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HARDWOOD DRY KILN OPERATION

A MANUAL FOR OPERATORS OF SMALL DRY KILNS

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Cooperative Extension Service | Agriculture and Natural Resources **|** Family and Consumer Sciences **|**
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The front illustration shows a sample board coated with B.O.S.S.® (Bright Orange Sample Sealer), made by U-C Coatings Corporation.

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All photographs were taken by the author with the exception of Figures 29 and 30, kindly provided by Dr. Phil Mitchell of North Carolina State University

Figure 11 is from Anonymous, 1993. *An Introduction To Wood Anatomy Characteristics Common To Softwoods & Hardwoods.* Publication FOR-59, published by the Cooperative Extension Service, College of Agriculture at the University of Kentucky. *http://www2.ca.uky.edu/agcomm/pubs/for/for59/for59.pdf.* (Figure 3).

Figure 14 is from USDA Forest Products Laboratory. 2010. *Wood Handbook - Wood as an Engineering Material*. General Technical Report FPL-GTR-190. Madison, WI: U.S. Department of Agriculture, U.S. Forest Service. 508 p. https://www.fpl.fs.fed.us/documnts/fplgtr/fpl_gtr190.pdf. (Figure 3-14)

Figures 39 and 40 were redrawn from Stelzer, H.E. 2011. *Air-Drying Hardwood Lumber*. Publication G5550.University of Missouri Extension. http://extension.missouri.edu/p/G5550. (Figures 2 and 1, respectively).

Figure 41 was redrawn from Denig, Joseph; Wengert, Eugene M.; Simpson, William T. 2000. Drying hardwood lumber. Gen. Tech. Rep. FPL–GTR–118. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 138 p. http://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr118.pdf. (Figure 7.4)

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INTRODUCTION

When I asked a colleague of mine to review a draft of this drying manual, he asked me, “Why write another drying manual? It’s all out there in other publications.” He’s right, of course; there are several other excellent books that have been published for dry kiln operators – and I’ve referred to some of them in this book. As good as they are, though, I’ve seen that people just starting to learn how to dry hardwood lumber tend not to read those books; they merely collect them and put them on a shelf somewhere. This seems to be especially true of small companies where the owner wears many hats, doing everything from buying logs to saw maintenance to stickering to drying to sales and marketing. There’s not a lot of time to sit down and try to digest something that looks like it will take some effort to learn, especially under time constraints.

I’ve written this manual with this small wood business operator in mind. I’ve tried to make the sections short and readable with good illustrations, and I’ve also tried to give examples wherever I can so you don’t have to read about something and then try to figure out what it all means on your own. There are a lot of types of kilns drying hardwood lumber successfully, both homemade and commercial, but most of the commercial small kilns available are either dehumidification kilns or direct-fired. I’ve aimed much of this manual at people who work with dehumidification dry kilns in particular, but the guidelines for drying lumber are much the same regardless of the type of dry kiln in use.

I hope you find the contents of this manual to be helpful. Of course, in any publication like this it’s inevitable that there will be photographs or references to different equipment and instrument manufacturers. The inclusion of manufacturer names, materials or photographs in this publication should not be construed as an endorsement, nor should my failure to mention any manufacturer be considered negatively.

WHY DRY WOOD?

The most important reason to dry wood is that your customer will request it! Green lumber is used mostly for local uses such as fence boards, barn siding and so forth. Lumber that will be glued or finished has to be dried, however, and that includes just about all the higher-value wood products used indoors such as flooring, furniture, wall paneling, cutting boards and so forth. Dry lumber can be used for more types of products and has greater marketability. Dry lumber is also worth more than green lumber. As I write this the price for a thousand board feet of kiln-dried 4/4 No. 1 Common red oak is almost 60% higher than the price for the same grade of unseasoned red oak. Additionally, dry lumber weighs less compared to green lumber and this might affect your ability to load/unload or deliver lumber to customers.

Dry lumber is that dry lumber is stronger than wet lumber. Wood that is properly dried will machine better, it will have better strength properties, and it will take a finish well. Too little or too much water can cause problems, so it's up to the kiln operator to dry wood to the correct degree of dryness (which is what we call **moisture content**). Wood that is too dry will be brittle when it's machined and might tear out under rotating knife edges in a moulder or router. Wood that is too wet, on the other hand, will be attractive to insects and fungal attack. This is where it all gets just a little bit tricky: even if it's properly dried to the correct moisture content, wood won't stay at that moisture content for long if it's stored improperly.

AN OVERVIEW OF HARDWOOD LUMBER DRYING OPERATIONS

Lumber drying operations usually operate in tandem with one or more sawmills. After sawing, the lumber is stacked with wooden spacers (called ***stickers***) so drying can proceed. Depending on how quickly the lumber has to be dried, and depending on the equipment that's available, hardwood lumber might be dried on an ***air drying yard*** until the ***moisture content*** is reduced enough to finish it off in a ***dry kiln***.

AIR DRYING ON YARDS AND IN SHEDS. Before hardwood lumber is placed in a dry kiln, it is often placed under cover someplace where the ambient temperature and air movement will begin the drying process. It probably seems counter-intuitive, but drying occurs fastest when the piles and alleyways are aligned with the prevailing wind direction. Air-drying stacks of lumber need to be kept off the ground because drying proceeds more slowly there; stacks of lumber that are not under shed roofs also need to be kept covered to prevent sun damage and rewetting due to rain. Sheds allow you to slow down drying by installing screen-like curtains to minimize sun or rain intrusion, and you might find that to be helpful in your operation. No matter how long you air-dry your lumber, though, it will never get as dry as it can in a kiln. At best, air dry lumber might reach around 12–15% moisture content; this is fine for barn siding, fence planks and such, but it's not dry enough for lumber to be used indoors for furniture. In my experience, lumber usually goes into a dry kiln either green from the saw (when the business needs to sell the lumber as quickly as possible), or when the moisture content drops to 20–25% or so after air-drying.

Air drying times will vary tremendously according to the species, the thickness, the time of year the wood is stickered and the location, and there's no magic formula to tell you how long the lumber should air dry. The USDA Forest Service Forest Products Laboratory has a publication called *Air Drying of Lumber* that you may find helpful.[1]

DRY KILNS. Kilns can increase the rate at which lumber dries compared to ambient conditions. In their simplest forms, dry kilns are basically heated and insulated boxes with fans and vents. More sophisticated kilns, like those used in most commercial operations, add the ability to control the temperature and relative humidity for better control of the drying environment.

Choosing the right type of kiln is important to becoming a profitable operation. There are essentially six types of dry kilns:

1) Conventional (steam-heated) dry kilns
2) Hot water-heated dry kilns
3) Direct-fired dry kilns
4) Vacuum kilns
5) Dehumidification (DH) dry kilns
6) Solar dry kilns

CONVENTIONAL (STEAM) KILNS. In conventional steam-heated dry kilns, water removal is induced by heat and mechanical ventilation. Many large kilns are heated by steam, often with the steam coming from biomass boilers consuming on-site wood residues. Steam kilns are heated by steam coils with the steam coming from a nearby boiler. These kilns are typically built from corrosion-resistant metals with large doors for convenient fork truck access (as shown in Figure 1). Steam coils are positioned inside the kiln to heat the air, the fans often reverse to make moisture removal more uniform, and vents are used to allow water vapor to escape. These kilns are commonly quite large; hardwood kilns often have a 40,000 board foot capacity or more, while steam kilns used for softwoods can have capacities over 100,000 board feet. Hardwood kilns typically operate at temperatures below 180°F to minimize drying defects and color darkening, but kilns drying southern pine often operate at 240°F using high-temperature steam. See Figure 1 for an example of a conventional dry kiln.

[1] Forest Products Laboratory. 1999. *Air Drying of Lumber*. Gen. Tech. Rep. FPL–GTR–117. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 62 p. Available for download at http://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr117.pdf

Figure 1. *Conventional steam-heated dry kilns. There are large doors for loading the lumber in the front of the kiln, and the kiln is constructed from corrosion-resistant materials. Notice the number of vents in the kiln roof. These are used to vent water vapor from the drying lumber.*

Whenever possible the steam for conventional kilns is produced on site by burning wood waste. Because of their size, these kilns are the most expensive to construct and they are expensive to operate if oil or gas is used for boiler fuel, but they offer the greatest flexibility in possible drying conditions. The steam that provides heat for drying is also be used to relieve lumber stresses when drying is finished.

HOT WATER-HEATED DRY KILNS. Hot water-heated dry kilns are relatively new to the North American market, though they have been available in Europe. They are similar in many respects to conventional steam kilns, but they are heated by circulating hot water or oil. Sawdust-fired boilers heat the water which is then injected into heating coils as needed to control the kiln temperature. Kilns are custom-fabricated, but sales literature indicates that they are available in sizes from approximately 4000 board feet to 60,000 board feet.

DIRECT-FIRED DRY KILNS. Direct-fired dry kilns dry wood by the introduction of heated air into the kiln chamber. Often the heat is generated by the firing of natural gas, but wood waste is also used for heat at some locations. Direct-fired kilns work quite well and are sometimes favored for fast-drying species (such as pine). To avoid hot spots, direct-fired kilns should not be operated with partial loads. Kilns offered by one company range from 9000 to 40,000 board feet capacity. Hot water and steam heating may be offered as options. If hot water or steam are not used, additional humidification equipment will likely be needed to relieve drying stresses for hardwood lumber.

