Lumber Drying:
An Overview of Current Processes

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Contents

Wood and water

All parts of a living tree contain water. Water is a critical component in the process of photosynthesis leading to the formation of new tree cells and subsequent growth. Water often makes up over half the total weight of the wood in a tree. This water in the tree is sometimes referred to as “sap.” Although the sap contains a variety of minerals and other materials in solution, from the drying perspective it is considered to be plain water.

The water or *moisture content* (MC) of wood is expressed, in percent, as the weight of water present in the wood divided by the weight of dry wood-substance. As an example, a 30-lb board, which contains 10 lb of water and 20 lb of dry wood-substance, would have a MC of 50%. MC may be greater than 100% because the weight of water in the wood can be larger than the weight of dry wood-substance.

Green (freshly cut) wood may have an MC as low as 30% to as high as 250%. Sapwood usually has a higher MC than heartwood. Average green-wood MCs may vary considerably from one tree to another, among boards cut from the same tree, and with the time of year the tree is cut.

Most of this water must be removed in order to obtain satisfactory performance from wood that is to be processed into consumer and other types of useful products.

When the tree dies from natural causes—such as fire, insects, disease, ice, snow, or wind damage—the wood immediately begins to lose some of its moisture to the surrounding atmosphere. When a tree is converted to logs, lumber, veneer, and chips, the wood immediately starts to dry. If drying continues long enough, the dimensions and the physical properties of the wood begin to undergo change.

Because wood is made up of various kinds of cells, some water remains within the structure of the cell walls even after it has been manufactured into lumber or other wood-based products. The physical and mechanical properties, resistance to biological deterioration, and dimensional stability of any wood-based product are all affected by the amount of water present.

To understand drying, we need to know that water is contained in wood cells in two ways: Wood can hold moisture in the cell *lumen* (cavity) as liquid or “free” water, or as adsorbed or “bound” water attached to the cellulose molecules in the cell wall. Figure 1 (page 2) shows these two conditions.

The occurrence of free water does not affect the properties of wood other than its weight. Bound water, however, does affect many properties of wood, and is more difficult to remove in the drying process.

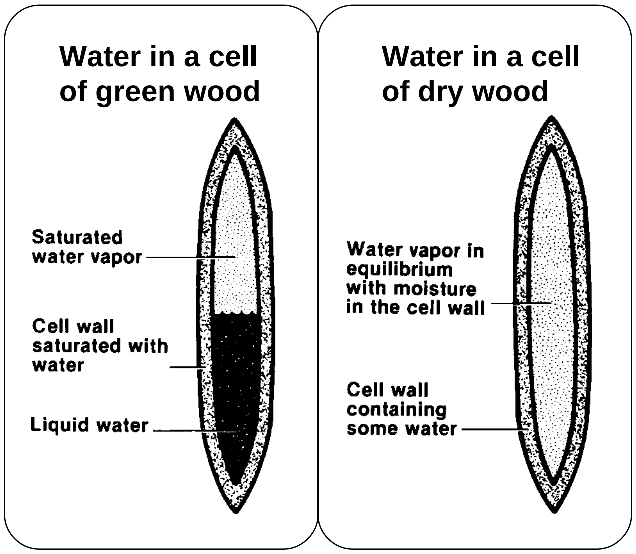

Figure 1. Two ways water is contained in wood.
Source: Haygreen, J.G. and J.L. Bowyer. 1996. "Forest Products and Wood Science." Iowa State Univ. Press, Ames, IA. 484 pp.

Green wood is considered to be in the condition where the cell walls are saturated and lumen contain a variable amount of liquid water. During drying, free water leaves the cell lumen first. When the cell lumen is completely empty, but the cell wall remains saturated with the more tightly held bound water, wood is said to be at the *fiber saturation point* (FSP). FSP is about 28 to 30% MC.

The FSP is of particular interest because changes in shrinkage and strength occur below this point. **It is only when bound water begins to leave the cell walls that the wood begins to shrink and its strength begins to increase.**

Related to wood **shrinkage** the FSP is commonly considered to be 30% MC, but for **strength property calculations**, FSP is taken as 25%.

