimensional change coefficient based on the dimension at 10% moisture content:

$$\Delta D = D_I \left[C_T \left(M_F - M_I \right) \right] \qquad (13\text{–}3)$$

where ΔD is change in dimension, D_I dimension in units of length at start of change, C_T dimensional change coefficient tangential direction (for radial direction, use C_R), M_F moisture content (%) at end of change, and M_I moisture content (%) at start of change.

Values for C_T and C_R, derived from total shrinkage values, are given in Table 13–5. When $M_F < M_I$, the quantity $(M_F - M_I)$ will be negative, indicating a decrease in dimension; when greater, it will be positive, indicating an increase in dimension.

As an example, assuming the width of a flat-grained white fir board is 232 mm (9.15 in.) at 8% moisture content, its change in width at 11% moisture content is estimated as

ΔD = 232[0.00245(11 – 8)]
= 232(0.00735)
= 1.705 mm

ΔD = 9.15[0.00245(11 – 8)]
= 9.15[0.00735]
= 0.06725 or 0.067 in.

Then, dimension at end of change

$D_I + \Delta D$ = 232 + 1.7 (= 9.15 + 0.067)
= 233.7 mm (= 9.217 in.)

The thickness of the same board at 11% moisture content can be estimated by using the coefficient C_R = 0.00112.

Because commercial lumber is often not perfectly flatsawn or quartersawn, this procedure will probably overestimate width shrinkage and underestimate thickness shrinkage. Note also that if both a size change and percentage moisture content are known, Equation (13–3) can be used to calculate the original moisture content.

Table 13–5. Dimensional change coefficients (C_R, radial; C_T, tangential) for shrinking or swelling within moisture content limits of 6% to 14%