VACUUM KILNS. Vacuum kilns work by reducing the atmospheric pressure, thereby enabling water to vaporize at lower temperatures. They’re used to dry specialty products such as baseball bat billets and guitar bodies, but because they’re expensive this is not appropriate technology for a small operation drying grade lumber. Capacities range from 500 board feet to over 10,000 board feet. Heat won’t transfer by convection in a vacuum, so as seen in Figure 2 heated blankets are used to directly transfer heat to the wood to be dried.

Figure 2. *This clamshell-like vacuum kiln is used to dry high-value hardwood blanks for a guitar factory. The silvery pieces of fabric are used to heat the wood.*

DEHUMIDIFICATION KILNS. Dehumidification kilns, commonly referred to as DH kilns, are often used to dry hardwood lumber. DH kilns are often used by companies that don't want to install a boiler on the property, as these units run entirely off of electricity. Both the temperature and relative humidity conditions are electronically controlled to maintain chosen set points. Hardwood sawmills using a portable band saw and with no more than a few employees probably need 4000–20,000 board foot total capacity, though commercial equipment can be purchased that is designed to dry quantities as small as a few hundred board feet of lumber. Larger DH kilns of 90,000 board feet and more have also been installed; see Figures 3, 4 and 5 for examples of small and large DH kilns.

Figure 3. *The DH kiln at the left holds 4000 board feet of lumber. The door at the right is for access to the office, all under one roof at this small company. The stove pipe serves as a chimney for a small wood-fired box stove used to heat the office. This kiln was designed with a narrow door and the lumber has to be loaded sideways.*

Figure 4 shows an inside view of the kiln shown in Figure 3.

Figure 4. *In this DH kiln the compressor unit is to the right. The hinged piece of plywood near the ceiling is a baffle that drops to direct circulating air through the stacks of lumber. There is a small powered vent at the rear.*

Figure 5. *These are dehumidification kilns, though it's hard to tell the difference from most other kiln types just by looking at the outside of the building. One difference from large conventional kilns is that the vents are smaller and fewer in number (in this photograph the vents are above the doors at the front of the building). Each of these large kilns holds about 50,000 board feet of lumber.*

It's typically the responsibility of the purchaser to erect the kiln chamber for small systems. Plans are available from several sources, but ultimately the chamber doesn't need to be much more than a well-insulated garage with materials and refinements chosen by the user. Installers need to apply a water vapor-proof barrier such as Kiln-Kote to the inside of the kiln as well. This helps to keep water vapor from condensing in the kiln walls and prolongs the life of user-erected buildings made of wood or concrete blocks. Interior vapor barriers are useful components of commercially-fabricated kilns as well.

If you design your own kiln, specify your loading door to be at least one foot wider than the actual length of your lumber to accommodate loading lumber packs with a fork truck. Be sure to insulate the concrete floor and use sheets of foam insulation instead of fiberglass to insulate the building; if water vapor does penetrate the walls and condense it will saturate fiberglass insulation and compromise its thermal properties. A small drain in the center of an appropriately sloped floor will help to remove condensation from cold lumber. Loading lumber into an insulated box endwise takes more time, but if you're just starting a business you might want to check out refitting a high-cube reefer truck as your kiln chamber.

DH Kiln Components and Operation. There are two separate components to DH kilns: 1) a refrigeration compressor with evaporation and condenser coils and 2) a supplemental heating unit. The compressor is sized according to the lumber volume; a 4000 BF DH kiln would be powered by a 2 HP compressor, for example. During operation, fans blow warm air across stacks of lumber. Water evaporates from the lumber as the air passes over the wood, and this moist air is circulated over the evaporator coil; water condenses on the chilled coils, drips into a collection pan and is removed from the kiln through a pipe. A compressor downstream from the evaporator coil compresses the refrigerant. This warms the refrigerant, and it then goes through a series of condenser coils where it gives up its heat to the kiln chamber. The kiln conditions are electronically controlled to maintain the temperature and relative humidity conditions set by the operator.

To supplement the heat generated by the compressor, DH kilns can use an auxiliary heating unit to help heat the kiln at startup and to reach set temperatures quickly. If resinous softwoods are to be dried in a DH kiln, the kiln manufacturer will size the heater to make sure the kiln can get hot enough to set the pitch.

In other types of kilns the RH is controlled by opening and closing the vents, but in DH kilns small vents are only activated when the kiln humidity exceeds the capacity of the compressor to control it; high humidities are especially common during startup though they may also occur at other times as well. Because there is so little venting, DH kilns are relatively energy efficient compared to other types of kilns.

One noteworthy problem with drying green lumber in a DH kiln is that it can be difficult for the compressor to remove water quickly enough from some species (*ex*., yellow-poplar) to prevent mold growth in the early stages of drying. This depends on the size of the compressor, of course, but most DH compressors are sized for overall efficiency rather than to accommodate worst-case situations. Other than air-drying lumber before putting it into the kiln, a common work-around for these species is to load less green lumber into the kiln. This allows the compressor to work within its rating and condense enough water vapor to keep the relative humidity below 80% (above which mold grows quickly), but the trade-off is that the kiln is under-loaded compared to its physical capacity. I know of at least one pine kiln operator who alternatively chooses to maintain a low initial kiln temperature for up to a week, thereby reducing the rate of evaporation, before he raises the temperature.

SOLAR KILNS. Solar kiln kits are commercially available, but they seem to be homemade more commonly. What visually distinguishes solar kilns from other types of dry kilns is the sloped roof which acts as a solar collector. Solar kilns are positioned facing south to catch the sun (Figure 6).

Figure 6*. Solar dry kiln. The sloped roof acts as a solar collector to heat the dry kiln.*

Solar kilns are typically used by very small companies or by hobbyists. The capacity varies, but the biggest one I've seen could hold about six thousand board feet of lumber. The capital investment required to erect one is typically a few thousand dollars or less, but they might dry only one or two loads of lumber per year. The throughput depends on the size of the kiln, the moisture content of the lumber going into the kiln and the final moisture content desired. The drying rate is affected by the kiln design, orientation and location. The amount of sunlight and the ambient temperature are critical; drying essentially ceases from October through April each year from the Kentucky–Tennessee state line and northward. I have seen some people add supplemental heat from a wood furnace to successfully extend the drying season.

There are a number of good designs for solar kilns available online from Virginia Tech, WoodWeb, Oregon State University and other institutions. A good place to start is *BuildItSolar.com*, which has a number of plans referenced on its website: http://www.builditsolar.com/Projects/WoodDrying/wood_kiln.htm.

Relative humidity (RH) and temperature conditions both affect the lumber drying rate, but these are minimally controllable in solar kilns compared to other types of kilns; usually the only control mechanisms are manually-operated vents. Without good environmental controls the kiln can get too hot for green lumber, resulting in drying defects. Here's an example: the temperatures in one solar kiln (without fans) I looked at in Kentucky in late spring ranged from 190°F near the peak to 105°F close to the floor. (This kiln probably has a larger area for solar collection than most.) When a couple of fans were added to this kiln the temperatures near the roof peak dropped to 140°F; that's still too hot for green lumber. This particular installation cleverly used a solar panel to run DC-powered fans for an off-the-grid location.

Lumber which is already air-dried can finish drying in a solar kiln more successfully, but temperature variability will affect how uniformly the lumber dries in the kiln. Fans might help to even out kiln temperatures, but they can't fix relative humidity control issues. Evaporated water must be vented if the lumber is to dry, but vents are typically opened or closed based on the kiln temperature. That's not the best way to control the RH inside the kiln.

Solar kilns do have their advocates. Lumber dried in a solar kiln may have less drying stress (known as ***casehardening***) than lumber dried in conventional kilns because cooler night time temperatures temporarily increase the relative humidity inside the kiln. As the temperature warms up the relative humidity decreases again, inducing further drying. It seems that the daily cyclic changes in relative humidity inside the kiln decrease the amount of drying stress in the lumber, though the tradeoff is that these kilns dry more slowly than other kilns even when the daytime conditions are favorable.

WHAT KILN OPERATORS NEED TO KNOW ABOUT WOOD STRUCTURE AND PROPERTIES

Wood is a natural composite. It's made from different chemicals (with different degrees of water absorbency) that combine to make fibers. Unlike man-made composites which can be manufactured with the properties we want, we have to take the trees as they are given to us by Mother Nature. Just like the kids we went to school with, some trees grow faster than others, some are fatter or skinnier than others, and some are well-mannered while others are troublemakers. Sawyers do their best to make good, sound lumber, but inevitably some problems will get passed along to the air drying yard or kiln operator. The air-drying yard supervisor has a difficult job: it's up to him to see that every board gets air-dried properly before it's sent to the dry kiln. Mother Nature and Human Nature being what they are, though, some lumber just won't get handled optimally, and some of the problems that air drying yards inherit (or even create) will get passed along to the dry kiln operators. Let's take a quick look at how wood is put together so you can better understand why lumber dries the way it does.

FIBERS. Roughly 90% of the cells in a tree run parallel with the trunk. These cells are what we commonly call ***fibers***, and they give the tree strength, supporting the trunk and the branches above. I like to think of a bunch of soda straws as my model for these cells – they're hollow like fibers, and they're strong when they're in a bundle. The rest of the cells are oriented at 90 degrees to the tree trunk, and groups of these cells are called ***rays***. You can think of rays as each tree's "moving and storage company" if you like. Rays move the waste products from the living cells in the cambium just below the bark into an area closer to the center of the tree. These compounds are often colored or scented, and the area where they are located is called ***heartwood***; heartwood is the portion of the trunk surrounding the ***pith*** (in the center of the tree). The lighter-colored region surrounding the heartwood and just beneath the bark is called ***sapwood*** (Figure 7).