Actually, all wood—not in direct contact with water—gains or loses moisture by adsorption and evaporation in an attempt to reach a state of balance or equilibrium with the atmospheric conditions within which it is stored or used. This state of equilibrium depends upon the relative humidity of the surrounding air and is called the *equilibrium moisture content* (EMC).

The relationship between EMC and ambient humidity is essentially independent of wood species. In most regions of the U.S. lumber piled out-of-doors will reach an EMC of 12 to 18%. Such lumber is termed *air-dried.*

As shown in Figure 2, Graph A, the EMC is the MC a piece of wood will eventually reach in a given relative humidity condition. Thus, the eventual MC of wood depends on relative humidity. The **rate** at which the EMC is reached depends on many factors, including temperature, lumber properties, thickness, and original MC.

In construction standards, *dry* lumber is defined as having 19% or less MC. *Kiln-dried* lumber used in furniture manufacture usually has from 6 to 8% MC. In the construction industry, kiln-dried lumber refers to wood of 15% MC and less.

Changes in the environment will subject wood

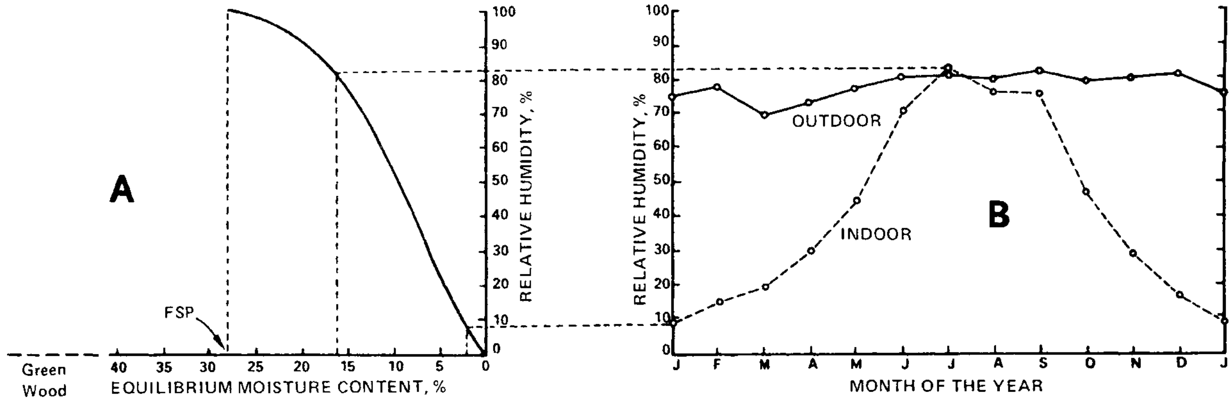

Figure 2. Relationships between (A) equilibrium moisture content (EMC) and relative humidity, and (B) average monthly indoor and outdoor relative humidities during a typical year in the Northeast. (Monthly averages plotted for Amherst, MA, 1981. Indoor data based on outdoor relatively humidity converted to 70° F basis.)
Source: Hoadley, B. 1981. "Understanding Wood." The Taunton Press, Inc., Newton, CT. 256 pp.

to seasonal long-term variations of temperature and humidity as well as daily, short-term variations. Through the evaporation / adsorption process, the MC of wood will attempt to follow these variations. Equilibrium indoor MC values are 12 to 15% in humid summertime conditions and can be as low as 2 to 5% for dry midwinter conditions indoors. Surface MC will adjust to ambient changes rapidly. Figure 2, Graph B shows some average monthly indoor and outdoor relative humidities in the Northeast.

The process of drying focuses on producing wood with an MC about the same as the equilibrium value for the intended service environment.

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

Drying concepts

Drying is the removal of water from wood. However, unlike many wet materials that must be dried, wood must be dried at **specified rates** to avoid *degrade* (value loss). If degrade were no concern, lumber could be dried in minutes.