Species	Dimensional change coefficient[a] C_R	C_T	Species	Dimensional change coefficient[a] C_R	C_T
Hardwoods					
Alder, red	0.00151	0.00256	Honeylocust	0.00144	0.00230
Ash, black	0.00172	0.00274	Locust, black	0.00158	0.00252
Ash, Oregon	0.00141	0.00285	Madrone, Pacific	0.00194	0.00451
Ash, pumpkin	0.00126	0.00219	Magnolia, cucumbertree	0.00180	0.00312
Ash, white	0.00169	0.00274	Magnolia, southern	0.00187	0.00230
Ash, green	0.00158	0.00248	Magnolia, sweetbay	0.00162	0.00293
Aspen, bigtooth	0.00112	0.00278	Maple, bigleaf	0.00126	0.00248
Aspen, quaking	0.00119	0.00234	Maple, red	0.00137	0.00289
Basswood, American	0.00230	0.00330	Maple, silver	0.00102	0.00252
Beech, American	0.00190	0.00431	Maple, black	0.00165	0.00330
Birch, paper	0.00219	0.00304	Maple, sugar	0.00165	0.00353
Birch, river	0.00162	0.00327	Red oak, black	0.00151	0.00400
Birch, yellow	0.00256	0.00338	Red oak, northern red	0.00137	0.00304
Birch, sweet	0.00226	0.00319	Red oak, pin	0.00148	0.00338
Buckeye, yellow	0.00123	0.00285	Red oak, scarlet	0.00151	0.00388
Butternut	0.00116	0.00223	Red oak: water, laurel, willow	0.00153	0.00348
Cherry, black	0.00126	0.00248	White oak, bur	0.00151	0.00312
Chestnut, American	0.00116	0.00234	White oak, live	0.00230	0.00338
Cottonwood, balsam poplar	0.00102	0.00248	White oak, white	0.00194	0.00376
Cottonwood, black	0.00123	0.00304	White oak, overcup	0.00183	0.00462
Cottonwood, eastern	0.00133	0.00327	Persimmon, common	0.00278	0.00403
Elm, American	0.00144	0.00338	Poplar, yellow	0.00158	0.00289
Elm, rock	0.00165	0.00285	Sassafras	0.00137	0.00216
Elm, slippery	0.00169	0.00315	Sweetgum	0.00183	0.00365
Elm, winged	0.00183	0.00419	Sycamore, American	0.00172	0.00297
Elm, cedar	0.00162	0.00365	Tanoak	0.00169	0.00423
Hackberry	0.00165	0.00315	Tupelo, black	0.00176	0.00308
Hickory, pecan	0.00169	0.00315	Tupelo, water	0.00144	0.00267
Hickory, true	0.00259	0.00411	Walnut, black	0.00190	0.00274
Holly, American	0.00165	0.00353	Willow, black	0.00112	0.00308
Softwoods					
Cedar, yellow-	0.00095	0.00208	Pine, eastern white	0.00071	0.00212
Cedar, Atlantic white-	0.00099	0.00187	Pine, jack	0.00126	0.00230
Cedar, Eastern Red	0.00106	0.00162	Pine, loblolly	0.00165	0.00259
Cedar, incense	0.00112	0.00180	Pine, pond	0.00148	0.00234
Cedar, northern white-[b]	0.00101	0.00229	Pine, lodgepole	0.00176	0.00263
Cedar, Port-Orford-	0.00158	0.00241	Pine, longleaf	0.00137	0.00248
Cedar, western red[b]	0.00111	0.00234	Pine, pitch	0.00176	0.00248
Douglas-fir, Coast-type	0.00165	0.00267	Pine, ponderosa	0.00133	0.00216
Douglas-fir, Interior north	0.00130	0.00241	Pine, red	0.00130	0.00252
Douglas-fir, Interior west	0.00165	0.00263	Pine, shortleaf	0.00158	0.00271
Fir, balsam	0.00099	0.00241	Pine, slash	0.00187	0.00267
Fir, California red	0.00155	0.00278	Pine, sugar	0.00099	0.00194
Fir, noble	0.00148	0.00293	Pine, Virginia	0.00144	0.00252
Fir, Pacific silver	0.00151	0.00327	Pine, western white	0.00141	0.00259
Fir, subalpine	0.00088	0.00259	Redwood, old-growth[b]	0.00120	0.00205
Fir, grand	0.00116	0.00263	Redwood, second-growth[b]	0.00101	0.00229
Fir, white	0.00112	0.00245	Spruce, black	0.00141	0.00237
Hemlock, eastern	0.00102	0.00237	Spruce, Engelmann	0.00130	0.00248
Hemlock, mountain	0.00151	0.00248	Spruce, red	0.00130	0.00274
Hemlock, western	0.00144	0.00274	Spruce, Sitka	0.00148	0.00263
Larch, western	0.00155	0.00323	Tamarack	0.00126	0.00259

[a]Per 1% change in moisture content, based on dimension at 10% moisture content and a straight-line relationship between moisture content at which shrinkage starts and total shrinkage. (Shrinkage assumed to start at 30% for all species except those indicated by footnote b.)
[b]Shrinkage assumed to start at 22% moisture content.

Calculation Based on Green Dimensions

Approximate dimensional changes associated with moisture content changes greater than 6% to 14%, or when one moisture content value is outside of those limits, can be calculated by

$$\Delta D = \frac{D_I (M_F - M_I)}{30(100)/S_T - 30 + M_I} \qquad (13\text{–}4)$$

where S_T is tangential shrinkage (%) from green to ovendry (Chap. 4, Tables 4–3 and 4–4) (use radial shrinkage S_R when appropriate).

Neither M_I nor M_F should exceed 30%, the assumed moisture content value when shrinkage starts for most species. In addition, as the FSP of a specific wood species varies, the resultant value of dimensional change varies as well, as one would expect (Comstock 1965).

Design Factors Affecting Dimensional Change

Framing Lumber in House Construction

Ideally, house framing lumber should be dried to the moisture content it faces in use to minimize dimensional changes resulting from wood shrinkage. This ideal condition is difficult to achieve, but some drying and shrinkage of the frame may take place without being visible or causing serious defects after the house is completed. If, at the time the wall and ceiling finish is applied, the moisture content of the framing lumber is not more than about 5% above that which it will reach in service, there will be little or no evidence of defects caused by shrinkage of the frame. For heated houses in cold climates, joists over heated basements, studs, and ceiling joists may reach a moisture content as low as 6% to 7% (Table 13–2). In mild climates, the minimum moisture content will be greater.