EXTRACTIVES. Boards from different species are different in both color and odor, and this is due to chemicals in the wood called ***extractives***. The differences are usually most pronounced when heartwood is compared, because the extractive content in heartwood is typically significantly higher than in sapwood. The chemicals are called extractives because they can be removed from wood using solvents such as hot water or alcohol. Extractives aren't part of the cell structure itself, though they might impregnate the cell wall or fill some cells entirely.

Figure 7. *The heartwood in these hickory logs is the darker-brown colored wood surrounding the center of the logs. The sapwood is the pale brown-colored wood between the heartwood and bark. The proportion of heartwood differs significantly from log to log, though this is not unique to hickory.*

PORES AND GROWTH RINGS. All hardwoods (trees with broad leaves instead of needles) have ***pores*** – continuous cellular tubes that convey sap from the roots to the leaves and vice-versa; they're also known as ***vessels.*** Pores run parallel to the fibers; the significance of pores to dry kiln operators is that they play an important part in the conduction of water out of the wood during drying. Water can exit lumber via the pores very quickly, especially on the end grain of a piece of lumber. This can cause headaches due to uncontrolled localized shrinkage (perhaps even splits) on the ends of hardwood boards, but it's easily managed. Softwoods (coniferous trees) do not contain pores, but water still exits from the board ends faster than it does from the side grain.

Each annual growth increment is called a ***growth ring***, and these are readily seen on the ends of logs. Most hardwood species have pores distributed within the growth ring according to one of two arrangements. In some species, the pores in the first-formed part of each growth ring (called the ***earlywood***) are significantly larger than the pores found in the rest of the growth ring (the ***latewood***), so the growth rings are easy to distinguish. These species are called ***ring porous*** species; examples of ring porous species include the oaks, elms, and ash. In other species the pores are essentially the same size and distributed fairly uniformly. These species are called ***diffuse porous*** species. Trees such as maple, beech and sycamore are examples of diffuse porous species (see Figure 8).

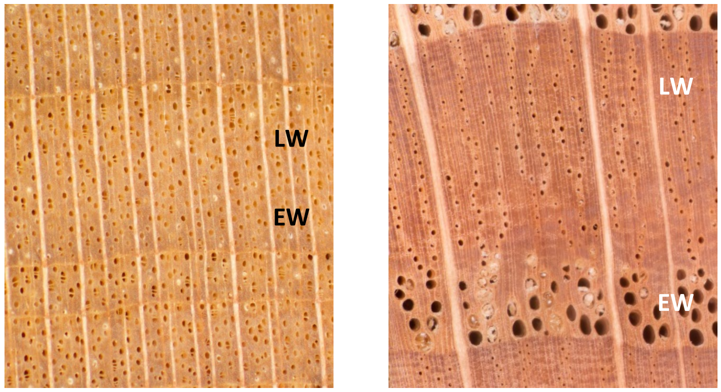

Figure 8. *These micrographs are of the end grain of two different wood species. A diffuse porous species (hard maple) is on the left, and a ring porous species (red oak) is on the right. EW and LW stand for earlywood and latewood, respectively. Earlywood and latewood together make up one year's growth (a growth ring).*

Notice how the large, earlywood pores are pretty open (except for a little sawdust) in the red oak shown in Figure 8. These pores are so large that I can blow air through them for demonstrations, and you can too! Take a piece of red oak (I use 5/8" x 5/8" x 3 ½" or so), dip one end in bubble soap and blow through the wood from the dry end. Instant bubbles!

Red oak pores are so open and so large that this species cannot be used for barrels used to hold liquids (such as bourbon). White oak is used for this purpose because the pores contain small balloon-like blockages called ***tyloses***. Figure 9 shows a micrograph of white oak for comparison:

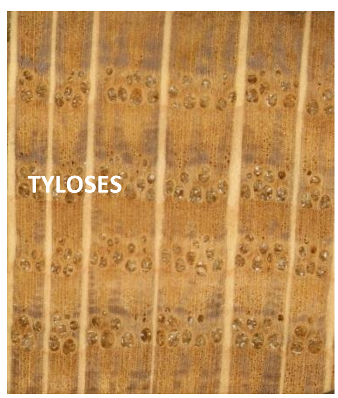

Figure 9. *This micrograph shows a cross-section (end grain) of white oak, a ring porous species, with the earlywood vessels plugged by tyloses. Only one row of earlywood with tyloses is marked, though this growth ring is no different from the rest.*

Tyloses can slow the drying rate of lumber, which is why their presence (or absence) is important.

RAYS. Keen-eyed observers will have noticed that there are light-colored stripes running perpendicular to the growth rings in Figures 8 and 9. These stripes are actually groups of cells called ***rays***. Rays are groups of storage and conduction cells that run perpendicular to the fibers and the pores, outwards from the direction of the pith towards the bark. See Figure 10, where these earlier figures are repeated (with the rays labelled this time).

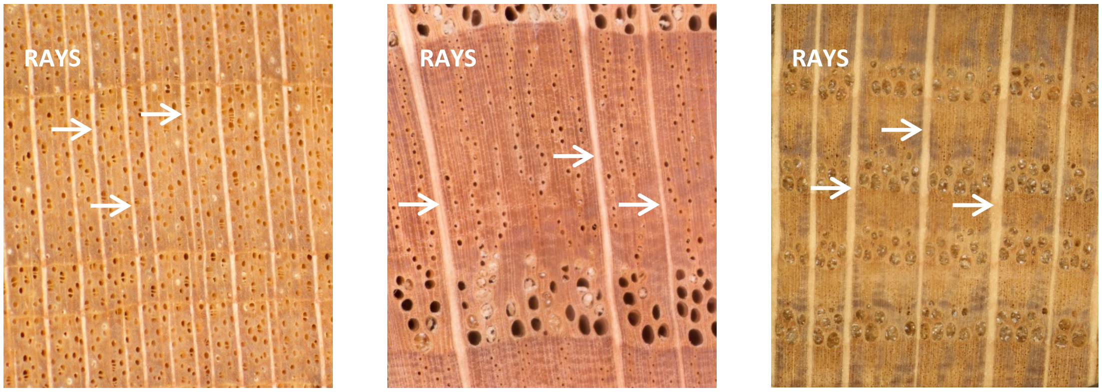

Figure 10. *A few of the rays are labelled on the end grain for each of these micrographs (of hard maple, red oak and white oak, shown above from left to right). The rays in the oaks are significantly wider than those in maple. These broad rays help to distinguish the oaks from other species.*

The size of each ray will vary, depending on how many individual cells are grouped into the ray. Sometimes the width of the rays can be used to help identify the species. ***Broad rays*** are noticeable to the naked eye and when combined with a ring porous structure positively identify lumber as coming from one of the oak species (refer to the oak micrographs in Figure 10). Ray cells run parallel to each other, and the number of ray cells that are stacked one on top of another will affect the ray height, while the number of rows of ray cells that run alongside each other will affect the ray width that is visible on the end grain. Ray heights and ray widths vary among species, so the rays will be easier to see in some species than in others. In some species there is a mix of both wide and narrow rays; in other words, all rays in a piece of wood are not necessarily going to look the same.

Shrinkage around the rays often initiates localized defects called **surface checks**. Large, wide rays act like stress concentrators more than small, narrow rays, so species with broad rays (such as the oaks, beech and sycamore) are much more prone to checking than species with narrow rays (like yellow-poplar or maple).

THE CROSS-SECTION AND THE SIDE GRAIN. You've probably noticed how the growth rings look different depending on where you look at a piece of lumber. Growth rings look a lot more like rings on the cross section than they do on the side grain. The appearance of the growth rings on the surface underneath the bark doesn't resemble the growth ring appearance on the side of a pie-shaped wedge, either – how the growth rings look on a board surface depends on how the tree is sawn.

Labels have been assigned to the different surfaces of a piece of wood so everyone can use the same terminology when we're discussing how lumber looks or behaves during drying. The "cross section" surface is the same as the end of a log or the top of a stump; it's sometimes referred to as the "transverse" surface. The "radial" and "tangential" names are related to geometry. The radius is a line extending from the center of a circle to its perimeter, like a bicycle spoke. Just as there are many spokes on a bicycle wheel, there can be an infinite number of radial surfaces in a piece of wood (though you'd have to make saw cuts to expose them). The tangential surface is any surface parallel to the bark; like the radial surfaces, there can be an infinite number of tangential planes exposed if you wanted to go to the trouble of cutting them. (See Figure 11.)

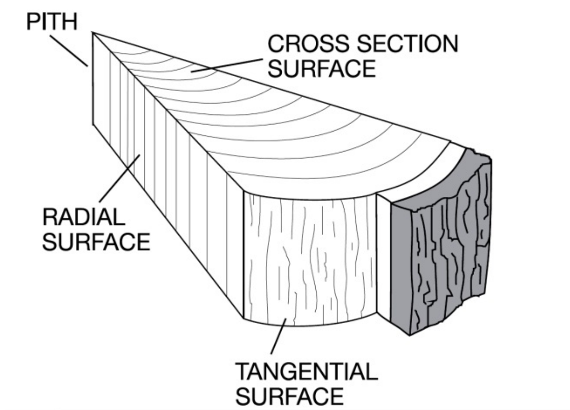

Figure 11. *This sketch labels the cross section, radial surface and the tangential surface on a wedge of wood.*[2]

Ring porous species are said to have a more open grain than diffuse porous species. The appearance of the large earlywood pores is quite pronounced on the side grain in ring porous species. In contrast, no such distinction exists in diffuse porous species where all the pores are essentially the same size. See the photographs of white ash (ring porous) in Figure 12 and yellow-poplar (diffuse porous) in Figure 13.[3]

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[2] Source*:* Anonymous, 1993. *An Introduction To Wood Anatomy Characteristics Common To Softwoods & Hardwoods*. Publication FOR-59, published by the Cooperative Extension Service, College of Agriculture at the University of Kentucky. http://www2.ca.uky.edu/agcomm/pubs/for/for59/for59.pdf

[3] These figures are photographic reproductions, made by this author, of actual thin wood sections prepared by Romeyn B. Hough and published by him in a fifteen volume set with plates representing twenty-five different North American species per volume. Hough's *The American Woods* was self-published between 1888 and 1913.