The dimensions of a wood specimen do not vary with MC if the MC value is above the FSP (except in the case of a drying problem called “collapse”). Below the FSP, however, substantial dimensional changes occur with MC changes.

Macroscopically, the dimensional change with MC is *anisotropic* (referring to the fact that wood has very different properties parallel to the grain versus the transverse direction). As the MC decreases, wood shrinks; conversely, as the MC increases, wood swells or grows larger.

Loss of water results in changes in many of the properties of wood, such as strength and both thermal and electrical conductivity. Of perhaps greater importance is the fact that moisture loss from the cell walls (i.e., below FSP) results in **shrinkage**. The basic cause of drying degrade is wood shrinkage often 5% or more.

To complicate things, wood shrinks different amounts in different directions. Shrinkage parallel to the annual growth rings (*tangential shrinkage*) is twice as much as shrinkage perpendicular to or across the annual rings (*radial shrinkage*). Shrinkage along the grain (vertical direction in a standing tree), also known as *longitudinal shrinkage*, is so small—usually less than 0.1%—that it is ignored in most cases. Shrinkage along the grain is important for juvenile, compression, and tension wood where longitudinal shrinkage may be as much as 3%.

In drying from the FSP to the oven-dry condition, wood will shrink an average of 8% of its green dimension tangentially (parallel to growth rings) and about 4% radially (across the growth rings).

As wood dries, then, from the outside inward, it also begins shrinking, or trying to shrink, from the outside inward. Changes in MC result in strain and strain-induced stresses, the magnitudes of which are sufficiently large to produce configurational strain known as *warp* and *fracture*. Specific types of warp are cup, bow, twist, and crook. Specific types of fracture are checking and splitting. Figure 3 illustrates various types of warp that develops in boards during drying.

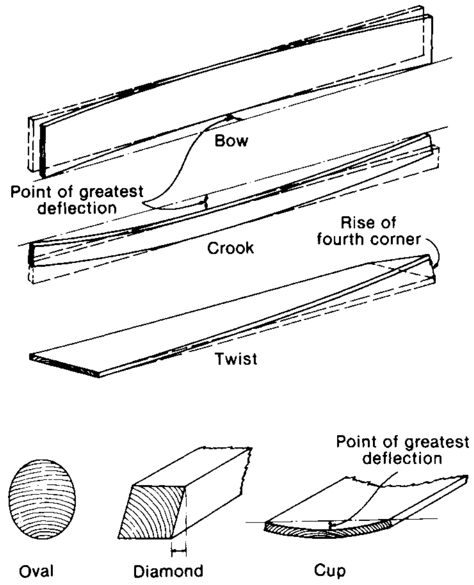

Figure 3. Various types of warp that develop in boards during drying.
Source: Simpson, W.T., ed. 1991."Dry Kiln Operator’s Manual." Agric. Handbook No. 188, U.S. Dept. of Agriculture. 274 pp.

Because of this anisotropic shrinkage, the resultant shape of a given wood specimen after drying—compared with the green-cut shape—will depend on the original orientation of the specimen with respect to the cylindrical coordinates of the tree.

The directional variations in wood shrinkage are illustrated in Figure 4. To minimize directional variations in use, wood needs to be dry enough to match the service environment.

Therefore, the key philosophy behind drying, as it is practiced today, is to control drying conditions so that shrinkage and resultant stresses and strains are controlled, which in turn will control degrade.

