Principles and Practices of Drying Lumber

Eugene M. Wengert, Extension Specialist
Brooks Forest Products Center
Virginia Polytechnic Institute and State University
Blacksburg, Virginia

Table of Contents

List of Tables and Figures

Why Dry Wood?

The answer to the question "Why dry wood?" must be "...To make money!" If it isn't profitable, then we generally don't do something. To understand what is profitable about an energy using, time consuming, labor intensive procedure, let us look more closely at what happens when we dry.

Wood is a biological material that, when in the tree, contains large amounts of water. As wood dries to a moisture content (MC) in equilibrium with its in-use environment, many of its properties and characteristics change.

- Much of the shrinkage that occurs when wood dries to its in-use MC will occur in the lumber dryer rather than in the manufactured product. Drying, therefore, eliminates, or reduces to a minimal level, a major source of frustration that a consumer has with wood-shrinkage and swelling.

- Dry wood has little or no likelihood of developing new cracks, checks, or splits.

- Dry wood (below 22% MC) will not decay, mold, mildew, or stain. At lower MC levels, there is not enough moisture for the fungi that cause decay, mildew, and so on to grow.

- Dry wood is much lighter in weight than wet wood. For many species, dry wood is nearly half the weight of wet wood. As an example, an "18-wheeler" can haul about 7500 BF of green oak without exceeding the load limits, but can haul 12,500 BF of dried lumber.

- Dry wood is nearly twice as strong and twice as stiff as green wood.

- Dry wood (if it is not too dry) fastens better, glues better, and machines better than wet wood.

- Dry wood can be treated more effectively with fire retardants than wet wood.

It is these changes in properties that make it profitable to dry lumber.

How Dry Should Wood Be?

In general, wood should be dried to a moisture content within two percent of its in-use MC. For furniture, cabinetry, millwork and other products used in homes or offices, the in-use MC is 6 to 8% (equivalent to 30 to 45% relative humidity, which is the typical range for interior climates in North America). Adjustments have to be made for drier humidities, such as occur during the winter in heated buildings that are not humidified, and for wetter humidities, such as along the Southern and West coast.

Wood intended for use outdoors, is generally dried to higher MCs-12 to 16% MC. Wood for bending is dried to 25% MC for severe bends and 18% for mild bends. Softwood construction lumber (2x4, 2x6, etc.) is usually dried to a maximum of 19%, 15%, or 12% MC, as governed by the American Lumber Standard requirements.

The relationship between humidity and wood moisture content is the critical factor in determining in-use MCs. Temperature has no important effect. Based on spruce, the following values were established:

Table I Approximate Relationship Between RH and EMC at Room Temperature

RH	EMC
-%-	-%-
0	0
15	3.5
30	6
50	9
65	12
80	16
90	20
95	24
100	28

The EMC (Equilibrium Moisture Content) is the numerical value of the in-use MC for the spruce at equilibrium with the indicated humidity. Almost all species of wood have similar values as spruce, varying by less than 2% EMC below 80% RH. Some species, especially those with a lot of extractives, and many tropical species will vary at the higher RH values, with the EMC for those species usually being lower than for spruce.

It should be noted that the most common cause of manufacturing defects in furniture and cabinet plants that occur after drying (probably 85% of the defects that I am called on to help cure) is incorrect MC. Careful attention must be paid to the humidity (not the temperature) in which lumber is stored, manufactured, shipped, and used to assure that the MC of the dried lumber or wood product is kept close to the final, in-use EMC at all times.

Wood Drying Methods

If the major objective of drying lumber is to make money, then the lumber must be dried with minimal development of degrade. Degrade includes splits, checks, warp, discoloration, and any other change in wood that lowers the wood's usefulness and therefore its value. Often degrade losses exceed all other operating costs in drying! For example, it costs approximately $3 per day per MBF to operate a dry kiln with oak lumber-saving one day in drying time will save $3 per MBF in operating costs. But if degrade increases $3 per MBF due to faster drying (and a $3 increase is certainly a small amount of degrade), there is no savings in faster drying.

There are basically five conventional methods of drying in use today-air drying, forced-air air-drying, low temperature drying (including both warehouse predrying and dehumidification drying), conventional kiln drying, and high temperature drying. These methods each have their own characteristics, which in turn affect performance and costs for difference species and thicknesses. These characteristics are briefly summarized below for all but high temperature drying; high temperature does not have any practicality for hardwoods today. In addition to these five methods, vacuum drying also has some industrial practicality, especially for drying squares and for smaller production requirements.

It is important to appreciate the characteristics of a drying system, as many times drying quality and costs are limited by the system and not by the controls or operator's procedures. With the proper equipment and tools and knowing how to use them, drying costs can be minimized and drying degrade will be under 2%.
The following discussion presents a summary of the various drying methods. These data were obtained from the author's experience and from several publications, including Drying Oak Lumber by Gene Wengert from the University of Wisconsin, Drying Eastern Hardwood Lumber, USDA Agricultural Handbook No. 520, and Opportunities for Dehumidification Drying from the Virginia Lumber Manufacturers Association.

Air Drying

Air drying is the exposure of lumber to outside environmental conditions, with no artificial heating, control of velocity, or control of humidity. The lumber may be protected from the rain and sunlight with a small roof on each pile of lumber or by sheds. Sheds greatly reduce degrade. The details of air drying are covered very well in USDA Handbook No. 402, Air Drying of Lumber written by Ray Rietz. High degrade risks make this method very expensive for degrade prone species and thicknesses. However, sheds can reduce the degrade substantially and make it possible to economically dry species such as oak. In fact, shed air-drying is often the best (most economical) method of drying thick oak.

Forced-Air Air-Drying (or Fan Shed Drying)

Forced-air air-drying is a drying system where the lumber is stacked conventionally and then placed under outside sheds for drying. The sheds have a large number of fans that pull outside air through the lumber pile. The roof (with an adequate overhang) keeps rain and sun off the lumber thereby providing very fast drying with minimal degrade losses. As a rough rule of thumb, air velocity is about 700 fpm and maximum air flow path is 20 feet. Typically, there is 1 hp of fan power for every 6 MBF in the dryer. This drying method is especially attractive for fast drying, low-degrade-risk species and thicknesses.

Low Temperature Warehouse Predrying

A warehouse predryer is a large building, holding as much as 1.5 million BF of stickered lumber. Fans circulate air through the lumber piles. Heat is provided typically with steam heating coils. Venting is provided with a fan powered exhaust system. Usually there is no humidification system other than moisture added by the drying lumber. This method of drying is most popular for oak and other hard to dry species.

Low Temperature Dehumidification Drying

Dehumidification drying is a form of kiln drying. With a dehumidifier, moisture is removed from the dryer by condensing the moisture on cold coils. When the water condenses, heat is released which is then put back into the dryer and used to evaporate more water from the lumber. As a result of this recycling, the dryer is very energy efficient. The heat pump is electrically operated. The pump is typically sized to provide 1 hp per MBF of lumber; smaller sizes are used for slower drying species and larger sizes for easier drying species. The building is usually well insulated, to avoid wasting electrically generated heat. The building may be wood frame or prefabricated aluminum.

Normal Temperature or Conventional Temperature Kiln Drying

This is the tried and tested method of drying lumber; it has been used for decades for both hardwoods and softwoods. Quality is usually outstanding, if the equipment is designed and operated correctly. Lumber is stacked for drying and placed in a kiln. Fans circulate air through the load, with heat provided by steam coils. Excess moisture is exhausted through vents. Moisture may be added with steam spray. Operating techniques are well covered in USDA Agriculture Handbook No. 188, Dry Kiln Operator's Manual. Today most new kilns are aluminum prefab, with a masonry structure sometimes being seen. In either case, at least two inches of insulation are worthwhile to conserve energy and avoid uneven temperatures in the dryer.

Drying Systems

The above mentioned drying methods are then combined into several different drying systems. An assessment of these systems is provided in Table 2.

Table II Drying Systems and Quality for 4/4 Lumber

Drying System	Oak, Beech	Hickory, Pecan, Hard Maple	Ash, Basswood, Yellow-Poplar, Gum, Soft Maple, Pine, Aspen
AD-NT	F-P	OK	OK
AD(Shed)-NT	VG	VG	VG
FAAD-NT	NS	F-P	VG
LT	VG	VG	VG
LT-NT	VG	VG	VG
NT	OK	VG	VG

VG = very good; **OK** = okay; **F-P** = fair to poor; **NS** = not suggested

Degrade

One of the key points in evaluating a drying system is the degrade level. Further, where two drying methods are combined into a drying system, such as air drying followed by kiln drying, any damage done in the first method cannot be repaired or mitigated in the second method. Specifically, lumber damaged in air drying or predrying will not improve during kiln drying, even when kiln drying is done perfectly.

The following comments on degrade in the various drying methods are intended as an outline. Further information is provided in the publications mentioned previously.

Air Drying Degrade

Degrade or loss in value in an air drying operation can exceed 10 percent of the lumber value. For a well maintained and operated air dry yard drying easy-to-dry species, degrade costs may be about $10/MBF. For a poorly operated yard, or for drying thick, hard-to-dry or high value species, degrade costs may exceed $150/MBF. The degrade costs are typically in the range of $21 to $54 per MBF. The keys to controlling air drying degrade are to avoid wetting and drying cycling (that is, exposure to rain and sun), to dry at a reasonable rate for the species and thickness being dried, and to move the lumber into the kiln as quickly as possible, (that is, avoid storage of dry lumber on the air drying yard).

Forced-Air Air-Drying Degrade

FAAD systems usually have low degrade for easy-to-dry species such as yellow-poplar, maple, and pine. Typically, the degrade costs range from $9 to $24 per MBF. Degrade is lower than air drying because the lumber is protected from rain and sunlight. However, for check-prone wood, such as oak, the drying will be too fast and excessive degrade will occur.

Predryer Degrade

If properly operated, predryers can have as little drying degrade as any of the drying systems. Predried lumber is bright, clean, and of excellent quality as compared with air-dried lumber. Drying degrade should be less than $10/MBF when the units are properly designed and operated.

DH Degrade

If properly operated, DH dryers can have as little drying degrade as any of the drying systems. Lumber is bright, clean, and of excellent quality as compared with air dried lumber. Drying degrade should be less than $10/MBF.

Kiln Drying Degrade

If properly maintained and operated, a dry kiln will provide good drying quality for most species. Drying degrade can be held to about $9 to $15 per MBF. When drying air-dried or predried lumber, it is rare to have any degrade attributed to the kiln operation; all degrade is formed beforehand.

How Wood Dries-Definitions

The following definitions are presented as background for understanding the principles of wood drying and for understanding the practical aspects of drying as well.

Definitions Related to Wood and Its Structure

Longitudinal

Wood has three directions, with different properties in each direction. The vertical direction in the standing tree, and therefore the length direction in lumber, is called the longitudinal direction. Two important characteristics of the longitudinal direction are that water moves up to 50 times faster in this direction (i.e., end grain dries much faster than side grain) and wood shrinks very little in this direction. (Note discussion of reaction wood and juvenile wood as well.)

Radial

The radial direction is along a radius of the circular cross section (from the bark to the center), like the spokes of a wheel. Water moves faster in this direction than in the tangential direction. Therefore, flatsawn or plain-sawn wood will dry faster than quartersawn or rift-sawn wood. Also, shrinkage is less (about one-half) radially than tangentially.

Tangential

The tangential direction is parallel to the annual growth rings (or perpendicular to the radial direction) in a circular cross section. Water moves most slowly in this direction. Shrinkage is greatest in this direction.

Flatsawn or Plain-sawn

Lumber that has its wide face parallel to the annual growth rings (i.e., its wide face is a tangential surface) is flatsawn. This lumber, as it dries or with changes MC after drying, will shrink more in width than quartersawn lumber, making it difficult to keep paint on flatsawn lumber when the lumber is exposed to frequent wetting and drying. Flatsawn lumber dries faster than quartersawn lumber. Flatsawn lumber is more likely to develop surface checking than quartersawn lumber.

Quartersawn or Rift-sawn

Lumber that has its wide face perpendicular to the growth rings (i.e., its wide face is a radial surface) is quartersawn. This lumber shrinks more in thickness than flatsawn lumber, but shrinks less in width. It also dries more slowly. There is virtually no risk of surface checking on the face.