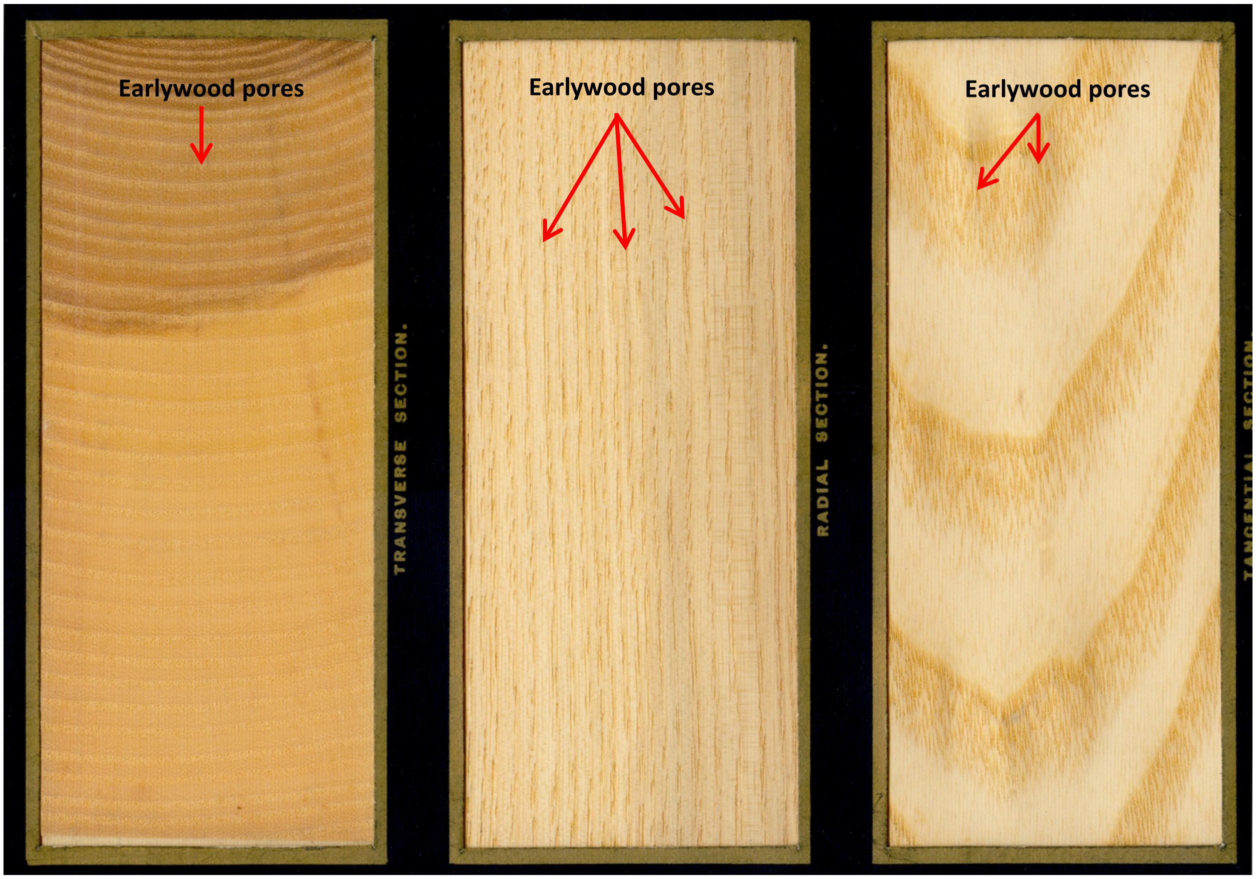

Figure 12. *This is a photograph of a cross section (marked transverse section), a radial section, and a tangential section of white ash, a ring porous species. Some of the earlywood pores are marked.*

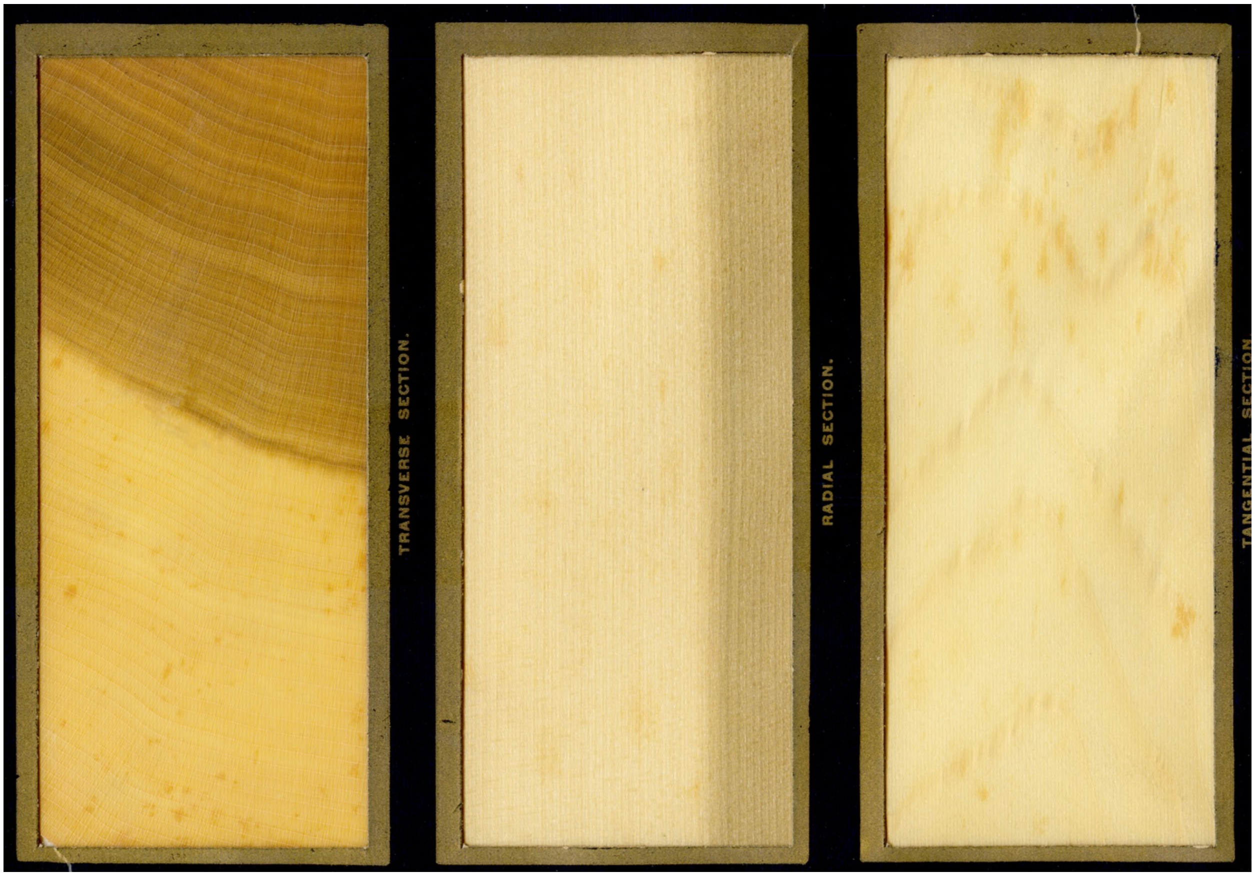

Figure 13. *This is a photograph of a cross section (marked transverse section), a radial section, and a tangential section of yellow-poplar, a diffuse porous species. Earlywood pores are not obvious at this magnification, unlike in ring porous species.*

FLATSAWN AND QUARTERSAWN BOARDS. Boards that are cut parallel with the bark (and therefore perpendicular to the rays along the tangential plane) are said to be ***flatsawn*** or ***plainsawn boards*** (synonymous terms) (see Figure 14, copied from the *Wood Handbook*[4]). As seen from the ends of the boards, the growth rings are oriented from 0° to about 35° to the wide edge of the board. Boards that are cut with the wide face more-or-less parallel with the rays (cut to emphasize radial surfaces with the growth rings oriented at roughly 65°–90° to the wide edge of the board) are said to be ***quartersawn***. Some boards, of course, will fall between these two categories, and these boards are termed ***riftsawn***. Depending on the market and the producer's willingness to sort his wood, lumber may be sold in two categories: quarter- and riftsawn (combined), and flatsawn. Quartersawn

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[4] Forest Products Laboratory. 2010. *Wood Handbook—Wood as an engineering material*. General Technical Report FPL-GTR-190. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 508 p. https://www.fpl.fs.fed.us/documnts/fplgtr/fpl_gtr190.pdf. Figure 3-14.

lumber often commands a higher price because the rays make a decorative figure in species like the oaks (white oak in particular), maple, sycamore and beech.