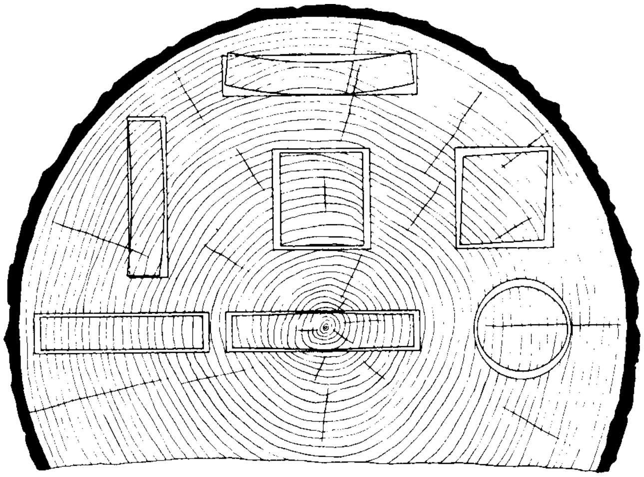

Figure 4. Characteristic shrinkage and distortion of flats, squares, and rounds as affected by the direction of annual growth rings. (The dimensional changes shown are somewhat exaggerated.) *Source: Simpson, W.T., ed. 1991. "Dry Kiln Operator's Manual." Agric. Handbook No. 188, U.S. Dept. of Agriculture. 274 pp.*

Why we dry wood

We dry wood for several reasons. Among the most important are the following:

Minimize changes in dimension: Wood will shrink or swell with changes in MC. If it is dried to the MC it will attain in use and is then placed in a reasonably stable environment, further changes in dimension will be imperceptible.

Improve strength properties: Increase in strength properties begins when the FSP is reached. Exception is toughness or shock resistance, which decreases.

Prevent stain and decay: Usually no fungal attack occurs when wood MC is 20% or less. Infected wood is sterilized at 150° F or greater. Wood can be re-infected if rewetted. No insect attack occurs at 10% MC or less. Exceptions are dry wood termites and some beetles.

Prepare for further treatment:

- <u>Gluing</u>: Wood needs to be stress free, with no checks or splits. Examples with target MCs:
  - Laminated timber: 10-12% MC
  - Softwood plywood: 3-5% MC
  - Furniture, interior millwork: 6-8% MC

- <u>Preservation</u>: Specifications for treatment of various wood products by pressure processes have been developed. These specifications limit pressures, temperatures, and time of conditioning and treatment to avoid conditions that will cause serious injury to the wood. They also contain minimum requirements for handling wood after treatment to provide a quality product. MCs are part of the specification process. Wood can also be treated by various non-pressure methods.

- <u>Fire retardants</u>: To meet the specifications in the building codes and various standards, fire-retardant-treated lumber and plywood is wood that has been pressure-treated with chemicals to reduce its flame-spread characteristics. Various target MCs are part of the specifications depending on application.

- <u>Paints and finishes</u>: The recommended MC for wood used in exterior applications varies somewhat depending on climatic conditions. However, problems associated with changes in MC should be minimized if the MC is between 9% and 14%. If MC of the wood exceeds 20% when the wood is painted, the risk of blistering and peeling is increased. Also, dark watersoluble extractives in woods like redwood and western red cedar may discolor the paint shortly after it is applied.

Reduce product weight: Shipping costs by rail and truck are based on weight. Kiln drying is preferred to air drying when it is critical to:

- maintain shipping schedules;
- reduce drying costs in some cases due to land rent and financing charges connected with air drying;
- attain a low MC (e.g., below 12 to 15%).

Drying methods

The various methods used to dry lumber can be divided into two categories: the commonly used procedures of air-drying and kiln-drying, and the specialized techniques using chemicals, solvents, vacuum retorts, solar energy dehumidifiers, high frequency generators, etc.

Although the primary objective of all drying methods is to remove water from wood, the selection of a particular procedure will depend on several other factors such as capital investment, energy sources, production capacity, drying efficiency, and end product. The special drying techniques are usually expensive and oriented to particular high-value end products.

Commonly used drying methods

The economically feasible, industry-adopted systems especially differ in the degree of environmental control they provide.

Air drying: Wood is exposed to the outside environment, possibly protected only from direct rainfall with portable roofs or by a shed.

Forced air drying: Wood is exposed to the outside environment, but fans provide circulation in addition to or in lieu of wind. Wood is protected from rainfall often in a shed or pole building with louvered sides.