Cells

The building block of wood is the wood cell, which is a tubular structure, much like a miniature soda straw, that is 100 times longer than its diameter. The cell is typically 2 to 3 mm (roughly a tenth of an inch) long in hardwoods and 3 to 5 mm long in softwoods. The cells are hollow (the hollow space is called the lumen) with a cell wall of varying thickness, the thickness depending on many factors including the time of year, the location in the tree, and the wood species. Most of the cells (85 to 95%) are oriented vertically in the tree. These cells are called tracheids, vessels, and parenchyma. A few cells are oriented horizontally, in the radial direction; these cells are called rays, and assist in conduction of water in the radial direction. (That is why flatsawn lumber dries faster than quartersawn.)

Sapwood

As cells are formed to increase the diameter of a tree, they are initially alive and participate in the conduction of fluids from the roots to the leaves and from the leaves to the roots. Soon, these cells reach their maximum size and die. However, they still participate in conduction of fluids for many years. These cells, which are usually white in color when in lumber and which dry quickly due to their open structure, are called sapwood.

Heartwood

As a tree matures and increases its diameter, the cells in the center, which are the oldest, are converted from sapwood to heartwood. This conversion usually involves the deposition of chemicals within the hollow spaces (the lumens) of the cells, changing the color and often the odor of the wood. These chemicals also slow water movement in the heartwood-heartwood dries more slowly than sapwood. It is also common to see that heartwood shrinks less than sapwood. Sapwood is more likely to check than heartwood in many species.

Juvenile wood

As a stem is first formed, whether near the ground or many feet in the air, the first several years of growth (for example, about 20 years in southern pine) are characterized by cells that shrink more (especially along the grain) and are not as strong as more mature wood. This wood is called juvenile wood or is called the juvenile core. Because shrinkage along the grain can exceed 3% in juvenile wood, longitudinal shrinkage defects including bow and crook are common when part of a piece of lumber has the juvenile core while the rest of the piece has more mature wood.

Reaction wood, (Tension wood and Compression wood)

Hardwood trees when stressed externally, such as when another tree falls against a tree, develop a reaction to this outside force. The reaction is the development of wood cells, called tension wood, in future growth where there are tension forces (usually on the opposite side of the stem from a leaning tree). Tension wood has an extra layer of material in the cell wall, making the cells more dense and making it more difficult for water to move. This extra layer, however, does not contribute substantially to the strength of the wood, so tension wood is often weaker than would normally be expected. Tension wood also machines poorly, creating abnormally fuzzy surfaces. The fuzz can be easily noted or may be very fine and require special lighting. Tension wood often causes finishing problems, especially with water based stains.

Compression wood is the opposite of tension wood in some ways-it develops in softwoods and on the same side of the stem where there are compression forces. The cell walls are very thick, slowing moisture movement, and are weak. Compression wood shrinks along the grain (longitudinally), resulting in bow and crook in lumber during drying.

Earlywood

The cells formed early in the growing season of a tree are called earlywood or springwood. They typically have thin cell walls and are quite large. Water moves quite easily in the earlywood.

Latewood

The cells formed toward the later part of the growing season are called latewood or summerwood. They typically are smaller in diameter and have thicker cells walls than earlywood. Water moves more slowly in summerwood.

Shrinkage

The change in dimension of wood that occurs when it dries is called shrinkage. The individual cells begin shrinking when they are at the fiber saturation point (28% MC) and the shrinkage continues linearly with a decrease in MC to 0% MC. Lumber, because some cells are at fsp very early in drying, begins shrinking very early in drying at very high MCs (within 5% of its "tree green" MC) and continues shrinking until equilibrium is reached. Whenever the relative humidity changes, wood will lose MC and therefore shrink if the humidity is lowered, or gain MC and therefore swell if the humidity is raised. Temperature change has no important effect on shrinking or swelling of wood. (See also **Fiber Saturation Point** on Page 15.)

There is a great deal of variation in the amount of shrinkage. It varies from very little (in teak shrinkage is a maximum of 5.8%) to quite a lot (as much as 12.7% in oak). There are variations in the same species, as well. In addition, wood shrinks differently in the different directions-longitudinally, wood shrinks a maximum of 0.3% which is so small as to be ignored; radially, wood typically shrinks 3 to 8%; tangentially, wood typically shrinks 6 to 16%. Usually, the more dense the wood, the more it shrinks.

As an example of the variation of shrinkage, consider some of the eighty species that we classify as red or white oak (Table 3). In general, the greater the shrinkage, the more difficult the wood will be to dry without developing cracks, splits, and checks.

Sometimes during the early stage of drying, water is removed too quickly from a cell and the cell is sucked inward (like sucking on a straw that has one end closed). The cell collapses. Shrinkage, where many cells collapse, appears much greater than normal or expected. After drying, when collapsed cells are exposed to liquid water or wet steam, they will usually return to their expected size as if they hadn't collapsed (i.e., the collapse is recovered).

Also important in shrinkage is the amount that occurs after drying when the MC is incorrect. Considering that glue lines can have gaps no larger than 0.006 inches, a small change in MC can result in poor gluing. For example, see the size changes in a 3 inch wide piece of wood when the MC changes (Table 4).

Fiber Saturation Point

Water is held in wood in two locations. One is in the hollow center region (the lumen) of the cell. This water is held due to the physical size of the cell. Theoretically, this water could be blown out of the cell just like blowing the soda out of a soda straw. This water is called "free water." Water is also held in the cell wall, but this water is chemically held in the wall. It is called bound water.

When a cell is dried, the free water is removed first. When all the free water is removed, but the cell wall is still saturated, the cell is at the fiber saturation point (fsp). The approximate MC of the fsp is 28%, but this varies with species. When drying up to this point (i.e., from "tree green" to the fsp), the wood cell has not shrunk (unless it has collapsed, which is rare). As the cell begins to dry below the fsp, bound water is removed from the cell wall and the cell begins to shrink. Shrinkage continues until 0% MC.

Note that the discussion above has referenced the wood cell. In a piece of drying lumber, cells on the outside will dry below the fsp and begin shrinking quite quickly. Cells in the center of the piece may require weeks, in some cases, before they reach the fsp and begin shrinking. Therefore, it is incorrect to say that a piece of wood is "at the fsp" when it is at 28% average MC. In fact, at 28% MC, some of the cells are well below the fsp and have shrunk, or tried to shrink quite a bit, while other cells are still well above the fsp and haven't begun to think about shrinking.

Table III Variation in Shrinkage for Different Oak Species

Species	Shrinkage, Green to 0% MC	
	Radial	Tangential
	-%-	-%-
Red Oak Group		
Black	4.4	11.1
Laurel	4.0	9.9
Northern red	4.0	8.6
Pin	4.3	9.5
Scarlet	4.4	10.8
Southern red	4.7	11.3
Water	4.4	9.8
Willow	5.0	9.6
White Oak Group		
Bur	4.4	8.8
Chestnut	5.3	10.8
Live	6.6	9.5
Overcup	5.3	12.7
Post	5.4	9.8
Swamp chestnut	5.2	10.8
White	5.6	10.5

Table IV Change in Width for a 3" Wide Piece When MC Changes

MC	Red Oak		Yellow-Poplar		White Pine	
Change	Radial	Tang.	Radial	Tang.	Radial	Tang.
-%-	-inch-	-inch-	-inch-	-inch-	-inch-	-inch-
1	0.005	0.011	0.005	0.009	0.002	0.006
3	0.014	0.033	0.014	0.026	0.006	0.019
5	0.024	0.055	0.024	0.043	0.011	0.031

Moisture Content

Wood contains varying amounts of moisture. The amount of water at any time is expressed as a ratio to the amount of dry wood. Mathematically,

$$\%MC = \frac{(Wet\ weight) - (Oven\text{-}dry\ weight)}{(Oven\text{-}dry\ weight)} * 100$$

The wet weight is the weight at any time when the MC must be determined (i.e., green from the sawmill, after or during air drying, after or during kiln drying, after storage, and so on). The oven-dry weight is the weight after all the water has been dried from the piece of wood. Drying is done at 217°F, preferably in an oven with a fan to circulate the hot air. Oven-dryness is reached when the piece of wood stops losing weight (i.e., two successive weight readings taken an hour or two apart during oven-drying are identical).

When using an electronic calculator to figure MC, an easier formula is

$$\%MC = \left[\frac{(Wet\ weight)}{(Oven\text{-}dry\ weight)} - 1\right] * 100$$

Sometimes, it is inconvenient or impossible to oven-dry a piece of wood in order to determine its MC. In that case, certain other properties of the wood, which are related to MC, can be measured. Most commonly, the electrical resistance of wood is measured.

This concept is discussed in more detail in Theory of Operation, LSA.

Moisture content is especially important in drying in that it is related to shrinkage and many other properties and characteristics. Further, almost all drying schedules in use today are based on the MC of the wood being dried and the daily rate of MC loss.

Definitions Related to the Air Around Wood

EMC (Equilibrium Moisture Content)

The EMC is a property of the air. It is defined as being numerically equal to the MC of a piece of wood in equilibrium with the temperature and humidity of the air. The values of EMC and RH at various temperatures (an excerpt is presented in Table 1) are based on oscillating conditions of RH for spruce that was being dried for the first time. The values were intended to be used for dry kiln operations. Although the original data, which are now used throughout the world, were quite limited, the EMC data are extremely useful and are applied to all species with little loss of accuracy. (See also **How Dry Should Wood Be?** on Page 3.) EMC is an especially important variable in drying in that the shrinkage of wood is directly, linearly related to EMC.

RH (Relative Humidity)

The relative humidity is a measure of the moisture in air. It is the ratio of the amount of water in the air at a given temperature to the maximum water that the air can hold at the same temperature. Relative humidity is an important variable in drying in that the drying rate is directly related to the humidity. That is, at a given temperature,

$$Drying\ rate = k\ (100 - RH)$$

where **k** is a coefficient that depends on species, MC, thickness, air temperature, and so on.

Dry-Bulb Temperature

The ordinary temperature of air is called the dry-bulb temperature. The term originates from the fact that the measuring sensor used to be a long rod, called a bulb, and this sensor was dry, compared with the sensor used to monitor RH which was wet.

Wet-Bulb Temperature

The temperature of a sensor covered with a wet muslin wick (using distilled water) with air flow across the wick of 600 feet per minute is the wet-bulb temperature. The wet-bulb is always cooler than the dry-bulb (or equal to the dry-bulb if the RH is 100%). The basic method of determining relative humidity is to measure both the dry- and wet-bulb temperatures of the air and then, using a published table developed over 75 years ago, look up the RH. Some electronic methods of directly measuring RH, such as those using a salt treated or solid state sensor, are not reliable enough, especially over the long term, in the acidic, high humidity environments in the dryer, to be used for drying. Measurement of the EMC by measuring the resistance of special pieces of wood or cellulosic materials, however, has been shown to be reliable. The RH and wet-bulb temperature, if needed, can then be looked up when the EMC and dry-bulb temperature are known.

Wet-Bulb Depression

The difference between the dry-bulb temperature and the wet-bulb temperature is the depression. Many of the dry kiln schedules give a dry-bulb temperature and a depression, rather than a dry-bulb temperature and an RH.

Entering Air and Leaving Air

As air moves through a stack of drying lumber, the air will cool and the RH will rise. To distinguish the different sides of a load, the side where the air enters the load is called the entering air side and the other side is therefore the leaving or exiting side. As the air conditions on the entering side are the hottest and the driest, meaning the most severe for drying, it is these conditions that **MUST** be monitored and controlled during drying (rather than the leaving air side). It is the entering air temperature and entering wet-bulb temperature (or depression) that is stipulated in a drying schedule.

With respect to air velocity, what goes into the stack must also come out. So, because it is generally easier and more reliable, the velocity is measured on the exit side.

How Wood Dries-Shrinkage, Stresses, Moisture Gradients

Wood does not dry uniformly, but dries from the outside first and then eventually the inside dries. This drying gradient creates stresses and many drying defects. The following discussion is based on drying 8/4 red oak, but represents what happens for every species and thickness. It even applies to vacuum drying. Therefore, this description should be studied over and over again until it "makes sense" and is thoroughly understood. Such an understanding will make drying with zero defects "a piece of cake."