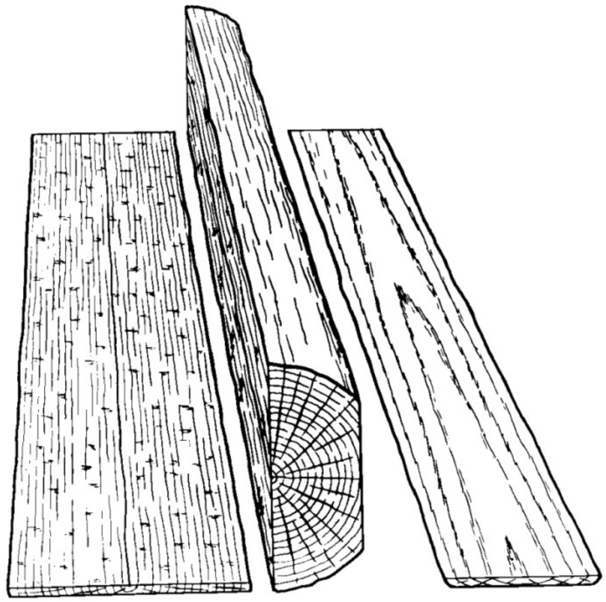

Figure 14. *This figure shows (A) a quartersawn board and (B) a flatsawn board. In quartersawn boards the rays are parallel to the wide dimension, and in flatsawn boards the rays run perpendicular to the broad surfaces.*

BOARDS CUT FROM A SINGLE LOG WILL DRY AT DIFFERENT RATES. The way that boards are cut will affect the drying rate. More ray ends are exposed on the wide faces of flatsawn boards than on the edges of quartersawn boards. As a result, quartersawn boards will dry more slowly than flatsawn boards. Quartersawn wood is also used for bourbon barrel staves because the rays act as channels for liquids; barrels assembled from quartersawn staves have the rays running around the barrel perimeter instead of from inside to outside, and this helps the barrels remain watertight.

Rays are conductive pathways for moisture leaving the wood. Because rays act like small pipes, boards that have more ray ends exposed will dry faster. Flatsawn boards expose lots of ray ends on the wide surfaces, so they will dry more quickly than quartersawn boards where the ray ends are exposed only on the board edges. See Figures 15 and 16.

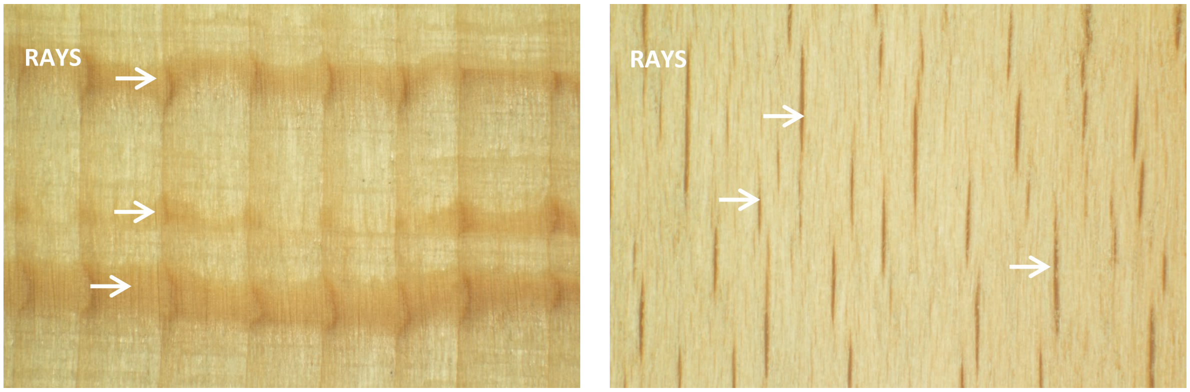

Figure 15. *American beech: Some rays are labelled on the radial (quartersawn) and tangential (flatsawn) faces, respectively. The quartersawn face exposes the side of the rays, making them look like ribbons; what you see on a flatsawn board is the ray ends. Each ray is made up of many individual ray cells, as shown in Figure 10 below.*

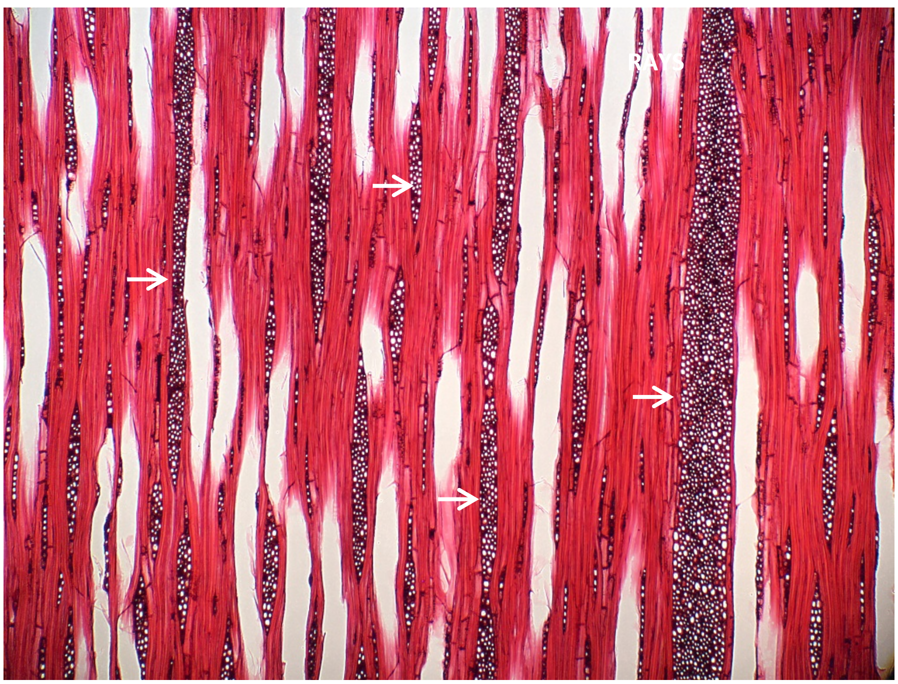

Figure 16. *This is a view of the ray ends for beech on a tangential surface (see the right-hand photo in Figure 9 for a similar photo taken with top-lighting at a lower magnification). In this micrograph of a thin section, the cells that are stained deep red are the fibers and the unstained areas are pores. The ray ends point directly towards the viewer like bunches of soda straws, and you can see how many cells group together to form each ray.*

JUVENILE WOOD AND SPIRAL GRAIN. Did you know that warp is most often caused by the wood structure and not by the dry kiln operator? The first 10-15 growth rings surrounding the pith are called **juvenile wood** and the wood cut from this region shrinks more than the surrounding “mature” wood as the lumber dries. If a board is cut such that one edge is close to the pith and the other edge is closer to the bark, the edge closer to the center will shrink more than the barkside edge, resulting in **side bend**. Another type of defect, known as **twist**, can be caused by the sawyer cutting a log with naturally-occurring **spiral grain** (Figure17), but twist is one of those defects that occurs more in some species than in others.

Figure 17. *This log with spiral grain was found in the woods.*

INTERLOCKED GRAIN Try to imagine a bundle of cells twisted around itself like a three-strand piece of rope, with some cells twisting clockwise while others go counter-clockwise. Now imagine this combined with two other similar pieces, making up an even bigger (wood) rope. Obviously the fibers aren't going to be aligned in a straight direction, and when you attempt to dry wood with grain like this it's harder to keep the lumber flat. This is called **interlocked grain**, and it's mostly found in em, black gum, sweet gum, sycamore and beech. Not every board of every species with interlocked grain will have a tendency to twist, but it seems especially difficult to dry the gums and sycamore and keep them flat.

Interlocked grain tends to keep long continuous drying checks from forming. This isn't usually an issue in boards but it can affect the quality of larger dried timbers such as railroad ties. Species such as the oaks and maples that don't have interlocked grain may develop long, linear, continuous checks unless these are prevented by incising the green ties at the tie plant. Species with interlocked grain usually develop shorter, curved checks.

MOISTURE CONTENT. One of the most important chemicals making up wood cells is cellulose. This is the chemical that gives wood a lot of its strength, but it takes up water readily. You probably know that cotton is almost pure cellulose, so think of how a cotton t-shirt behaves on a clothesline. T-shirts take up water on a damp day and release it when the sun comes out and the relative humidity drops. Wood behaves in the same way, so once wood is dried you have to make sure that it's kept in an environment that will keep the wood at the ***moisture content*** (**MC**) to which you just dried it. If conditions are stable, wood will come to an equilibrium with the surrounding air conditions (temperature and relative humidity), and the moisture content at which the wood eventually acclimates is therefore called the **equilibrium moisture content** (EMC). Both the moisture content and the equilibrium moisture content are expressed as a percent (ex., 12% moisture content).

Most woodworkers prefer to buy wood that is at 6% to 8% moisture content, because that's the moisture content to which wood inside our heated and air-conditioned houses will eventually equilibrate. Kiln drying is needed to reach a moisture content this low, because air-dried lumber will only get to 12%–15% or thereabouts (depending on the location). The amount of water in a piece of wood affects its strength and it affects its dimensions; wood shrinks as it dries out. If the moisture content doesn't change the wood won't shrink or swell either, and that minimizes problems with finishes, sunken glue lines, mitered corners and so on.

Water is distributed throughout the tree; not only does it saturate the cell walls, but when wood is wet enough liquid water is even present in the hollow parts of the fibers and other cells. Water located in the hollow parts of the cells (the ***lumens***) is called **free water** because it can be removed with little effort; water located in the cell walls is called **bound water** because it's harder to get out of the wood. By way of analogy, think of a cellulose kitchen sponge: once you rinse it in the sink all of the large pores are filled with water, and this is similar to green wood. If you squeeze the sponge most of this water is easily removed; this easily-lost water is equivalent to the free water in the wood cell lumens. The sponge still feels wet because the cellulose material itself is saturated, and the remaining water needs to evaporate from the internal surfaces and the smallest pores before the sponge becomes dry. The water that can't be squeezed out is similar to the bound water in wood.