Low-temperature drying: Wood is exposed in a building, with temperatures as high as 130° F, but usually between 80° and 110° F; humidity may be partially controlled i.e., usually vents are provided in order to lower humidity. Circulation is provided by fans with velocities through the lumber pile around 500 feet per minute (fpm). There are three types of low-temperature dryers: 1) **solar-heated or solar dryer**: low cost, but dependent on the weather; 2) **dehumidifier dryer**: very good control system, but expensive; and 3) **steam-heated dryer**: medium cost range, but control is usually not as precise.

Conventional kiln drying: Wood is exposed in a permanent, insulated structure with temperatures as high as 200° F, with humidity control often provided by steam spray and vents. Circulation is provided by fans with velocities of 250 fpm to 400 fpm common. Note: The name "kiln drying," although very widely used, is somewhat a misnomer, as a kiln is used in both low- and high-temperature drying as well. Perhaps more descriptive terms would be moderate-temperature or conventional kiln drying.

High-temperature drying: Wood is exposed as in kiln drying, except the temperature range is 212° F to 240° F and research is being conducted at temperatures over 300° F. Velocities are usually above 800 fpm.

Specialized drying approaches

Dehumidification drying: The major difference between dehumidification and other types of drying 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.

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; they offer good control in drying *refractory* (difficult-to-dry) 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 electric 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.

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.

Solar drying: 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. This free energy is also low-intensity energy, which often limits the operating temperature of a solar kiln to about 130° F unless expensive special solar collectors are used. Another advantage of solar kilns is that relatively small, simple, and inexpensive kilns are possible, and this level of technology is often well suited to small-scale operations.

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 operate with solar energy alone or with supplemental energy. There are four types of solar kilns:

- Direct collection or greenhouse
  a) Solar only, which is typified by wide diurnal (within a 24-hour period) and day-to-day changes in temperature and relative humidity.
  b) Solar with supplemental energy, which is typified by the ability to follow a drying schedule and has large nighttime heat losses because of the low insulating ability of the transparent cover.
- Indirect collection or isolated drying compartment
  a) Solar only, where the diurnal change in temperature and relative humidity can be reduced by energy storage and decreased heat losses at night.
  b) Solar with supplemental energy, where scheduled drying is possible and nighttime losses are minimized.

A solar kiln design for northern latitudes is shown in Figure 5.

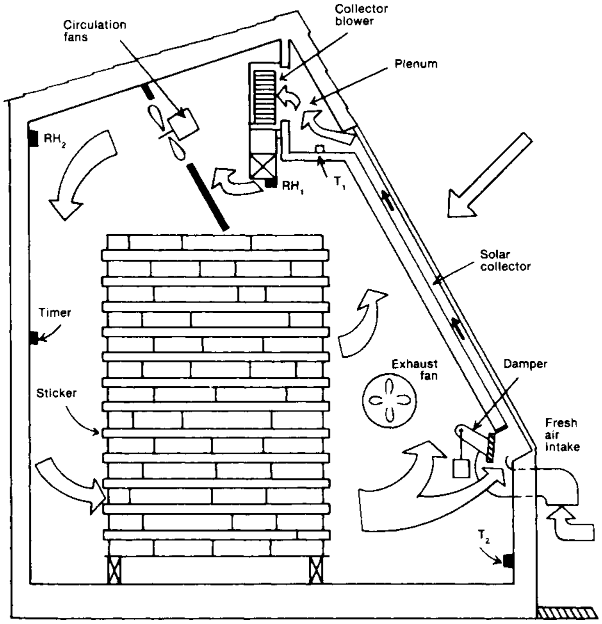

Figure 5. Solar kiln design for northern latitudes, showing inexpensive control system.
Source: Simpson, W.T., ed. 1991. "Dry Kiln Operator's Manual." Agric. Handbook No. 188, U.S. Dept. of Agriculture. 274 pp.

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

Non-industrial private forest landowners are showing increased interest in employing small-scale dry kilns (solar and other types) linked to their sustainable forest management activities.