Stage I

Stage I is also called the surfacing checking stage, as it is during this stage that new surface checks are formed. Stage I exists from green (i.e., "tree green") to 2/3 of green. For red oak, with a green MC of 75%, Stage I is from 75% to 50% MC. For white oak with a green MC of 66%, Stage I exists from 66% to 44% MC. Stage I may require 20 days in the kiln for 8/4 red oak lumber.

During this Stage, the cells on the surface rapidly dry and drop below the fsp, which means that they are trying to shrink. However, the cells below the surface are still above fsp and therefore resist the shrinkage force from the surface cells. This surface layer is also called the shell; the interior is the core. As the shell tries to shrink, it exerts a compressive force onto the core. According to Newton's Third Law, "For every action there is an opposite, equal reaction." Therefore, if the shell creates a compressive force on the core, then the core exerts a tensile force on the shell. If this tension force exceeds the strength of the wood, then "Bang!", a surface check. The tension on the shell is greatest on the fifth day (approximately) of kiln drying green-from-the-saw with 8/4 red oak.

To create a surface check requires a tension in the shell and it is only during Stage I that there are any large tension forces on the shell. Hence, it is only in Stage I that surface checks are created. This fact is important in deciding who or what is the cause of surface checking. When wood is checked, something went wrong at very high MCs. Note that although surface checks may close as drying continues (Stage II) and may worsen and go deeper later (Stage III), the situation is analogous to jumping out the ninth story window. The damage from improper actions at the ninth floor shows up much later. Further, the damage is hard to control toward the end. The best method of damage control is exerted at the ninth floor. Likewise the best method of surface checking control is exerted at very high MCs, not later.

To prevent surface checking in Stage I, it is necessary both to minimize the stress development by controlling humidity and velocity and to maximize the wood's strength by keeping the wood cool. (See also **How Wood Dries-Environmental Effects** on Page 27.) Note that because 99% of all honeycomb is originally a check that then grows internally, controlling checking in Stage I will also control honeycomb. In fact, it is accurate to state "The most critical time in drying is during the loss of the first 1/3 of the moisture." (The second most critical time is at the end when final MC is determined.)

To achieve check free conditions when drying typical red or white oak lumber, the recommended Stage I kiln conditions are 87% RH, 350 feet per minute, and 110°F. If the velocity is lowered and/or temperature is lowered, then the checking risk is lowered, which can mean that the RH can be safely lowered. In a warehouse predryer, conditions of 85°F with 65% RH and 125 feet per minute are satisfactory. In essence, there is no one correct set of conditions for drying oak in Stage I; rather all three-temperature, RH, and velocity-must be considered together. The key variable to monitor in Stage I, then, in order to determine whether the conditions are satisfactory, is the daily rate of MC loss from correctly prepared samples. (Selecting and preparing samples is discussed in **Operating a Lumber Dryer**.)

Each piece of lumber has a safe drying speed limit (Table 5). The limit depends on species, thickness, and outside factors such as the presence of bacteria. Exceeding the safe limit greatly increases the risk of checking. Operating much below the limit extends drying time and increases the risk of staining. It is important to state that the limit is the maximum limit for every piece of wood, not just the average of most of the pieces. Further it is the daily loss, not the average loss over several days.

It must also be mentioned that the safe rates are based on normal wood. If anything has happened to the wood, such as being infected with bacteria, being cut with a dull saw at the sawmill, being dried too fast on a preceding day, being subjected to high temperatures prior to drying, or having small surface checks from previous drying, then the rates quoted would not apply. (I am not sure what rates would apply for these cases; the best advice is to avoid these problems at all costs.)

Also note that with presurfaced lumber, that is lumber that was planed green to remove the rough surfaces which are often the source of checks (planed lumber had 18 times fewer checks than rough lumber in one study by McMillen), the drying rate can be safely increased.

When studying tension stresses in drying, as the stress level increases the wood becomes plastic. This plastic level is reached before the wood fails (checks). When in this plastic range, the wood cells are permanently stretched and are larger than they would have been if they had been free to shrink without being restrained by the wet core. This phenomena is called tension set or casehardening. (Note that the case or shell is not harder, however.)

Table V The Maximum Safe Rate of Drying

Species	Thickness 4/4	Thickness 8/4
	- % MC loss per day -	
Beech	4.5	1.8
Birch, yellow	6.1	2.4
Cherry	5.8	2.3
Elm, American	10.4	4.1
Maple, soft (sap)	13.8	5.5
Maple, hard	6.5	2.6
Oak, red upland	3.8	1.5
Oak, white upland	2.5	1.0
Oak, lowland	1.0 - 3.0	?
Sweetgum (red gum)	5.3	2.1
Tupelo (black gum)	10.9	4.3
Walnut	8.2	3.3
Yellow-poplar	13.8	5.5

Based on properly selected and prepared samples whose MC is accurately measured

Stage II

Stage II begins at 2/3 green and continues to 30% MC. (Recall that when the lumber is at 30%, the core is wetter and the shell is drier; it is incorrect to say then that the lumber is at fsp.) During this Stage, the tension in the shell is falling off and tension is now developing deeper into the wood as cells inside drop below the fsp. Typical drying time for Stage II for 8/4 red oak is 20 to 30 days.

The tension inside is usually not as large as the tension levels in Stage I. Nevertheless, it is still important to keep the wood temperature fairly low to maximize its strength and prevent small surface checks from developing into internal checks or honeycomb. However, as the risk of forming new checks has greatly diminished, the relative humidity can be lowered slightly without risk **IF THERE ARE NO CHECKS UP TO THIS POINT.**

As the interior continues to dry, the shrinkage of the interior will pull the checks on the surface closed-they will become invisible from the rough surface. (This is also called "stress reversal.") Yet they are open inside and may increase in depth, width, and length inside the wood with no indication from the outside. This increase in internal checking will only occur if the drying rate is too fast at this stage, however. Therefore, when checks are seen after planing lumber, but were invisible in the rough, most often the error was made during Stage II. Once stress reversal occurs, it is essential to prevent the wood from regaining moisture as such regain will increase the internal tension and worsen checking and honeycomb.

If we want to call Stage II by another name, we might call it the stage that determines whether there will be subsequent internal checking or honeycomb. But bear in mind that almost all interior defects are a result of surface checks or end checks penetrating inward and not the spontaneous creation of interior failures. If we can't control checking in Stage I (which may occur with thick oak where a small amount of checking might be considered normal or inevitable), then we must treat the lumber gently enough in Stage II to prevent further growth of the checks. (See also **Checking the Quality of Incoming Lumber** on Page 39.)

If checks in Stage I were subjected to alternate wetting and drying or were especially severe, then they will not close when stress reversal occurs. In fact, they will be open at the end of drying, while "ordinary" checks will be closed at the end.

Stage III

Stage III exists from 30% MC to the final MC. Drying time is 30 to 50 days for 8/4 red oak. In this Stage, it is nearly impossible to initiate new degrade (except with the most severe drying conditions or if water is added back to the wood). In this stage, the temperature of the wood can be raised as high as 200°F for some species and the humidity can be lowered to very low levels (50°F depression). For optimum quality, however, the maximum temperature should not exceed 160°F and the depression should not exceed 40° to 45°F for all species and thicknesses.

It is in this stage that small checks will develop into honeycomb; but such development is usually inevitable due to improper drying in Stage I or II. It is seldom, if ever, due to errors in Stage III. It is, in most cases, impossible to fix in Stage III or IV what has been done wrong in the previous stages.

Stage IV

The final stage involves equalizing and conditioning. <u>Equalizing</u> is a process using a modest humidity level that results in the moisture within a piece of lumber and between various pieces being within several percent MC. The driest piece is stopped from drying any further; the wettest piece continues drying until the desired final MC is achieved. The procedure is discussed in **Drying Schedules** on Page 43.

Conditioning is a process using a high relative humidity steaming treatment to rapidly increase the MC of the surface cells. These cells had tried to shrink in Stage I and were prevented, so they were stretched (i.e., tension set developed) and that is called casehardening. To remove casehardening, the surface is wetted quickly, causing the surface cells to try to swell, but the cells underneath resist this swelling. (It is the reverse of Stage I.) The cells then develop compression set, which offsets the tension set; the result is a piece free of stress. The procedure is discussed in **Drying Schedules** on Page 43.

How Wood Dries-Environmental Effects
(RH, Temperature, Velocity)

There are three environmental variables that control that rate at which wood dries. And if they control the rate, they also control degrade development. These three variables are temperature (dry-bulb), relative humidity (or wet-bulb or EMC), and velocity. Whenever drying is unsatisfactory-takes too long or degrade is excessive-then these three variables must be modified. The phases of the moon, time of year, or a horoscope do not affect how wood dries.

Temperature

As the temperature increases, five changes occur that affect drying:

a. Water moves faster in wood at higher temperatures;

b. Drying is more uniform in wood at higher temperatures;

c. The relative humidity of the air will decrease, unless water is added to the air;

d. Wood is weaker at higher temperature; and

e. Warp is usually worse at higher temperatures (except in high temperature drying-over 212°F).

With these principles in mind, then it should be clear that the temperature in drying should be kept quite low during Stage I to minimize the weakening of wood (and subsequent degrade such as checking or honeycomb). The schedules (see **Drying Schedules** on Page 43) provide **maximum** temperatures recommended. Often, such as when wood quality is not as high as desired or expected, lower temperatures will be used to prevent or lower the risk of degrade.

Relative Humidity

As the relative humidity is lowered, five changes occur that affect drying:

a. Water moves faster as the humidity is lowered;

b. Drying is more uniform at lower humidities;

c. Warp is less at lower humidities;

d. Checking is more likely at lower humidities; and

e. Staining is less likely to occur as humidity is lowered.

With these facts in mind, then, it is clear that with species that are likely to check or crack during drying, the humidity must be quite high, yet not too high so that the risk of staining and warping is increased above tolerable levels. For species that can tolerate lower humidities, then these low humidities should be used to provide brighter and flatter lumber, and faster drying.

Velocity

As the velocity through a load of lumber increases, several changes occur that affect drying:

a. Above 40% MC, wood will dry faster as the velocity increases;

b. Below 20% MC, wood will NOT dry faster as velocity increases;

c. Between 40% and 20% MC, the effect of increases in velocity diminishes; and

d. At higher velocities, drying is more uniform.

As always, faster drying increases the risk of checking and cracking, but decreases the risk of stain and warp. When the cost of velocity changes is assessed, it is found that the cost of doubling the velocity can increase by 4 times, depending on the electric rate. So lower velocities below 20% can result in very significant cost savings. Because velocity is not well understood and is not well discussed in drying handbooks, a special detailed section **The Role of Velocity in Drying** is included in this chapter.

Changing the Rate of Drying (or) Changing the Amount of Degrade

When lumber is drying, if it is drying too fast (i.e., checks, splitting, and honeycomb are likely), the drying rate can be slowed by lowering the temperature (That's why low temperature predryers are so popular for oak drying!); by raising the relative humidity (Some equipment performs poorly and there may be a risk of staining if the RH is too high!); and/or by lowering the velocity (With long air flow paths in wet lumber, uniformity may suffer tremendously if velocity is too slow!). If the wood is drying too slowly (i.e., stain or warp is excessive), then the humidity can be lowered and the velocity increased. Generally, the temperature is not increased, due to the potential effect on the wood's strength. So, degrade control is as easy as one, two, three-temperature, RH, and velocity.

It should be understood that there is not one correct set of drying conditions. Rather, for the given MC, species, and thickness of lumber and for the quality needed, there are many sets or combinations of temperature, relative humidity (or EMC), and velocity that will dry the lumber at the correct, degrade-free rate and keep the wood strong and flat. As an illustration of this fact, consider that the drying rate for a certain species is 1% per day. Previous research has, for this species and thickness, established the affect of changing humidity and velocity (Figure 1). So, to use this data, choose either a velocity (or humidity). Then proceed vertically (or horizontally) to the 1% rate line and then horizontally (or vertically) to obtain the appropriate safe humidity (or velocity).