MEASURING MOISTURE CONTENT

It's obvious that wet wood has more water than dry wood, but there's a more quantitative way to define moisture content. Chemical industries define moisture content as the ratio of the water weight to the combined weight of water and dry substance (wet basis), but that's not how it's done in the wood industries. It's confusing at first, but the way that wood moisture content is calculated in the solid wood and composite industries is based on the ratio of the water weight to the dry wood weight (dry basis).

You won't be selling wood to the pulp and paper industry, but I'm going to show you a couple of examples to illustrate what I'm talking about.

WET-BASIS MOISTURE CONTENT. First, let's consider some wood chips bound for a pulp mill. Pulp mills are run by chemical engineers, so they're going to define moisture content as a percentage of the original weight:

$$\boldsymbol{Moisture\ Content} = \frac{(\boldsymbol{Original\ Wood\ Weight} - \boldsymbol{Ovendry\ Wood\ Weight})}{\boldsymbol{Original\ Wood\ Weight}}\ \boldsymbol{x\ 100\%} \qquad [1]$$

- **DON'T** use Equation [1] to calculate moisture content for lumber. This equation isn't used by the wood industry.

Ovendry weights are determined by drying wood samples to a constant weight in ovens that are at least as hot as boiling water at sea level (212°F). According to Equation [1], if you dried ten pounds of wood chips fresh from the mill in an oven at 212–215°F and evaporated all the water to get five pounds of ovendry wood chips, the moisture content would be calculated as

$$\boldsymbol{Moisture\ Content} = \frac{(\boldsymbol{10\ pounds} - \boldsymbol{5\ pounds})}{\boldsymbol{10\ pounds}}\ \boldsymbol{x\ 100\% = 50\%} \qquad [2]$$

meaning the wood chips were one-half water (by weight).

DRY-BASIS MOISTURE CONTENT. Equation [1] might make perfect sense to a chemical engineer who deals with tanks full of fluids, but because the water content of a piece of wood fluctuates with the environment it's impossible for people working with solid wood products to know what the original weight of a piece of wood actually was. Instead of making the calculation based on the original (wet) weight of the wood, then, people in the lumber and composites industries make moisture content calculations based on the ovendry weight of the wood:

$$\boldsymbol{Moisture\ Content} = \frac{(\boldsymbol{Original\ Wood\ Weight - Ovendry\ Wood\ Weight})}{\boldsymbol{Ovendry\ Wood\ Weight}}\ \boldsymbol{x\ 100\%} \qquad \textbf{[3]}$$

➢ **Use Equation [3] to calculate lumber moisture content.**

Using the same example as above, a person in the solid wood industry would calculate the moisture content as

$$Moisture\ Content = \frac{(10\ pounds - 5\ pounds)}{5\ pounds}x\ 100\% = 100\%. \qquad [4]$$

If you're confused you're not alone. Most people think, "How can you have 100% moisture content? That can't be right!" That 100% isn't a typo, though. Think about it – a wood moisture content of 100% calculated using the dry weight as the basis for the calculation (Equation 3) means that 50% of the weight comes from the dry wood and 50% of the weight comes from the included water; the ratio of the wood and water weights is 1.0, hence the MC comes out to 100%. The number might look strange and unexpected, but it's okay.

The moisture contents of freshly-sawn logs or boards might be 75% or even higher – and sometimes the moisture content will be calculated as being over 100%. MCs over 100% are possible and can even exceed 200%!

There's an alternative form of the moisture content formula that some people prefer. The results are the same:

$$\boldsymbol{MC\%} = \left(\frac{\boldsymbol{Initial\ Wood\ Weight}}{\boldsymbol{Ovendry\ Wood\ Weight}} - \boldsymbol{1}\right)\ \boldsymbol{x\ 100\%} \qquad \textbf{[5]}$$

Using the numbers used above (the original ten pounds of chips containing both wood and water, dried to only five pounds of ovendry wood), you could calculate MC using Equation [5] like this:

$$MC\% = \left(\frac{10}{5} - 1\right)x\ 100\% = (2-1)\ x\ 100\% = 100\% \qquad \textbf{[6]}$$

(*See Appendix A for some sample numbers if you'd like to practice. The answers are provided.*)

WAYS TO MEASURE MOISTURE CONTENT. There are two ways to measure moisture content in wood: 1) using an oven and drying out the wood, then substituting the appropriate values into one of the equations above; and 2) using an electric moisture meter.

THE OVENDRY METHOD. The ovendry method is the gold standard for measuring wood moisture content, and it's the method used to calibrate electrical moisture meter measurements. It's easy to do but it takes a bit of time, anywhere from an hour to a day or so depending on the size of the sample and its original moisture content.

If you use the ovendry method to measure hardwood lumber moisture contents you will have accurate results every time! The only equipment you need is an oven capable of holding 212°-215°F and a balance. Water boils at 212°F, so that's the minimum temperature at which to set your oven.

You don't need to buy expensive lab grade equipment; I found a convection oven that would be large enough for most samples at a chain discount store for about $40, for example. Most of your samples won't be over 12" long and an inch or two wide (you could even cut them in half), so almost any oven will be big enough. A convection oven is better than a toaster oven, because the forced air will make the drying more uniform. The temperature controls in these inexpensive ovens are only approximate, however, and the actual temperature will cycle up and down around the set point. For an additional $15 or so I purchased a digital oven thermometer in the cooking supplies section of the store, and it works just fine – I used wire to attach the sensor to the metal rack and trailed the thermometer wire outside of the oven between the door and the door seal. For the oven that I purchased, I found that I could get a range of about 208° to 220°F with a temperature setting at the top end of "warm." Be sure that 215°F isn't too close to the top end of your temperature range because you want to be sure the oven is hot enough.

You'll want two balances: one for small samples and one for large samples, and the smaller balance especially should have pretty good sensitivity to reduce potential errors (Figures 18 and 19). I found two properly-sized balances at a national chain discount hardware store. The small balance has a 2.2 pound (1000 grams) capacity with a resolution of 0.1 gram; that one works really well with the small moisture sections I cut, usually 100 grams or less. My larger balance has a capacity of 11 pounds (5000 grams) with a resolution of 1 gram. I always set the balances to read in grams instead of pounds and ounces because it makes moisture content calculations easier.

Figure 18. *Low capacity balance for weighing small moisture sections. This balance weighs to the nearest 0.1 gram and has a capacity of 2.2 pounds (1000 grams).*

Figure 19. *Higher capacity balance for weighing sample boards. This balance measures to the nearest gram and has an 11 pound (5,000 gram) capacity.*

For those times I need to weigh something over eleven pounds, I bought something labelled a postal scale; that scale has a 70 pounds (32 kg) capacity with a resolution of 0.2 ounces (5 grams). The capacity of the postal scale is more than I usually need, but too much capacity is never a bad thing to have and it's good to have a backup. Even if I weighed sample boards on this balance, the uncertainty wouldn't likely affect my moisture calculations by more than 0.25% or so.

Before you start your moisture content determinations, clean up your samples–knock off any sawdust or loose splinters. The next step is to weigh them using the appropriate balance for the sample. I often record the weights by writing on the samples themselves with a fine point permanent marker while I'm standing at the balance, and I recopy the original and the final dry weights into a spreadsheet when my drying is complete. Copying these numbers into a spreadsheet will make a good contribution to your recordkeeping. Recordkeeping might seem like a bit of extra work sometimes, but having numbers to look back on can really help when you're trying to troubleshoot a problem.

After you've recorded the original ("wet") weight of your samples, check the oven temperature to be sure it's hot enough. Oven temperatures might drift as ovens get older, controls get bumped and so forth, but you have to remember that your test results won't be correct if your temperature isn't at least 212°F; lower temperatures will never dry wood samples completely, no matter how much time you let them sit in an oven.

You won't know that you've completely dried your samples until you get two or more identical weights, so take your samples out periodically to reweigh them and record the weights each time. Keep the oven door closed as much as possible and don't leave the samples out in the open any longer than necessary, because they can change weight more quickly than you'd imagine. If your oven and the balance are in different locations, it's a good idea to put the samples into small plastic bags to minimize air contact. Once you've gotten two identical weights in succession (two hours apart) then it should be safe to use those weights in the moisture content calculations.

Not every sample will dry at the same rate, so you will have to exercise a bit of patience. The amount of time you will need to dry samples will vary according to the species, the moisture content, the size and so forth. You'll get a good feel for how long it will take for your samples to dry after you've done this a few times but it's often going to be in the range of ten to twenty-four hours.

Microwave Ovens. Some people say that you can use microwave ovens to dry wood for moisture determinations if you use a low power setting and a carousel tray, but I've encountered problems with this method. In one of my tests, it took only a moment of extra time in the oven before yellow-poplar and oak samples started to smoke and burn from within, even at 270 watts (3/10 power in a 900 watt oven).

The smoke isn't a problem, because mass loss due to smoke is negligible, but it's rather unsettling to see smoke pouring out of the oven nonetheless! Low density samples (yellow-poplar) were more forgiving than high density samples (oak, knots); denser wood seemed to absorb the microwave power more quickly and started to burn sooner, or perhaps these samples just dissipated microwave energy less well.