The most common signs of excessive shrinkage are cracks in plastered walls, truss rise, open joints, and nail pops in drywall construction; distortion of door openings; uneven floors; and loosening of joints and fastenings. The extent of vertical shrinkage after the house is completed is proportional to the depth of wood used as supports in a horizontal position, such as girders, floor joists, and plates because shrinkage occurs primarily in the width and thickness of members, not the length.

Thoroughly consider the type of framing best suited to the whole building structure. Methods should be chosen that will minimize or balance the use of wood across the grain in vertical supports. These involve variations in floor, wall, and ceiling framing. The factors involved and details of construction are covered extensively in Wood-Frame House Construction (Sherwood and Stroh 1991).

Heavy Timber Construction

In heavy timber construction, a certain amount of shrinkage is to be expected. A column that bears directly on a wood girder can result in a structure settling as a result of the perpendicular-to-grain shrinkage of the girder. If not provided for in the design, shrinkage may cause weakening of the joints or uneven floors or both. One means of eliminating part of the shrinkage in mill buildings and similar structures is to use metal post caps; the metal in the post cap separates the upper column from the lower column. The same thing is accomplished by bolting wood corbels (tassels or braggers) to the side of the lower column to support the girders.

When joist hangers are installed, the top of the joist should be above the top of the girder; otherwise, when the joist shrinks in the stirrup, the floor over the girder will be higher than that bearing upon the joist. Heavy planking used for flooring should be near 12% moisture content to minimize openings between boards as they approach moisture equilibrium. When standard 38- or 64-mm (nominal 2- or 3-in.) joists are nailed together to provide a laminated floor of greater depth for heavy design loads, the joist material should be somewhat less than 12% moisture content if the building is to be heated.

Interior Finish

Normal seasonal changes in the moisture content of interior finish wood products are not enough to cause serious dimensional change if the woodwork was properly installed. Large members, such as ornamental beams, cornices, newel posts, stair stringers, and handrails, should be built up from comparatively small pieces. Wide door and window trim and base should be hollow-backed. Backband trim, if mitered at the corners, should be glued and splined before erection; otherwise butt joints should be used for the wide faces. Design and install large, solid pieces, such as wood paneling, so that the panels are free to move across the grain. Narrow widths are preferable.

Flooring

Wood flooring is usually dried to the moisture content expected in service so that shrinking and swelling are minimized and buckling or large gaps between boards do not occur. For basement, large hall, or gymnasium floors, however, leave enough space around the edges to allow for some expansion.

Wood Care and Installation during Construction

Lumber and Trusses

Although it is good housekeeping practice, lumber is often not protected from the weather at construction sites. Lumber is commonly placed on the ground in open areas near the building site as bulked and strapped packages. Place supports under such packages that elevate the packages at least 150 mm (6 in.) off the ground to prevent wetting from mud and ground water. In addition, cover the packages with plastic tarps for protection from rain.

Pile lumber that is green or nearly green on stickers under a roof for additional drying before building into the structure. The same procedure is required for lumber treated with a waterborne preservative but not fully redried. Prefabricated building parts, such as roof trusses, sometimes lie unprotected on the ground at the building site. In warm, rainy weather, moisture regain can result in fungal staining. Wetting of the lumber also results in swelling, and subsequent shrinkage of the framing may contribute to structural distortions once installed. Furthermore, extended storage of lumber at moisture contents greater than 20% without drying can allow decay to develop.

If framing lumber has a greater moisture content when installed than that recommended in Table 13–2, shrinkage can be expected. Framing lumber, even thoroughly dried stock, will generally have a moisture content greater than that recommended when it is finally delivered to the building site. If carelessly handled in storage at the site, the lumber can take up even more moisture. Builders can schedule their work so an appreciable amount of drying can take place during the early stages of construction. This minimizes the effects of additional drying and shrinkage after completion. When the house has been framed, sheathed, and roofed, the framing is so exposed that in time it can dry to a lower moisture content than could be found in yard-dried lumber. The application of the wall and ceiling finish is delayed while wiring and plumbing are installed. If this delay is about 30 days in warm, dry weather, the framing lumber should lose enough moisture so that any additional drying in place will be minimal. In cool, damp weather, or if wet lumber is used, the period of exposure should be extended. Checking moisture content of woodwork such as door and window headers and floor and ceiling joists at this time with an electric moisture meter is good practice. When these members approach an average of 12% moisture content, interior finish and trim can normally be installed. Closing the house and using the heating system will hasten the rate of drying.