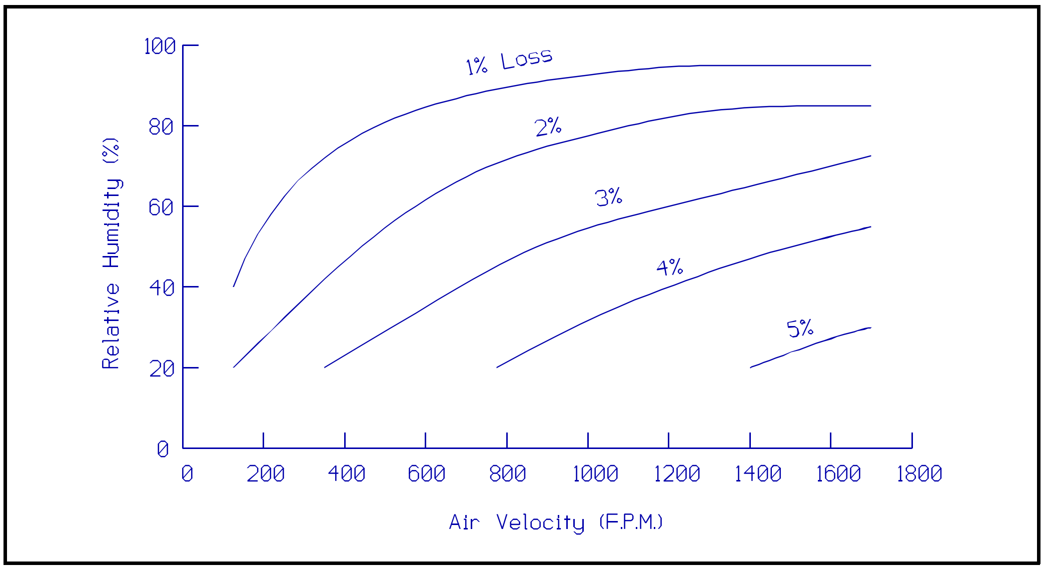

Figure 1 Effect of Velocity on Drying Rate at Different MCs

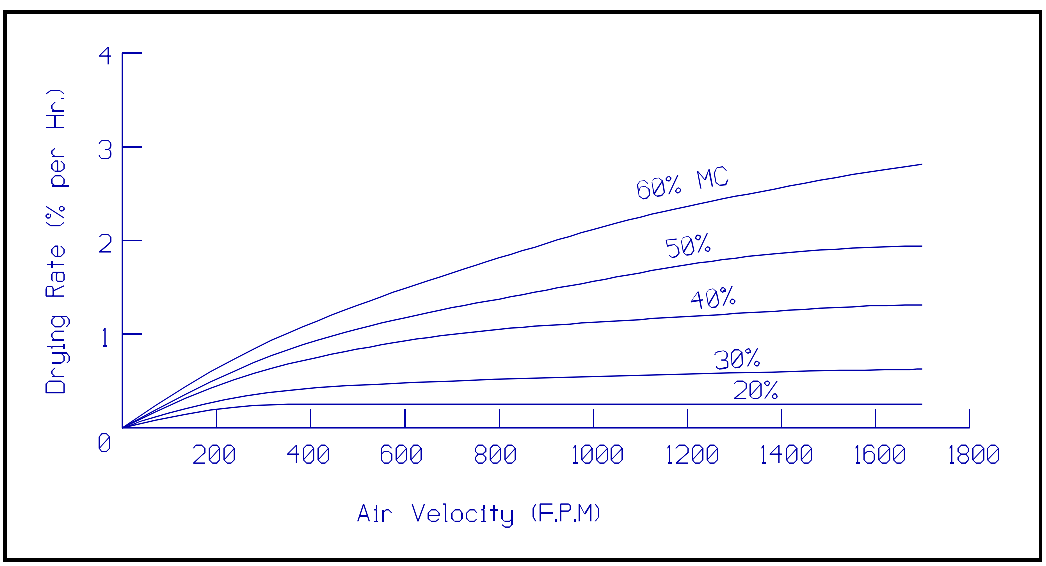

Figure 2 Combined Effect of Velocity and Humidity on Drying Rate

The Role of Velocity in Drying

Drying Rate

The first effect of velocity in drying lumber is to remove moisture from the lumber's surface, while at the same time providing energy to the wood so that evaporation can take place. It should be remembered that drying always requires energy-about 1000 BTUs of energy to evaporate a pound of water. Therefore, 1000 BF of lumber, which typically contains about 2500 pounds of water that needs to be evaporated, will require 2.5 million BTUs of energy from the air. If a cubic foot of air blowing through a load of lumber changes temperature by 10°F, the air will have supplied only 0.2 BTUs of heat to the wood. It should be clear that a lot of cubic feet of air are required to carry the heat to the lumber-the actual volume can be calculated if necessary.

Likewise, the amount of air required to carry the moisture away from the lumber can be calculated. A cubic foot of air can carry less than 0.001 pounds of water at low temperatures and high humidities, and up to 0.01 pounds at low relative humidities and higher temperatures. To carry 2500 pounds of water will require, again, large air volumes.

While the lumber's surface is quite wet (the average MC of the lumber is over 40%), an increase in velocity will result in an increase in the rate of drying. Higher velocities mean faster heat transfer to the lumber, faster removal of moisture from the lumber's surface, and more cubic feet of air passing through a sticker opening. However, as the outer shell of the lumber becomes drier (average MC of the lumber is between 40% to 20%), then the effect of increasing velocity begins to diminish. Finally, as the lumber surface becomes quite dry (average MC of the lumber is under 20%), changes in the velocity of the air have almost no effect on the drying rate.

Let's look at this more closely. With wet wood, the molecules are at or close to the surface of the lumber, so that they don't wiggle very far to be evaporated into the air. In essence, they are waiting for energy from the air and/or for the air to scrub them off the surface. What changes as the wood dries to lower MCs, is that the major resistance to drying switches from the resistance that the air provides to the resistance within the wood itself. In other words, as the MC drops, we begin waiting for the water molecules to wiggle their way out of the inside of the wood up to the surface, rather than for the air to scrub the molecules off the surface or for the air to provide energy to the wood. This effect can be shown graphically (Figure 2), where at 60% MC, it can be seen that the drying rate increases with increasing velocity, while at 20% MC the rate is constant for any velocity.

Questions may arise concerning the roughness of the lumber. Surprisingly, variations in lumber roughness do not result in major variations in drying. The air flow through a load of lumber begins as laminar flow, which is several times less effective in transferring heat and removing moisture than turbulent flow. Air flow becomes turbulent after about 4 feet of travel into the pile, the distance depending on the velocity and whether the individual pieces of lumber in the layer are the same size and therefore are smooth from piece to piece, or whether there are gaps between each piece. Trying to encourage turbulent flow could result in faster drying at high MCs, but lowering humidities and increasing velocities can do the same thing.

Integral Effect

The second effect of velocity on lumber drying is termed the integral effect. As velocity increases, there is an increase of volume flow of air through the sticker spaces or channels. This means that as the air moves through the load, if there is more volume, the conditions of the air (that is, its temperature and humidity) will change more slowly as it enters the load and passes through the lumber pile. When volume is very low, the air will give up its heat and will pick up enough moisture rather quickly; this means in turn that it will become saturated (100% RH) soon after it enters the load of lumber. With low velocity, then, only the edge of the pile will dry very much; the rest of the load will be subjected to very humid air and just won't dry much. (Staining and cupping are likely too.) So, the higher the volume flow rate (which in practice means the higher the velocity and the thicker the sticker), the more uniform drying will be from the edge of the pile to the center and then to the exit edge. Of course, we often reverse the direction of flow to also provide more uniform drying from side to side.

In the previous paragraphs, the role of volume has been mentioned. Volume is related both to velocity and sticker thickness. Consider the following example. A kiln is loaded with 50 MBF of 4/4 green lumber stacked on 3/4-inch thick stickers and with a velocity of 300 fpm through the load. If the sticker size is increased to 1-inch thickness, the kiln capacity would be decreased 12% to 44 MBF. There would also be 12% fewer sticker openings, but the area of sticker opening would increase by 33% (3/4 to 1 inch). The net effect is an increase in sticker spaces of 17%. Now if we assume that the volume of air delivered by the fans would remain constant, there would be 12% more volume per sticker opening (because there are 12% fewer openings), but the average velocity in each opening would drop from 300 fpm to 250 fpm. The net result of thicker stickers at high MCs would be slower drying due to the velocity drop, but more uniform drying throughout the pile due to the increase in volume flow. A little lower relative humidity could offset the slower velocity. On the other hand, at low MCs, there would be little effect on drying rate and uniformity of drying through the pile. So, thicker stickers can be advantageous when drying green lumber, although the price is decreased kiln capacity and therefore potentially higher operating costs. Note that with only 44 MBF, often the kiln's heating and venting systems will be better matched to the load as well, giving better performance.

Venting Effect

The third effect of velocity in conventional dryers is to cause venting from the inside of the kiln to the outside and from the outside inward. (Dehumidifier dryers would not have vents, so this effect would not be present.) Venting is the method that conventional dryers remove moisture from inside the kiln-humid air is exhausted and drier outside air is brought into the dryer. If the vents are properly operating, they will open whenever the conditions in the kiln are too humid and will close when the humidity is at or below the desired level. This means that excessive venting is avoided no matter what the velocity is.

The kiln fans that determine the velocity of air through the lumber pile also are used to force air through the vents when they are open-the higher the kiln velocity, the higher the venting rate. Therefore, changes in velocity will not affect the overall or net amount of air vented; but velocity changes result in changes in the rate of venting.

With fast drying woods that releases moisture quickly to the air, high venting rates to keep the air from getting too humid are required. These high rates can be achieved by using large vents or high air velocities (or both). The venting effectiveness is also increased with higher temperatures-hotter air holds more moisture.

Heat Effect

The fourth effect of velocity is to cause heat transfer from the steam heating fin pipes, coils, or other heating system to the air. The higher the velocity through the coils, the greater the heating rate. This effect would be most important when energy demands for drying are highest. The largest heat demand exists when the lumber is the wettest. As the lumber dries, the heat demand decreases. Therefore, somewhat lower velocities across the coils at lower lumber MCs are generally not of great concern. Poor velocity across the heat coils can be offset by increasing the fin size, increasing the amount of fin pipe, or increasing the steam pressure.

Electrical Consumption

The fifth effect of velocity is electrical consumption. As velocity increases when fan speeds (RPMs) are increased, electrical consumption increases; likewise, when speeds are lowered, electrical consumption decreases. A decrease in velocity of 20% (all else being kept equal) will reduce energy consumption by approximately 50%! So, as mentioned in the previous sections, there are times (low MCs) when velocities can be decreased (thereby reducing energy consumption) without a decrease in quality or an increase in drying time. It should be noted, however, that if the energy use is reduced by 50% for most of the month, the monthly electrical bill will probably only be reduced by 25%. The reason for this smaller savings is that most electric utilities have a demand charge, based on the maximum usage rate over a 15 minute period for the month. The demand charge won't change if the peak usage remains unchanged, which would happen if fan speed is reduced for only part of the month. The demand charge is often one-half of the bill; hence, the predicted money savings, by reducing fan speed when below 30% MC, is 25% maximum.

Other Concerns With Velocity

One might argue that it would be better if the flow were turbulent, because turbulent flow results in faster drying. Indeed, it is true that lumber at MCs greater than approximately 30% will dry faster with turbulent flow rather than laminar flow. But is faster drying a desirable and economically beneficial event for all woods? Certainly for most hardwoods, faster drying will result in more degrade-checks, splits, and honeycomb. Further, to achieve faster drying, the humidity can be lowered without much effort, which can be easier than creating turbulence. Further faster drying can be achieved by increasing velocity. So turbulence is not a desirable objective for hardwood lumber drying above 30% MC. Below 30% MC, the velocity has only a minor or insignificant role in controlling the drying rate, so certainly any effort to create turbulence is not worthwhile-that is, there is no benefit in quality and or drying rate. For drying softwood dimension lumber in today's high temperature kilns, the velocity is so high (over 1000 fpm) that air flow is turbulent soon after the air enters the pile.