The biggest problem I had was identifying the end of drying. I microwaved some samples for a minute or two at a time until I achieved successive weight measurements that were identical, but when I afterwards placed these pieces in an laboratory oven at 215°F to verify that I had achieved total dryness I sometimes found that I had not actually dried my pieces completely in the microwave. The calculated MC difference was usually several percent. For this reason I cannot recommend using microwave ovens for moisture content determinations, though microwaving could be a useful way to partially dry the samples and shorten the subsequent drying time in a convection oven.

METER METHOD. There are two different types of moisture meters used by the wood industry. Each method has limitations on the range at which they are accurate, but regardless, they are both very useful! They are much better suited to boards rather than to small samples used to monitor drying progress however.

Resistance Meters. Resistance meters work by measuring the electrical resistance of moist wood, measured by inserting insulated steel pins with uninsulated tips into wood at the appropriate depth. There is a relationship between wood resistance and moisture content and these meters display moisture contents directly, but the meter readings have to be adjusted for both the species and the wood temperature (not the air temperature). Different North American species have different electrical resistance at the same moisture contents due to their extractive content, and without adjustments the moisture contents readings could be off by one or two percent. Adjustments are provided by the meter manufacturers. It's particularly important to use the recommended adjustments for tropical species because the extractive contents in tropical woods are often higher than in most North American species and can affect moisture content readings significantly.

Heartwood and sapwood often contain different amounts of extractives so these chemical differences might affect the accuracy of the meter reading. This is true for sapwood in particular since calibrations are based on heartwood specimens.

Without correction, resistance meters will read up to 1% different from the true moisture content for each 20°F difference from room temperature. (Cold wood is a little wetter than the meter reading at the room temperature setting and vice-versa.)

Resistance moisture meters are only accurate between 7% MC and 28% MC. Drying lumber is wetter at its core than at the surface, so insulated meter pins (with uninsulated tips) must be driven to about 20–25% of the board thickness to measure the *average* moisture content for boards with drier surfaces/wetter cores (as normally happens in drying lumber). About 1/16" penetration will work well if you want to measure the surface MC. Surface condensation can become an issue if you aren't using insulated pins in cold weather; you might put samples into a plastic bag if you have to move them into a colder environment to take a moisture meter reading with a pin-type meter.

There are several reputable manufacturers of resistance-type meters. Many instrument makers (*e.g.*, Delmhorst) calibrate their meters for pins placed parallel to the grain, while the meters made by Lignomat are calibrated for pin placement perpendicular to the grain. The pin alignment is not critical below 15% MC for any brand.

The accuracy of resistance meters will vary according to the moisture content. Delmhorst states that their resistance meters are accurate to ±0.5% MC for samples between 6–12% MC, to ±1% for samples from 12-20% MC, and to ±2% MC for samples between 20–30% MC.

Dielectric Meters. Dielectric meters don't need pins to be inserted into the lumber (no holes!) because these meters work by measuring the capacitance properties of wood. For these meters, all you need to do is to put the plate-like sensor on the bottom of the meter onto a wood surface. The boards must also be flat so the entire sensor plate can make good contact with the board. The moisture measurement will be the same regardless of whether the meter is aligned parallel or perpendicular to the grain, but the meter has to be set for the species being examined because the readings are affected by wood density.

Dielectric meters are accurate between about 5% and 25% MC, but they can't differentiate the moisture at different depths inside the wood like you can with a pin-type meter. The space beneath the board being measured has to be either free air or another board at a similar moisture content in the same stack, as anything that is conductive (like metal or even your hand) will affect the results. Temperature corrections are generally very minor.

Wood density can vary even within a single board or sample, so a dielectric moisture meter reading may be slightly incorrect even if the meter is well-calibrated and even if the species correction has been correctly specified. If the metered location has a density similar to the one that the meter manufacturer used in his calibration curves for the species you are checking, you will likely find that most meter readings are accurate to within ±1% MC of the true value. Due to density variations between and within boards, it's probably safer to think that 95% of moisture meter readings are accurate to within ±2% MC. Multiple readings within a stack of lumber will give you a better picture of the lumber moisture content distribution than one or two readings.

IMPORTANT METER USAGE NOTES. Both types of moisture meters are accurate with standard samples, but due to the limits of what is achievable with calibration of these electronic devices even two well-calibrated meters from the same manufacturer might read differently. Manufacturers such as Delmhorst and Wagner sell calibration standards for their moisture meters, and these can be used to demonstrate that a meter is within calibration tolerances. Delmhorst resistance moisture meters with digital displays are in calibration if they read within 0.2% of the calibration block standard and within 0.5% of the standard for analog resistance meters. The tolerance for most Wagner dielectric meters is ±0.5% MC using their standard calibration plate, so two different meters might read as much as 1% different in the same location.

Try not to defeat yourself by taking measurements in obviously inappropriate locations. Regardless of the type of meter, don't take MC readings close to the end of a board, for example (try to stay at least a foot and a half away), and don't take readings around knots or distorted grain. The MC might be a little different than the rest of the board in those locations, or dielectric meters might read the MC inaccurately due to density differences.

Moisture meters cannot substitute for the use of common sense and good drying practices; they are very useful instruments, but there are too many unquantifiable factors for you to rely upon them for complete accuracy.

HEARTWOOD AND SAPWOOD MOISTURE CONTENTS

The unseasoned (green) moisture contents for hardwood heartwood and sapwood are often different. The numbers in Table 1 (below) are based on sampling and you can't take them as gospel, but for most species the sapwood moisture content will be higher than the heartwood moisture content. This information will be more meaningful when I discuss how to use sample boards to monitor the moisture content of boards in an operating dry kiln, but for the moment just look over the numbers and note that the green moisture content varies considerably for different species. (I doubt that you'll be drying all of these species anyway.)

Table 1. *Average MC values for North American hardwood species*[5]

	Average Moisture Content (%)			Average Moisture Content (%)	
Species	**Heartwood**	**Sapwood**	**Species**	**Heartwood**	**Sapwood**
Alder, red	**-**	**97**	**Chestnut, American**	**120**	**-**
Apple	**81**	**74**	**Cottonwood**	**162**	**146**
Ash, black	**95**	**-**	**Elm, American**	**95**	**92**
Ash, green	**-**	**58**	**Elm, cedar**	**66**	**61**
Ash, white	**46**	**44**	**Elm, rock**	**44**	**57**
Aspen	**95**	**113**	**Hackberry**	**61**	**65**
Basswood, American	**81**	**133**	**Hickory, bitternut**	**80**	**54**
Beech, American	**55**	**72**	**Hickory, mockernut**	**70**	**52**
Birch, paper	**89**	**72**	**Hickory, pignut**	**71**	**49**
Birch, sweet	**75**	**70**	**Maple, silver**	**58**	**97**
Birch, yellow	**74**	**72**	**Maple, sugar**	**65**	**72**
Cherry, black	**58**	**-**	**Oak, California black**	**76**	**75**

[5] Source: *Wood Handbook - Wood as an Engineering Material*. Table 4-1.

	Average Moisture Content (%)			Average Moisture Content (%)	
Species	**Heartwood**	**Sapwood**	**Species**	**Heartwood**	**Sapwood**
Chestnut, American	120	-	Oak, northern red	80	69
Cottonwood	162	146	Oak, southern red	83	75
Elm, American	95	92	Oak, water	81	81
Elm, cedar	66	61	Oak, white	64	78
Elm, rock	44	57	Oak, willow	82	74
Hackberry	61	65	Sweetgum	79	137
Hickory, bitternut	80	54	Sycamore	114	130
Hickory, mockernut	70	52	Tupelo, black	87	115
Hickory, pignut	71	49	Tupelo, swamp	101	108
Hickory, red	69	52	Tupelo, water	150	116
Hickory, sand	68	50	Walnut, black	90	73
Hickory, water	97	62	Yellow-poplar	83	106
Magnolia	80	104			

MOISTURE CONTENT VARIABILITY IN LUMBER

The heartwood-sapwood comparisons in the table above show that the moisture content in logs isn't uniform; the moisture contents of the boards sawn from logs are nonuniform as a consequence. To further complicate things, different logs even from a single species will have different moisture content profiles, especially if they were cut at different locations or at different times. Obviously we can't think about green lumber having a single moisture value – what should we expect the moisture content distribution of drying boards to look like?

One way to describe the moisture distribution of a pack of lumber would be to calculate the ***Average MC*** of the boards in the pack. To do this accurately we'd need to measure the MC of each board, but that's neither practical nor necessary. We can often get a pretty good estimate by sampling some of the boards in the pack; based on what you already know, you might expect that the heartwood boards are probably going to be a little different from the sapwood boards; there will be a ***distribution*** of MC values. Even a package that's entirely heartwood or entirely sapwood will have a range of values, though.

In a perfect world, there will be as many boards wetter than the average as there are boards that are drier than the average. Most of the boards will have a moisture content close to the average, but some are likely to be more different than you might expect. The individual board moisture contents will vary more for packs made up of boards from multiple logs, but for fairly uniform lumber from a single log it's possible that the distribution will be a bell-shaped curve.