Before the wall finish is applied, the frame should be examined and defects that may have developed during drying, such as warped or distorted studs, shrinkage of structural horizontal blocks over openings (such as headers), or loosened joints, should be corrected.

Exterior Trim and Millwork

Exterior trim, such as cornice and rake mouldings, fascia boards, and soffit material, is typically installed before the shingles are laid. Protect trim, siding, and window and door frames on the site by storing in the house or garage until time of installation. Although items such as window frames and sashes are usually treated with some type of water-repellent preservative to resist absorption of water, store in a protected area if they cannot be installed soon after delivery. Wood siding is often received in packaged form and can ordinarily remain in the package until installation.

Finished Flooring

Cracks can develop in wood flooring if the material takes up moisture either before or after installation, then shrinks when the building is heated. Such cracks can be greatly reduced by observing the following practices:

- Specify flooring manufactured according to association rules and sold by dealers that protect the material properly during storage and delivery.
- Measure random pieces of flooring using a nonpenetrating meter to ensure that moisture content is correct upon arrival and prior to installation.
- Have flooring delivered after masonry and plastering are completed and fully dry, unless a dry storage space is available.
- Install the heating plant before flooring is delivered.
- Break open flooring bundles and expose all sides of flooring to the atmosphere inside the structure.
- Close up the house at night and increase the temperature about 8 °C (15 °F) greater than the outdoor temperature for about three days before laying the floor.
- If the house is not occupied immediately after the floor is laid, keep the house closed at night or during damp weather and supply some heat if necessary.

Better and smoother sanding and finishing can be done when the house is warm and the wood has been kept dry (FPL 1961).

Interior Trim

In a building under construction, average relative humidity will be greater than that in an occupied house because of the moisture that evaporates from wet concrete, brickwork, plaster, and even the structural wood members. The average temperature will be lower because workers prefer a lower temperature than is common in an occupied house. Under such conditions, the interior trim tends to have greater moisture content during construction than it will have during occupancy.

Before the interior trim is delivered, the outside doors and windows should be kept closed at night. In this way, interior conditions are held as close as possible to the higher temperature and lower humidity that ordinarily occurs during the day. Such protection may be sufficient during dry warm weather, but during damp or cool weather, it is highly desirable to heat the house, particularly at night. Whenever possible, the heating system should be placed in the house before the interior trim is installed, to be available for supplying the necessary heat. Portable heaters can also be used.

Keep the inside temperature during the night about 8 °C (15 °F) greater than the outside temperature but not below about 21 °C (70 °F) during the summer or 17 °C (62 °F) when the outside temperature is below freezing.

After buildings have thoroughly dried, less heat is needed, but unoccupied houses, new or old, should have some heat during the winter. A temperature of about 8 °C (15 °F) greater than the outside temperature and above freezing at all times will keep the woodwork, finish, and other parts of the house from being affected by dampness or frost.

Plastering

During a plastering operation in a moderate-sized, six-room house, approximately 450 kg (1,000 lb) of water is used, all of which must dissipate before the house is ready for the interior finish. Adequate ventilation removes the evaporated moisture and keeps it from being adsorbed by the framework. In houses plastered in cold weather, the excess moisture can also cause paint to blister on exterior finish and siding. During warm, dry weather, with the windows wide open, the moisture will be gone within a week after the final coat of plaster is applied. During damp, cold weather, the heating system or portable heaters are used to prevent freezing of plaster and to hasten its drying. Provide adequate ventilation constantly because a large volume of air is required to carry away the amount of water involved. Even in the coldest weather, the windows on the side of the house away from the prevailing winds should be opened 50 to 75 mm (2 to 3 in.), preferably from the top.

To find similar courses based on other chapters of the