With today's standard kiln schedules for hardwood lumber based on laminar flow at 375 fpm, any change in air flow would have to be accompanied by a change in schedule (primarily humidity). For example, in an experimental kiln for hardwoods with 1000 fpm, the drying rate was so high that the wet-bulb had to be raised so that the relative humidity was over 95%, thereby slowing the drying rate to acceptable levels. Even then, surface checking in oak was excessive.

So what air flow is best? The answer is that for a given relative humidity and temperature, the best air flow is that velocity that results in drying the wood at a rate close to (but not exceeding) its safe drying rate. For hardwoods, the schedules used throughout the U.S. are based on experiences with drying at 375 fpm. Therefore, this should be the general target for most hardwood lumber kiln operations today. For drying green hardwoods in a warehouse predryer, most work has been done at 125 fpm (or thereabouts). For most softwoods and easy drying hardwoods, velocities are often over 1000 fpm to assure uniform drying, as much as to produce fast drying. In any case, once the wood is under 30% MC, then the best flow rate is that velocity that provides good control of kiln conditions with a drop in EMC across the load of less than 2%.

Diagnostic Tools

There are three tools available for measuring the effect of velocity and assessing whether velocity can be increased or decreased. First is measuring the final moisture content variation across the load of lumber. When variations exceed 1% MC from the edges to the middle, higher velocities to achieve more uniform drying, especially at MCs greater than 30%, should be considered. When variations are less than 1%, then reductions in velocity can be considered.

Second, the temperatures and humidity on each side of the load (entering air side and exit air side) should be measured and then the EMC calculated for each side. When EMC difference are less than 2%, reductions in velocity can be considered; when greater, then increases may be justified. In either of these first two cases, the drying rate of the lumber at MCs greater than 30% must also be monitored to assure safe drying rates.

Finally, the current draw for each fan motor can be measured. Lower than normal current can indicate a lack of velocity which can be caused by a variety of reasons, including loose belts, loose fans, and baffle problems. Higher current draw indicates increased energy consumption, often due to increased bearing friction or loose blades on the fans.

Velocity itself can be measured with many different instruments. Generally a hot wire anemometer is the most accurate, but these readings can be affected by perturbations and by eddies from side to side. A small pressure-type instrument is probably best for lumber drying as it measures net flow and it fits between the stickers to measure the actual flow in the sticker space. It is rugged and not too expensive, and reasonably accurate and easy to use. In all cases, velocity is measured as the air leaves the load of lumber, rather than on the entering side-unless there are a lot of leaks, the entering velocity will be the same as the exiting velocity.

Operating a Lumber Dryer

There are many techniques for operating a dryer that must be used to assure high quality and efficient operation. Many of these techniques, such as how to insert and use moisture probes for moisture content measurement, are mentioned in other chapters. This discussion is meant to provide, from a wood standpoint, how to operate a dryer.

Log Handling and Storage

Logs should be handled correctly if drying degrade is to be controlled. Specifically, logs should be end coated. If not, then end checks will develop in the logs and these checks will develop into serious end splitting degrade as the lumber is dried. Checks do not get better when lumber is dried; they get worse. In studies done by Virginia Tech on red oak, end coating reduced end splits in 5/4 lumber to zero in 75% of the pieces. The lumber was predried and then kiln dried conventionally.

Logs that are stored in ponds can also develop degrade, including bacterial infections, which make the lumber much more likely to check and honeycomb. Logs stored in warm weather, even when sprinkled with water, can develop the precursors for chemical stains, making staining of the lumber during drying inevitable.

Stacking

Lumber must be stacked immediately for drying if the risk of staining is to be minimized. Fungicides will prevent some damage, but chemical stains can still occur. Stickers must be properly aligned, in line with the stickers directly above and below. Bolsters must be in alignment and under every sticker. Foundations must be flat.

Preparing and Selecting Samples

The key to successful drying is accurately knowing the MC of the lumber in the dryer. The following procedure has been developed after decades of experience. There are no shortcuts.

In order to measure the moisture content of lumber during drying, it is impractical to weigh every board in the dryer. Therefore, we use the sample board method to estimate the moisture of the lumber in the kiln. This method uses short, carefully chosen sample boards sawn from larger pieces of lumber. These samples boards are weighed periodically and their moisture contents are calculated. Generally, because the wettest lumber in the kiln has the highest risk of degrade development, most of the sample boards should represent the wettest lumber in the dryer; this means the lumber that is the most recently cut, is the widest and thickest, contains the heartwood, and is quartersawn. To avoid overdrying, a sample or two should also be taken from the driest piece (the opposite characteristics for the wettest samples). The precise procedures to prepare sample boards are:

1. Select lumber to be used.

2. Cut a 30-inch sample board and then two 1-inch moisture sections from the sample board, avoiding areas near knots and areas closer than 12-inches from the ends of the lumber.

3. Number the sections and the sample board.

4. Immediately weigh the sections (accuracy of about 0.1 gram required for 100 gram sections). It is important that they not lose weight after cutting and before weighing. Record weight on the section with a marker pen.

5. Weigh the sample board (accurately of about 0.1 pounds required) and record the weight on the sample.

6. End coat the sample board; a double coating is best.

7. Place sample board in the lumber stack in a location where it will dry at the same rate as the rest of the lumber in the dryer. (Note: In a package kiln the samples on the outer edges will dry faster than the lumber in the center of the load, especially for green lumber.) It is hard to locate samples in the interior of the load and yet have them available for weighing.

8. Place sections in an oven at 215-217°F or use a microwave oven.

9. After the sections are dry-usually 18 to 36 hours, depending on the oven-reweigh and obtain the oven-dry weight.

10. Calculate the moisture content of each section separately.

$$\%MC = \left(\left[\frac{wet\ weight,\ Step\ 4}{oven\text{-}dry\ weight,\ Step\ 9} \right] - 1 \right) * 100$$

Then average the MC of the two sections to obtain the estimated MC of the sample board when it was cut (Step 2).

$$Average\ \%MC = \left[MC_1 + MC_2\right] / 2$$

11. Calculate the oven-dry weight of the sample board using the average MC from Step 10 and weight from Step 5.

$$Calc.\ O\text{-}D\ Weight = \left[\frac{(wet\ weight,\ Step\ 5)}{100 + (\%MC,\ Step\ 10)}\right] * 100$$

12. Write the estimated O-D weight on the sample board (when it is weighed the next time) so that this number is readily available.

13. Periodically reweigh the sample board to obtain a new current moisture content.

$$Current\ \%MC = \left[\frac{Current\ Weight,\ Step\ 13}{Calc.\ O\text{-}D\ Weight,\ Step\ 11}\right] - 1 * 100$$

14. Occasionally, it is necessary to cut new sample boards when the lumber is at 20% MC to obtain more accurate MC values (that is, to make a mid-course correction). To do this, cut one new moisture section 6-inches from the end of the sample board. Then follow Steps 3 through 13, except only one section is used. The "wet weights" in Steps 10 and 11 are the weights determined after the sample and new section are sawn.

Checking the Quality of Incoming Lumber

When lumber is purchased, we always double check the grade and footage, but seldom is the quality checked. That is, the lumber is not checked for surface checks, end checks, and internal checks. The procedure for evaluating quality is illustrated in Figure 3. It might be surprising how often the cause of checks and honeycomb noted after drying is not the fault of the predryer or kiln operator. Rather, the lumber was received with checks already in it. Further, if lumber is already checked, a different schedule must be used.

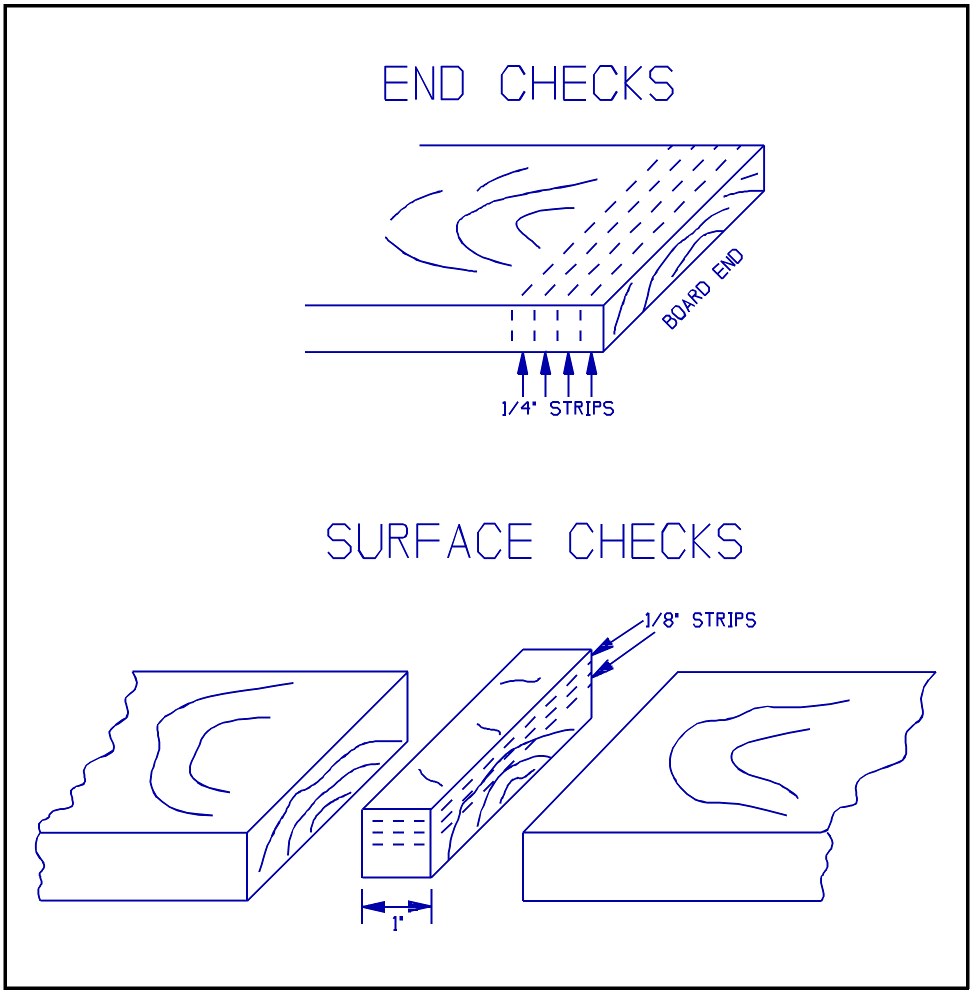

Figure 3 Checking for Checks

Loading a Dryer

Every dryer has a correct method of loading to assure that plenum spaces are adequate. The manufacturer's instructions must be followed. Common sense can also be used to assure that there will be adequate and uniform air flow throughout the dryer.

Starting a Dryer

The temperature and RH (or EMC) to use when starting the dryer is discussed in the section on schedules. In addition, it is important when the lumber is cold or frozen to turn the fans on first before the doors are closed. This will avoid implosion damage. Again, the manufacturer's instructions must be followed as well.

Final Quality Checks

The lumber, when it leaves the kiln, should be sampled for average MC, shell and core MC, stress (longitudinal and transverse), surface and internal checks, and, in some cases, end checks. It is better to know that there is a problem before the lumber is shipped. Such tests also can be used to monitor quality and evaluate new drying procedures. These tests also will assure the kiln drying personnel of the adequacy of their procedures and give them confidence that any problems that are subsequently encountered are not their fault. In many cases it is a cheap insurance policy.

Safety

Dryers can be dangerous, so adequate safety precautions must always be adhered to. Some important factors are that everything should be well grounded, especially the dryer buildings. All electrical circuits should be capable of being locked out. Before going into a kiln, the operator should always assure himself that there is plenty of oxygen available. With a fast drying species, being dried at temperatures above 160°F, there can be a lack of oxygen inside the kiln. Kiln conditions with wet-bulbs above 110°F are probably not safe due to the heat. The large kiln doors must have safety brackets in case the door comes loose from the carrier. (This is a federal regulation in the U.S.) The man doors must always have inside releases. In the dryer, lumber often has the tendency to shift and a piece may be ready to fall when the operator enters. Always wear a hard hat. Always look up toward the ceiling before entering the dryer to make sure some lumber has not shifted against the door and is waiting to greet you. There are many other safety areas that the equipment manufacturer must address.