Vacuum drying: Prior to the 1970s, vacuum drying was considered uneconomical. Since then, the economics of vacuum drying have become more favorable, especially for drying thick, refractory, high-value species. Such stock can be safely dried in a vacuum kiln in a small fraction of the time required in a conventional kiln.

The major 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^o F. Vacuum drying is basically high-temperature drying at low temperatures.

The main difference between the several types of vacuum kilns is the way in which heat is transferred to the lumber. Air is effectively eliminated as a heating medium during the vacuum period, and without heat the diffusion of moisture through wood is extremely slow.

Indoor humidity variation

It is important to know—especially for wood craftspersons and hobbyists—that in a heated building there is drastic seasonal variation in average relative humidity, which can affect the moisture content of wood. Warm air is capable of holding more moisture than cool air. Therefore, when cold outside air with a given amount of moisture is heated to room temperature, its capacity to hold moisture increases—i.e., the relative humidity drops. So, the colder the outdoor temperature, the lower the relative humidity drops when the air is heated to room temperature.

As Figure 2, Graph B (page 2) shows, the relative humidity indoors may be less than 10% on a cold, below-zero day in winter. On a summer day, with doors and windows open, hot and humid air entering a building retains its high relative humidity. Therefore, indoors, a thin piece of unfinished wood, or the surface of a thick piece may drop to 2% MC or less on winter days and rise to 16% or more during summer.

Storage

Storage conditions for lumber should be selected with consideration for the original moisture condition of the lumber, its intended use requirements, and the relative humidity in its storage location. For example, kiln-dried lumber at 8% MC should not be left outdoors in unprotected piles. Covering or wrapping kiln dried lumber with plastic film or heavy paper, especially if seams are taped, will help to retard moisture exchange with the atmosphere. Basements may be quite humid, especially in summer. Areas near heat sources, such as boiler rooms, may be much too dry, especially in winter. Humidification or dehumidification units aid in controlling humidity to desired levels.

Glossary

Air-dried lumber: Lumber with an equilibrium moisture content (EMC) of 12 to 18%. Lumber dried by exposure to outside air without artificial heat.

Anisotropic: Refers to the fact that wood has very different properties parallel to the grain versus the transverse direction. This contrasts with materials like metals, plastics, and cement products which are *isotropic*—i.e., have the same properties in each direction.

Degrade: Loss of value due to drying defects.

Dry lumber: Lumber having 19% or less moisture content.

Equilibrium moisture content (EMC): State of balance with the atmospheric conditions within which wood is stored or used. The MC at which wood neither gains nor loses moisture when surrounded by air at a given relative humidity and temperature.

Fiber saturation point (FSP): When the cell cavity is completely empty but the cell wall remains saturated with the more tightly bound water. Usually taken as approximately 30% MC based on oven-dry weight.

Fracture: Configurational strain—physical separation of wood fibers; specific types are checking and splitting.

Green: Freshly cut wood; may have an MC as low as 30% to as high as 250%.

Kiln-dried lumber: Lumber used in furniture manufacture, usually having from 6 to 8% moisture content. Lumber dried in a kiln with the use of artificial heat.

Longitudinal shrinkage: Shrinkage along the grain (vertical direction in a standing tree).

Lumen: In wood anatomy, the cell cavity.

Moisture content (MC): Water content of wood, expressed in percent, as the weight of water present in the wood divided by the weight of dry wood-substance.

Radial shrinkage: Shrinkage perpendicular to or across the annual growth rings.

Refractory: In the case of wood, refers to species that are difficult to dry.

Tangential shrinkage: Shrinkage parallel to the annual growth rings.

Warp: Configurational strain—any variation from a true or plane surface; specific types are cup, bow, twist, and crook or any combination thereof.

Further reading and specialized reference handbooks

The specifics of operating a lumber air-drying yard or dry kiln are explained in detail in several excellent handbooks. These detailed publications are invaluable reference guides for kiln operators and managers in charge of wood-drying operations. They are also very helpful for home hobbyists, craftspersons, and others involved in small-scale drying of lumber.

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