Dry Lumber Storage

No matter how well the lumber has been dried, poor storage after drying can result in poor lumber. Storage hazards are primarily insects infestations and an unwanted MC change-the latter is a major risk and can be very costly for the user of the lumber. Therefore, storage conditions must be dry and free of insects.

Table 6 indicates the effect of changes in RH, EMC, and/or MC on the shrinkage of oak. The initial MC is 7% (called the base line in the table).

Proper lumber storage uses a storage environment where the EMC is within 2 percentage points of the lumber's MC. Such a condition can be achieved by heating the air in the storage building, thereby lowering the RH to the desired level. For example, heating the storage atmosphere 22°F above the outside morning's low temperature will result in an RH in the building under 40%.

In short, the effect of improper storage should not be underestimated; the effect is great. Proper storage is easy to achieve with minimal heating.

Table VI Relationship Between Shrinkage, MC, EMC, and RH

Shrinkage	MC	EMC	RH	
-%-	-%-	-%-	-%-	
1.5	3	3	12	
1.1	4	4	18	
0.7	5	5	23	
0.4	6	6	30	
0.0	7	7	37	(Base Line)
-0.4	8	8	44	
-0.7	9	9	50	
-1.1	10	10	57	

(Based on red oak, tangential shrinkage.)

Drying Schedules

The combination of temperature, relative humidity (or EMC), and velocity-that is, the schedule-that is correct is the combination that dries the lumber at the correct, safe rate without causing degrade. As mentioned earlier, there are many combinations that will work well with a given species and thickness. So there is no one correct schedule. However, the U.S. Forest Products Laboratory in the 1950's developed a systematic approach to schedule development. This systematic approach has many advantages, when compared to a random schedule development process. The advantage today from their approach is that every recommended schedule has been used for over thirty years to dry millions, if not billions, of board feet of lumber successfully. There is something comforting about that, especially when a kiln has $50,000 (or more) worth of lumber in it.

U.S. Forest Products Laboratory Schedules

The philosophy of the U.S. FPL schedules is based on the four Stages of drying mentioned earlier.

- Keep an initial mild condition for the loss of the first 1/3 of the moisture, the degree of mildness depending on the likelihood of surface checking.

- Slowly lower the relative humidity, beginning after the first 1/3 of the green moisture is lost.

- Keep the temperature low until average MC is below 30%, the actual temperature depending on the species and its degrade risk.

- Slowly raise the temperature after the average MC is below 30%.

- Equalize and condition at the end of drying.

The schedules also were developed with the assumption that there may be slight variations in equipment and conditions. This necessitated building in a safety factor. Therefore, almost all of the schedules are conservative. With better, more accurate and more reliable controls possible today, this conservatism is no longer necessary. In other words, the old schedules can be accelerated safely with today's modern equipment.

All the U.S. FPL schedules have a four character code, such as T4-D2. A master code listing is given in the book Kiln Schedules for Commercial Woods, available from the U.S. Forest Products Laboratory at no cost.

The coding system works as follows:

- All codes begin with the letter "T".

- The first number is the temperature number, indicating how hot the conditions will be, especially at the higher MCs (Stages I and II). The numbers range from 1 to 14. With a number "1" or "2" temperature schedule, the initial temperature for MCs above 30% is 100°F; for numbers "3" and "4," 110°F; and so on.

- The third character indicates the MC at which 1/3 of the green MC has been lost and therefore, Stage II begins. When Stage II begins, the relative humidity can be lowered slightly. The letter "A" is the lowest MC condition, making the first change in RH at 30% MC; an "F" schedule begins to change RH at 70% MC.

- The final character is a number that indicates the humidity level. A "1" is a high humidity schedule, while an "8" is a low humidity schedule. The lower numbers would be used for check prone lumber.

These schedules, especially for oak, were developed for high quality wood. Today, the quality of our wood is often not as good as in the past. Therefore, many firms have modified the final conditions of the schedule so that the temperature never exceeds 160°F and the depression never exceeds a 40° or 45° depression.

Sampling Moisture Content

The key to using the U.S. FPL schedules is knowing the moisture content of the wetter pieces of lumber. This is done with the samples mentioned in the previous section. Only the wettest half of the samples are used in determining the average MC, which is then in turn used to establish the correct temperature and humidity levels. The U.S. FPL schedules are based on the average MC of each sample board and not just the shell or just the core MC.

As a general rule, there should be at least one sample for every 5000 BF of lumber in the dryer. This will assure that there will be an adequate cross-section of MCs representing the variety of MCs in the kiln. Again, it is essential that the samples represent the wetter lumber, as it is this lumber that has the greatest risk of degrade. At the same time, a drier piece or two must be included to avoid over drying and to indicate when to begin equalization.

It should be noted that the U.S. FPL schedules assume a velocity of 375 fpm. Higher velocities would result in faster drying than desired and thereby increase the risk of checking; lower velocities could slow drying too much and increase the risk of stain or warp.

The recommended schedule for 4/4 and 5/4 red oak is T4-D2. The actual conditions specified for this schedule are presented in Table 7.

Table VII Recommended Kiln Schedule (T4-D2) for 4/4 and 5/4 Upland Red Oak

Moisture Content	Dry-Bulb	Wet-Bulb	Depression	EMC	RH
-%-	-°F-	-°F-	-°F-	-%-	-%-
Above 50	110	106	4	17	87
50 to 40	110	105	5	16	84
40 to 35	110	102	8	13	75
35 to 30	110	96	14	10	60
30 to 25	120	90	30	5	31
25 to 20	130	80	50	2	10
20 to 15	140	90	50	3	14
15 to end	180	130	50	3	26

Note: The MC is based on properly prepared and placed samples and is the average of the wettest half of the samples. The dry-bulb is the maximum level; lower settings can be used to assure higher quality, although drying may be slower.

Modifying kiln schedules

As mentioned above, the present kiln schedules have a built-in safety factor and, in many cases, our wood today is not of the same quality as the wood used to develop the schedules in the 50's. Therefore, some modification is possible, if not warranted, for efficient, degrade-free operation. In addition, we now have computers that can take the step schedules with their abrupt changes in conditions (which we know put additional stress on the wood, increasing degrade risk), and instead use many very small steps. This multi-mini-step schedule means better quality and faster drying, as confirmed by the U.S. Forest Products Laboratory over twenty years ago.

The first modification is limiting the temperature to 160°F and the depression to 40°F (or

45°F). Considering the previously given schedule for red oak, the new schedule (and the one that will do a better job with today's equipment and lumber quality) is presented in Table 8. With this schedule, the driest any wood will be is 4%, with most being a little wetter. There is no question that this schedule will produce lumber with fewer splits and that will machine and glue much better than the "old" schedule.

When computer controls are available, then the steps in the schedule can be smoothed. Typically, the approach is to graph the present schedule as a function of dry-bulb or EMC versus moisture content and then connect the highest points with a smooth curve. With this approach, most of the acceleration occurs at the lower MCs when degrade risk is minimal.

Another acceleration is possible when using better controls in the kiln. The "old" schedule was based on controls that might vary as much as a degree in control of the wet- and dry-bulb temperatures. With better controls, this variation will not occur and therefore the depression can be increased slightly, perhaps 1/2 to 1°F, depending on the species and the risk that can be tolerated. It is well to remember, however, that a savings of 10% in drying time can be offset by as little as a 2% increase in degrade.

When the lumber being dried has been damaged in previous drying in Stage II and III or is weaker than normal, such as with bacterially infected wood, then it is **not** safe to slowly lower the humidity according to the schedule. Instead, the humidity changes must be delayed up to 10% MC (i.e., the setting for 40 to 35% MC become the settings for 30 to 25% MC). This will slow drying significantly, but that is what will assure the highest quality possible from this damaged lumber. It is also wise to keep the dry-bulb 10°F below the maximum level recommended in the schedule for "normal" wood.

Table VIII Modified Kiln Schedule (T3-D2) for 4/4 and 5/4 Upland Red Oak

Moisture Content	Dry-Bulb	Wet-Bulb	Depression	EMC	RH
-%-	-°F-	-°F-	-°F-	-%-	-%-
Above 50	110	106	4	17	87
50 to 40	110	105	5	16	84
40 to 35	110	102	8	13	75
35 to 30	110	96	14	10	60
30 to 25	120	90	30	5	31
25 to 20	130	90	40	4	21
20 to 15	140	100	40	4	25
15 to end	160	120	40	4	31

Note: The MC is based on properly prepared and placed samples and is the average of the wettest half of the samples. Dry-bulb temperatures are the maximum level recommended.

Start-Up Procedures

No matter if the lumber is predried or air dried before kiln drying, or even if it was just held for a day or two at the sawmill before shipping, the first step in preparing the lumber for drying is to carefully examine the lumber. The examination should include a check on the MC (Green lumber should be at the typical green MC level; if lower, than someone has already started to dry the lumber and could possible have damaged it.) and a check for surface, interior, and end checks. The extent of checking is determined by cutting a sample as illustrated in Figure 3. A kiln will not fix or repair existing damage. In fact, when preexisting damage is found, the schedule in the kiln should be modified by delaying the changes in kiln conditions by several days to a week (depending on the extent of the damage), by keeping temperatures lower than normal to enhance the wood's strength, and by avoiding any moisture regain.

Whether the lumber has been damaged or not, one of the key concepts to successful drying is "Once drying begins, **NEVER** let the lumber pick up moisture!" This means, never expose the lumber to a higher humidity than the humidity to which it was exposed just before going into the dryer. (The exception is in equalizing and conditioning, when there is no risk of degrade.)

Therefore, with very wet lumber (Stage I), begin the schedule at the indicated first step of the schedule. However, do not inject moisture into the dryer's atmosphere during heat-up of the dryer and warming of the lumber. If moisture is added, it is likely that it will condense on the cool lumber, thereby increase the lumber's MC.

With partially dry lumber (Stage II or III), it is even more critical to avoid adding moisture back to the lumber. Doing so will greatly increase the extent of surface checking, honeycomb, and warp. Therefore, the best way to start-up the kiln is to measure the MC of the surface of the lumber (a moisture meter is the most reasonable way to get this MC-just touch the needles to the surface; don't drive them into the wood) and then set the initial kiln EMC to be 0%, 1%, or 2% below the surface MC. After 12 to 24 hours, these conditions are then gradually changed to the conditions required in the schedule. In any case, however, never let the start-up conditions be drier than the level recommended in the schedule. The choice of 0%, 1%, or 2% is based on the risk of checking and the quality of the lumber up to this point. If the species has little risk and is in good shape, then use 2% below. In most cases, especially with oak, 1% is the recommended value. With lumber with checks or other degrade, then 0% would be best (but even then, damage can occur). In all cases, the dry-bulb can be the setting recommended in the schedule, or lower.

With predried lumber entering the kiln directly from the warehouse predryer (and not stored outside), the EMC in the kiln should be 1% or 2% lower than the EMC in the predryer.

Equalizing and Conditioning Procedures

Equalization is accomplished by setting an EMC in the kiln that is 2% or 3% below the average final MC desired. For example, if the average final MC is 7% (i.e., 6 to 8% MC), then the equalization MC is (7 - 2 =) 5% or (7 - 3 =) 4%. The lower EMC does not provide as good of machining and gluing quality. The required equalization settings are presented in Table 9.

Equalization begins when the driest sample reaches 2% (or 3%) below the average target final MC. The higher the temperature, the faster drying will continue. Usually, the temperature used is the same as the final step in the schedule. Equalization continues until the wettest sample reaches the target final MC. For 7% target, equalization begins when the driest sample reaches 5% and continues until the wettest reaches 7%. At this point all lumber in the kiln, if samples are properly taken, will be between 5 and 7% MC.

Table IX Traditional Wet-bulb Temperatures for Equalizing Hardwoods

Final Avg.	Dry-Bulb Temperature, °F						
MC	**140**	**150**	**160**	**170**	**180**	**190**	**200**
-%-	-°F-	-°F-	-°F-	-°F-	-°F-	-°F-	-°F-
6 (5)	92	101	110	120	130	140	150
7 (6)	99	108	118	127	137	147	157
8 (7)	105	115	125	135	145	156	167
9 (8)	111	121	131	141	152	163	174

The numbers in **()** are for **target-2%** and usually produce better quality.

Conditioning begins when equalization is completed. (Note: Conditioning requires equalized lumber; otherwise stress relief will be spotty.) As mentioned, the key to conditioning is high temperature with rapid increase of moisture on the surface. Therefore, to condition, saturated, low pressure steam is injected into the dryer (Table 10). No heat is added for at least the first four hours. Then heat may be added as necessary. Usually the settings used for conditioning are calculated at a dry-bulb 10°F higher than the equalization setting. The heat in the steam spray will drive the dry-bulb up to this level initially. Conditioning continues until satisfactory stress relief is obtained. Unfortunately, the amount of stress in the lumber can only be assessed after the lumber has cooled, so determining the end point for conditioning requires a great deal of experience. **Operating a Lumber Dryer** discusses how to prepare sections to evaluate stresses.

Table X Traditional Wet-bulb Temperatures for Conditioning Hardwoods and Softwoods

Final Avg.	Dry-Bulb Temperature, °F					
MC	**140**	**150**	**160**	**170**	**180**	**190**
-%-	-°F-	-°F-	-°F-	-°F-	-°F-	-°F-
6 (5)	126	136	147	157	168	178
7 (6)	128	138	149	159	170	180
8 (7)	130	140	151	161	172	182
9 (8)	132	142	152	163	173	183

Numbers in **()** are for softwoods.

Computer Automation for Hardwood Lumber Drying

Previous sections have detailed the requirements for an efficient drying of hardwoods. From these discussions, the following criteria for an automatic, computer controlled drying system, for hardwoods intended for high value uses where MC is critical, can be established. The ideal system must be able to perform the following functions:

- measurement of the average moisture content of both the wetter and wettest pieces of lumber,
- measurement of the average moisture content of the driest piece of lumber,
- calculation of the drying rate of individual pieces of lumber,
- calculation of the average moisture content of the wettest pieces, control of kiln temperature within 1/2°F and relative humidity within 1 or 2%,
- measurement of moisture contents above 40% quite accurately (within 5% MC) and with a repeatability of 1/2% MC, and extremely accurate (within 1/4% MC) measurement of low MCs-5 to 8% MC,
- ability to control kiln temperatures to within 1/2°F and relative humidity to within 2%, and to change kiln conditions very smoothly, avoiding the step schedules of today.
- ability to begin, control, and end equalization,
- ability to begin, control, and end conditioning, and
- visual inspection of samples for degrade.

Present Options

Certainly the above criteria are possible with today's technology, but the cost would make such a system impractical. So compromises must be made, getting the best system for the dollars spent. As the major economic benefit will be in improved quality rather than in faster or less labor intensive drying, we must consider an automatic system in terms of drying quality.

Determining Moisture Content

Moisture content can be measured by weighing. Weighing inside the kiln of individual pieces or samples of lumber is difficult due to changing calibration of the conventional weighing cells. However, if an accurate temperature correction calibration can be obtained, it is possible that a computer can process the raw data from a weighing device and make any needed corrections. Because we are looking at a piece of lumber that may weigh up to ten pounds and are concerned about weight losses of 0.01 to 0.03 pounds (equivalent to 1/2% MC), it is an extremely difficult job to accomplish at a reasonable price. Even if the calibration is found for one cell, each cell has its own calibration that must be determined. No matter how the weight of the sample is obtained, the moisture content is calculated based on the estimated oven-dry weight, which in turn is based on the moisture content of small 1-inch moisture sections.

Moisture content can also be estimated by measuring electrical resistance between two needles. This relationship between resistance and moisture content has been known for a long time. Unfortunately, Nature has not put the same relationship in every piece of wood. There are substantial variations between resistance and moisture content for different species, and even for lumber from different pieces of wood from the same species. So although we can accurately measure resistance, the relationship to MC cannot always be accurately given due to the natural variation that exists. This variation results in an uncertainty of several percent MC under 20% MC.

Above 20%, especially above 25%, the variation in resistance as MC changes is very small-so small, that the natural variations in resistance from piece to piece can be greater than the changes in MC from 30 to 50% MC. In essence, each piece of wood has its own calibration of resistance to MC at high MCs. If moisture sections are cut (as mentioned above), then it is possible that the resistance method of measurement could be used to determine MC. If the MC is not measured with a high degree of accuracy, then the schedules used must be conservative-that is, have a built-in safety factor.

It must be remembered that these concerns apply to hardwoods intended for exacting uses where small errors in MC measurement can lead to degrade during drying or lead to subsequent manufacturing problems. For non-exacting uses of hardwoods (upholstery frames, for example), the present electrical moisture measuring systems are accurate enough. Electrical measurement of moisture in the kiln for non-degrade-prone species (such as yellow-poplar, aspen, or soft maple) can also be done with present systems and without concern for potential errors, as any errors will not be economically serious-that is, won't result in degrade.

Computerized Control

Today it is possible to purchase very sophisticated, yet reasonably priced control systems for lumber dry kilns. Temperatures can easily be controlled, with properly designed and functioning equipment, to within 1/4°F. The control systems are able to measure and control the moisture in the air very accurately. With computerized memory, they are able to change kiln conditions smoothly, rather than abruptly. In addition, they are able to equalize and condition as well. Research and experience has shown that these systems do save money by producing higher quality in less time than conventional equipment of the past.

Visual Inspection

Computerized visual recognition is a new and expanding field. Computers can now look at lumber and assist in making edging decisions. Computerized lumber grading is already possible in the laboratory. With fiber optics, it is not hard to envision a computer vision system that could watch for degrade better than we can do it ourselves today. Let's hope that the cost comes down low enough so that we can afford it.

Temperature Drop Across the Load

The TDAL measurement provides average MCs at any time during drying, although the values are most accurate below 40% MC. The difficulty we have faced is relating the average MC, or the average drying rate, to the behavior of individual pieces of lumber. I have seen too many cases in lumber drying where the average is not suitable for predicting the individual's behavior. However, for non-exacting uses or for those species where degrade is not very likely, operation on the average can be valid. Presently we do not spend very much effort drying these non-exacting or non-degrade-prone woods, so I am not sure what the benefits of the more sophisticated control system would be.

Drying Degrade

Causes of and Cures for Drying Degrade

At times there is a great deal of mystique regarding the causes of degrade. However, it is really quite straightforward.

Drying too fast (i.e., temperature too high, humidity too low, and/or velocity too fast), as indicated in Table 11, will result in failure of the wood (checking, splitting, honeycomb, etc.). In 99% of all cases, these failures will occur or become inevitable during Stage I-the loss of the first 1/3 of the lumber's "tree green" MC. (Recall that many times the wood is damaged in Stage I, but the damage doesn't show up until later.) Often the problem with "drying too fast" is that the operator doesn't realize that the lumber being dried is not of as high quality as expected and therefore requires slower drying. For example, it may be bacterially infected; or it may have been slightly checked prior to receipt. Such factors mean that standard practices must be modified to accommodate the weaker lumber. Drying too fast may also occur in those scattered areas where velocities are too high.

Drying too slowly (i.e., humidity too high, velocity too low, and rarely temperature too low) will result in staining and discoloration, as well as warp. The risk is greatest above 50% MC. Below 30%, the risk is probably nil. Drying too slowly, when conditions oscillate between good drying and very slow drying, especially when the cycle is over 3 hours, result in aggravation of surface checks and end splits. Drying too slowly also includes the time after sawing but before stacking. Three days of tight piling before stacking at temperatures over 70°F, even when the lumber is dipped in an antifungal chemical, can result in severe staining. Depressions initially in the kiln, even for 12 hours, less than 10°F can result in staining. All staining will typically not develop the actual color change until the MC is below 20% Further, often the stain is not visible on the rough surface. It is only after the lumber is planed that it shows up. (Note: Slow drying and therefore a risk of staining may also occur in those scattered areas in a dryer where the velocity is much below the average.)

Poor stacking (i.e., having stickers out of alignment, having bolsters out of alignment or not under every sticker or not level, or having too few stickers) can accentuate warp, especially waviness or bow along the lumber's length. Crook, twist, and cup are not too sensitive to stacking, except when stacking is very poor. Humidity and natural factors (tension wood, compression wood, and juvenile wood) dominate the causes of warp in most operations with "average" stacking. Because a kiln or predryer for hardwoods will have higher humidities than in air drying, it is not unusual to see an increase in warp when drying "green-from-the-saw" compared to air drying.

Table XI Drying Defect Identification

I. Drying too fast
   a. surface checks
   b. end checks
   c. internal checks (including honeycomb)
   d. splits and cracks
   e. collapse

II. Drying too slowly
   a. stain, fungal (e.g., blue stain)
   b. mold
   c. mildew
   d. decay
   e. chemical stains (e.g., brown stain; pinking)
   f. warp
   g. checking

III. Poor stacking
   a. warp, especially bow
   b. uneven drying

IV. Operational errors
   a. too wet (MC = EMC, + or - 2%)
   b. too dry
   c. casehardened
   d. resin not set
   e. loss of aromatic odors

V. Miscellaneous
   a. ring failure, shake
   b. checked or loosened knots
   c. fallen knots
   d. heart splits
   e. crook, twist, and cup

VI. Processing defects related to drying
   a. raised, chipped, fuzzy, or torn grain
   b. gluing problems, esp. end splits
   c. planer splits
   d. saw pinching
   e. warp
   f. bad odors

Operational errors (i.e., lumber at the wrong MC, casehardening not relieved well enough, and, in softwoods, resin not set) are unfortunately all too common. Many times, drying too rapidly or too slowly and poor stacking are operational errors too. All operational errors are preventable if the operator has enough information and enough time, and if the operator has the support of management. Short courses in lumber drying are offered throughout the country and throughout the year. Many associations, such as the National Hardwood Lumber Association, Southeastern Lumber Manufacturers Association, and Hardwood Manufacturers Association, sponsor these seminars. Further, computerized controls are now available that virtually eliminate operator errors, and further can accurately convey management objections and can provide process control of drying conditions. Drying too hot (over 85°F), will drive off the cedar oils and therefore the cedar smell is lost.

Miscellaneous drying defects are those defects which are inevitable due to the properties or characteristics of the tree. Drying too quickly, drying at too high a temperature, or drying at too low an RH will accentuate these defects.

Processing defects, except for saw pinching and bad odors, are defects that result when the MC is not at the correct level (i.e., within 2% of the EMC in storage, manufacturing, and use). Saw pinching is an indication of casehardening. Bad odors are an indication of the presence of bacteria in the tree.

Types of Drying Degrade

Surface checks are a result of using too low an RH and/or too high a velocity, especially during Stage I. They are more likely to occur with bacterial infected wood or lumber sawn with a dull circle saw. The checks will close and become invisible from the surface, but will appear when the lumber is planed. Checks can also develop into serious degrade if the lumber is cycled between humid and dry conditions, such as caused by long fan reversals cycles at high humidities.

End checks are a result of too rapid drying of the ends. Nearly all end checks can be prevented with end coating on the logs and on freshly sawn lumber ends. (A delay of just a few days in applying the coating to lumber reduces the benefit by 50%.) When a check goes through from face to face, it is called a split.

Internal checks, or bottleneck or honeycomb checks, are almost always (99%) a result of an end check or surface check penetrating inward. Once surface or end checks develop, the drying rate must be slowed or else the checks will develop into internal checks.

Collapse is common in low density woods with high green MCs. The water is pulled out of the cells so fast that the cells collapse inward, reducing the lumen size. Very slow drying is the only potential preventative measure. However, almost all collapse can be recovered at the end of drying by steaming the lumber at 100% RH.

Fungal stains are a result of slow drying above 40% MC. They are easily prevented by immediate stacking after drying and then placing the stacked lumber in a location where the RH is below 92% (throughout the lumber pile).

Mold, mildew, and decay are caused by fungi, which again means that the lumber was dried too slowly at high MCs. Chemical dips may not always control these forms of degrade.

Iron stain is a result of the tannic acid in the wood reacting with iron. The iron can be in the steam or water pipes or can drip from a fixture in the dryer.

Chemical stain is a result of naturally occurring chemicals in the wood changing color via an enzymatic oxidation reaction. The reaction occurs at very high MCs whenever the lumber is dried too slowly. The final discoloration step often occurs under 20% MC, but slow drying must be done at the high MCs. The kiln schedule must start with an initial 10° to 12°F depression to prevent staining in light colored woods.

Warp can be a result of drying at an excessively high RH. Warp, especially bow, is also a result of poor stacking. Much warp is a natural occurrence in the tree and is difficult to control. Warp can be a result of increasing the RH of partly dried lumber-never steam a load of partly dried lumber when it first goes into the kiln.

Uneven final MC is usually a result of varying air velocity in the dryer at high MCs. Varying incoming MCs can also cause a significant problem. Poor stacking also contributes to this problem.

Too wet or too dry lumber is usually a result of poor practices in sampling the lumber. Sometimes, poor instructions from management can contribute.

Casehardening in dry lumber even after a conditioning treatment is usually a result of a conditioning EMC that is too low. (Remember, it is what you **get**, not what you **set** for temperatures and EMC that is important!) Poor sampling or poor equalizing can also be important causes.

Resin exudation will occur with softwoods that are not dried at a high enough dry-bulb temperature. Temperatures over 160°F are essential in order to evaporate those chemicals in the resin that will flow at room temperature.

Loss of aromatic odors is a result of a dry-bulb temperature being too high. Usually 85°F is the maximum temperature when odors must be retained.

Ring failure, or shake is a natural occurrence in the tree and is seldom a true drying defect.

Checked, loosened, or fallen knots are a result of drying too fast at too high a dry-bulb temperature, but the characteristics of the wood also contribute to the cause of this degrade.

Heart splits are considered inevitable whenever the pith is in the piece.

Raised, chipped, fuzzy, and torn grain are related to the presence of tension wood in hardwoods and MCs that are too high or too low. Knife and machine set-up can contribute.

Gluing problems, especially end splits, are a result of incorrect MC of the lumber.

Planer splits are usually a result of excessively dry lumber. Avoid 180°F dry-bulbs and 50°F depressions.

Saw pinching or warp immediately during manufacturing is a result of inadequate stress removal. Warp that does not occur immediately is related to incorrect MCs.

Bad odors in dried wood are usually a result of a bacterial infection that originated in the tree.

Quality Control

Almost all defects can be prevented by proper operation of the dryer, assuming that the equipment is correctly designed and in acceptable operating condition. The key to controlling defects is a quality control program. A good program will identify the cause of degrade (often before the amount of degrade becomes catastrophic), indicate the cost of fixing what is wrong, and indicate the benefit of fixing it.

Following up on the benefit of eliminating degrade, it must be appreciated that there is a difference in benefit (or perspective) if the dried lumber is to be sold under conventional grading rules or if the wood will be used in-house. In general, the grading rules do not appreciate the improvements in quality as much as the user will benefit from the quality improvement. For example, with hardwoods, a 12" long end check in an FAS piece of lumber does not, by itself, eliminate a clear 8" x 12' piece of lumber from the FAS grade.

Yet the 12" split can easily reduce the useful area of the lumber for a furniture manufacturer by 1/12 or 8%.

One way to look at a QC program is to ask the question "If someone stole 5% of your lumber, would you go after him/her (spending time and money) and try to get it back?" Sure, we all would. It is common that drying losses exceed 7%; yet a good operation can limit losses to under 2%. A QC program will go after that 5% or more that is being stolen.

The following techniques or procedures can form the basis for a topnotch QC program. Note that most of these techniques are simple to implement, require minimal labor, and can be done "in-house." They are divided into three categories: analyzing the lumber, analyzing the equipment, and operating techniques.

Analyzing the Lumber

Drying quality control analyses involve assessing the level of degrade after drying. Although one measure of degrade might be the yields when the lumber is cut up into furniture parts or processed into a finished piece, such studies are quite involved and time consuming.

One alternative analysis is a double grading study. In this study, the lumber is graded green and then is regraded after drying. The differences in grade between the two is attributed to normal shrinkage or to drying degrade. Double grading is especially effective with hardwood lumber.

For softwood lumber, especially dimension lumber, an analysis technique is to have the lumber grader at the planer mill indicate the cause for any downgrading or remanufacturing to maintain grade. (For example, the grader might indicate that if the piece were straighter it would be a No. 2, but because of warp it is a No. 3. Or, he may indicate that the piece must be trimmed four feet to eliminate an end check, thereby avoiding downgrading the piece.)

Another analysis technique is to measure the thickness of green lumber. If there is a much overly thick lumber, then drying time will be longer, energy use higher, over-drying more likely, and so on, adding up to significantly higher drying costs. Thickness analysis programs are commonplace in most state natural resource departments.

As has been stated in previous discussions in this text, incorrect moisture content is probably the single, most common operator error. Incorrect MC also is the cause of as much as 80% of the furniture manufacturing defects. It is possible to sample the MC of a load of lumber with a moisture meter. When these values are averaged, then one obtains the estimated average MC for the load. But what about the spread of the data? If the standard deviation of the MC readings is calculated, and then multiplied by 1.96, then the region between [average - (1.96 x std. deviation)] and [average + (1.96 x std. deviation)] represents 95% of all the MC readings in the lumber pile. The standard deviation is easy to calculate; in fact, many small hand-held calculators have this calculation built-in. Virginia Tech also has a free IBM-PC version of such a calculation program available.

After drying is completed, it is a good idea to cut several QC samples. These samples will indicate if there are any problems with the lumber, such as checks, honeycomb, stress, wet lumber, and so on. A picture of these samples is given in Figures 3 and 4. (Note: It is helpful to cut these same samples when green or partly dried lumber is received from an outside vendor. It is surprising to me how many times I am called on to analyze what a kiln operator is doing wrong, but when I arrive, I find that the problem is poor quality lumber.)

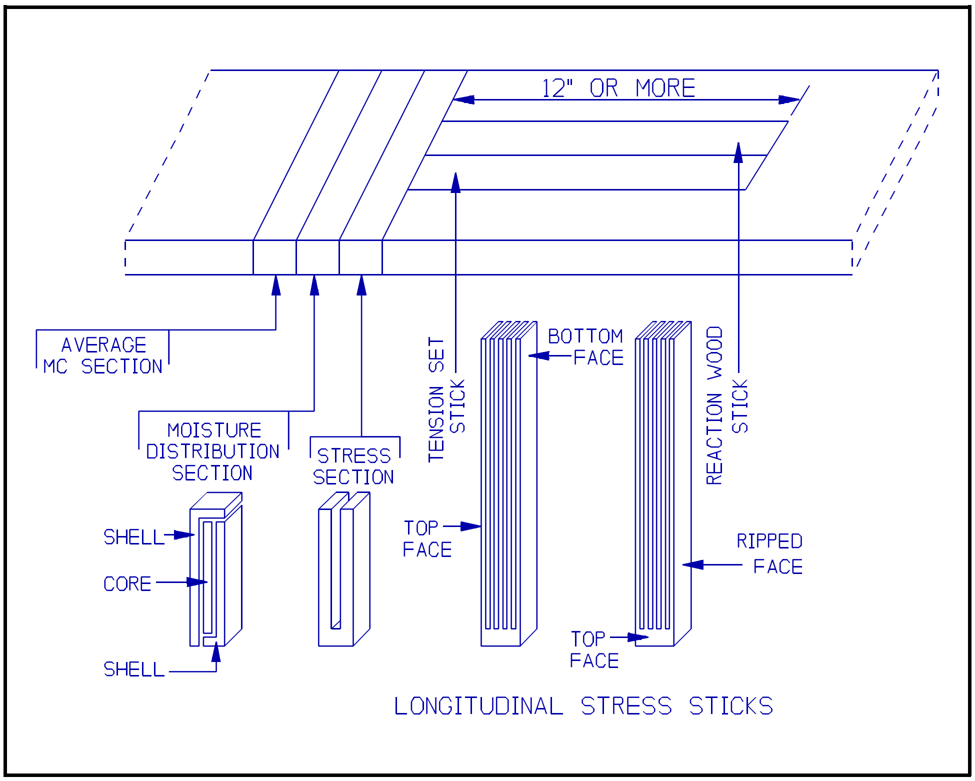

Figure 4 Final Moisture Content and Stress Tests

Analyzing the Equipment

Another analysis technique is to measure the MC of a load of dry lumber and then relate the values to location within the dryer. Often (in fact, much too often), large variations in MC are found in a load of lumber and these variations result from either variation in incoming MC or from variations in drying equipment. The uniformity of final MC is a strong quality assessment tool. When variations are found then, in most cases, the equipment is the cause.

When drying variations are found, then it is either the temperature, RH (or EMC), or velocity that is causing those variations (unless the dryer has mixed incoming MCs or mixed thicknesses). Inexpensive instruments are available for measuring velocity. One air velocity meter is about 3/4-inch thick and fits between the stickers quite nicely. Always measure velocity on the exit side of the load. (Remember, what goes in, must come out. Therefore, the exit velocity is a good measure of what is going on in the dryer.) Temperature and humidity (or EMC) is measured in one spot by the control instrument. However, for analysis, the conditions should be measured throughout the dryer. Accurate, low cost, portable temperature/RH meters are now available. A graphical profile of velocity, temperature, and RH variations as a function of location can assist in analyzing the readings obtained. (Note: these instruments are widely available from scientific supply companies.)

Another helpful bit of information is knowing the location of a particular stack of lumber during drying. Often drying degrade can be related to a particular location in the dryer. This information might be kept on a QC slip which also includes the species, thickness, date that drying was started, incoming MC, time when stacked, date when the load was dried, and so on.

Yet another equipment analysis technique is to cut several samples at the beginning of drying from the same piece of lumber. (Normally, each sample is from a different piece of lumber.) In this case, the samples will be identical and should dry the same unless there are variations within the kiln. So the samples are placed in different sections of the kiln and their drying rate is measured. Any variation indicates equipment problems.

Operating Techniques

In terms of operating techniques, it is strongly encouraged to keep the kiln samples with the load after it leaves the kiln. In this way, any changes in MC that occur in storage and/or transit can be monitored. If a sample weighs 6.32 pounds (and that is 6% MC) when it leaves the kiln, then when there is a complaint of wet lumber two months later and the lumber is 800 miles away, it is easy to ask someone to take the sample and weigh it accurately, and then report back to you. If the weight has increased, then we know that drying was proper, but the increased MC is a result of improper storage or transit.

Another operating technique is to graph the MC of the samples as a function of time (i.e., date). This graph will show any time when drying was too fast or too slow. It is a good picture of what is happening in the kiln. Further, when a load is dried successfully, such a graph provides both a time estimate for the next load and a yardstick to measure how fast the lumber can be dried without damage.

Summary

The objective of lumber drying is to make money. To accomplish this objective requires proper equipment and proper procedures so that the lumber is at the correct final MC (EMC in use ±2%) and has minimal quality loss.

The critical parameters in drying are the temperature, humidity, and velocity of the air passing through the lumber stack. The response of the lumber to the drying conditions is ascertained primarily by measuring the drying rate-the MC loss per day-and comparing the rate to the accepted standard. As most degrade or quality loss occurs above 40% MC, it is most critical to control the drying rate from the moment the lumber is sawn until the MC is below 40% MC. The second most critical point in drying is at the end of drying when the final MC is measured. All too often, incorrect final MCs lead to catastrophic losses in the secondary manufacturing plant.

Dry kiln schedules today must be modified from the older U.S. schedules established over forty years ago. Such changes include never exceeding 160°F and never exceeding a 45°F depression. Improved control instruments now offer faster drying with improved quality. Computer controls with smoothly changing schedules are especially attractive.

The key to managing a successful drying operation is feedback on the quality of the lumber dried. Often the quality impressions of managers of secondary manufacturing plants are not accurate enough or may be confused by the grade of lumber, by several months delay between drying and processing, or by the handling of the lumber after drying was completed. There are quality samples and procedures that can be used at the dryer to accurately estimate quality, however. When quality drying is achieved by an operator and such performance is then recognized and rewarded by management, lumber drying will be an extremely profitable operation.