Here are a few hypothetical examples of what the moisture distribution might look like for green lumber. I chose to illustrate moisture variability for hickory, and I plotted heartwood, sapwood and the combination separately in the following figures. Hickory isn't commercially available as shagbark hickory or pignut hickory or bitternut hickory, etc., so I used the average moisture content data from *Air Drying of Lumber*[6] for combined hickory species instead of numbers from Table 1. I simulated the moisture distributions using data variability that is typical of data observed at mills.[7, 8]

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[6] Forest Products Laboratory. 1999. *Air Drying of Lumber*. Gen. Tech. Rep. FPL–GTR–117. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 62 p. http://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr117.pdf

[7] Simpson, W.T. and X. Wang. 2001. *Time-Based Kiln Drying Schedule for Sugar Maple for Structural Uses*. Research Note FPL-RN -0279. Madison, WI: United States Department of Agriculture Forest Service Forest Products Laboratory. 4 pages. https://books.google.com/books?id=YZNYDegP_dsC&pg=PP3&lpg=PP3&dq=Time-based+kiln+drying+schedule+for+sugar+maple+for+structural+uses&source=bl&ots=AhO6WzUX68&sig=pwAmusR6XhjNhJFaW2XW3nb1tZc&hl=en&sa=X&ved=0ahUKEwjrgfienc3KAhVE7CYKHWbhBnwQ6AEIIjAB#v=onepage&q&f=false

Let's look at the moisture distributions for unseasoned heartwood first (Figure 20).

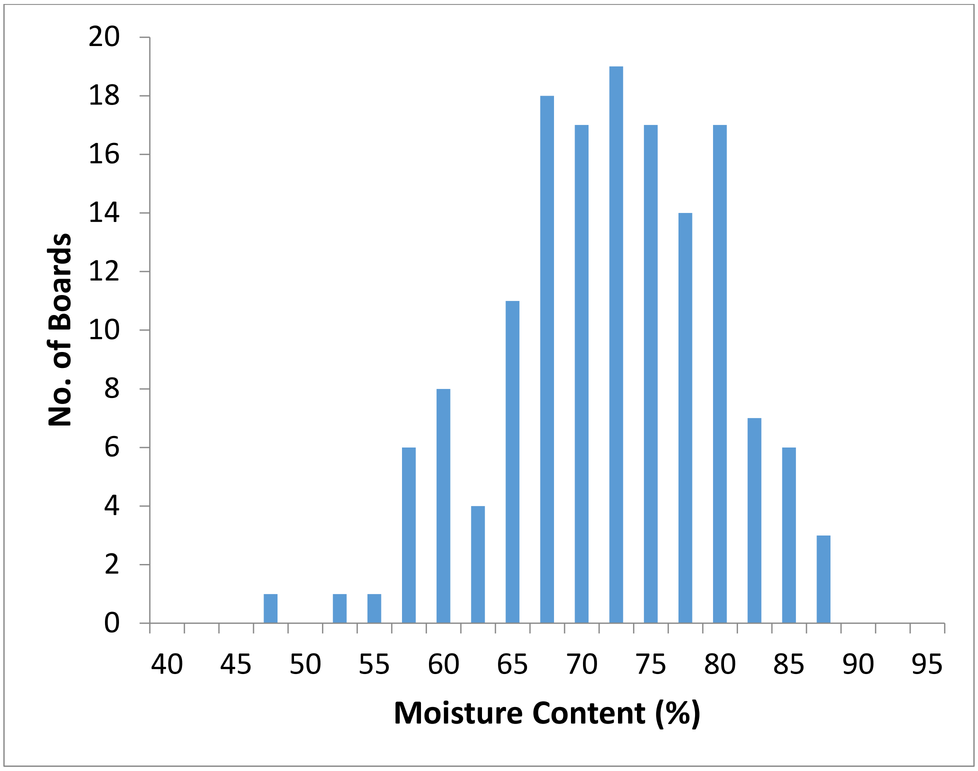

Figure 20. *This is a simulated distribution of the moisture contents of 150 green hickory heartwood boards. The overall average moisture content is 70%.*

As shown in Figure 7, some hickories have big hearts and some hickories have small hearts, and this will affect the percentages of heartwood and sapwood cut from the log. For this example, I assumed that the sawyer ended up with 20% sapwood boards (Figure 21).

[8] Welling, J. (editor). 2010. *Dried Lumber-How to specify correctly*. European Drying Group and COST E53. European Science Foundation. 38 pages. http://www.coste53.net/downloads/Literature/Dried%20Timber%20how%20to%20specify%20correctly/Dried_Timber_how_to_specify_correctly.pdf

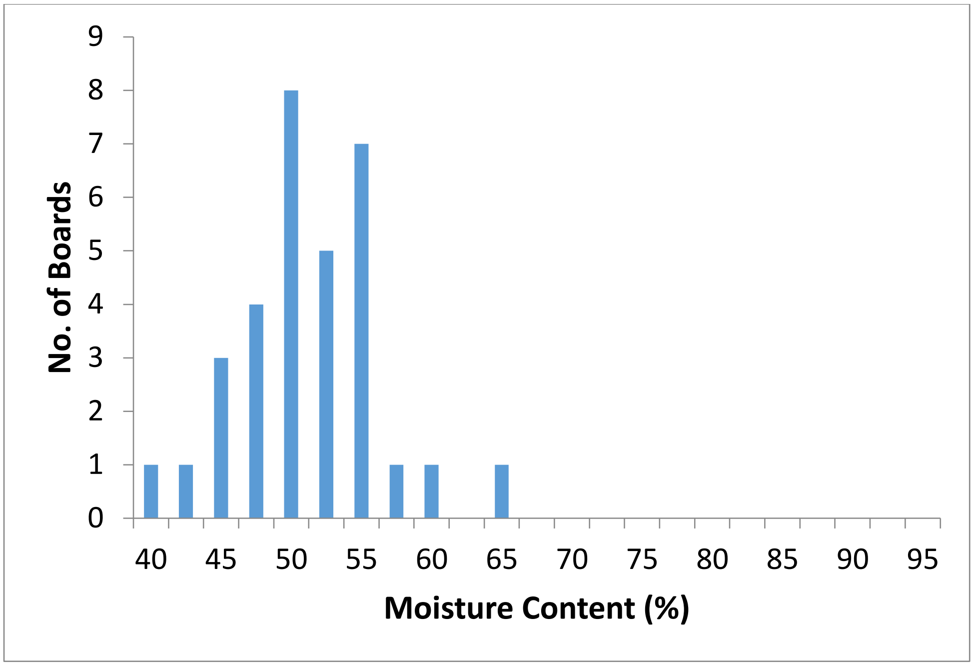

Figure 21. *This is a simulated distribution of the moisture contents of 38 green hickory sapwood boards. The overall average moisture content is 51%.*

The moisture content distributions for hickory heartwood and sapwood shown in these two figures are very different. Figure 22 shows what the combined moisture content distribution might look like:

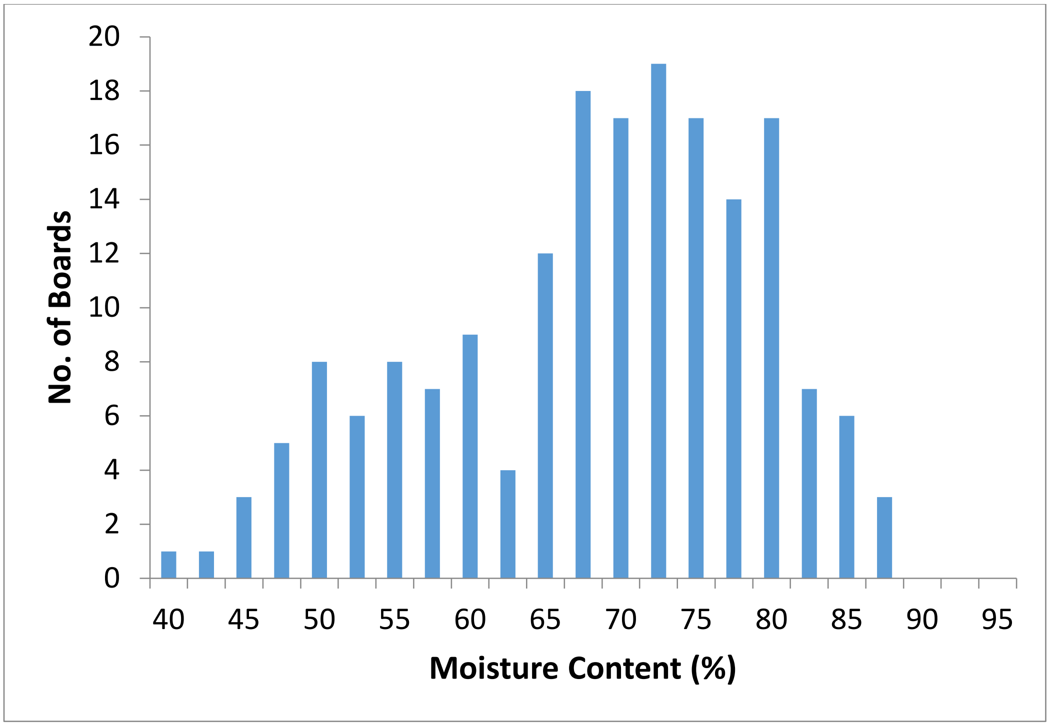

Figure 22. *This graph combines the simulated distribution of the moisture contents of the previous 150 green hickory heartwood boards (70% average MC) and the 38 green hickory sapwood boards (51% average MC). The overall average MC for heartwood and sapwood combined in this example is 67%.*

This example is only intended to show how much variation you *might* get in your lumber. Take note of several things:

1. The overall MC distribution isn't bell-shaped– it's skewed. (If the sapwood had been wetter than the heartwood the skewness would have reversed.)

2. Observe how much variability there could be in lumber from a single species.

3. Imagine what the MC distribution might look like if you loaded your dry kiln with logs from more than one species of lumber!

The moisture spread will get smaller as drying progresses. You likely would air-dry your lumber before putting it into the dry kiln; perhaps your preferred air-dried MC for a given species is 30% (or less). What might that distribution look like if you had a pack of air-dried black cherry that was almost all heartwood? Figure 23 shows one possibility.

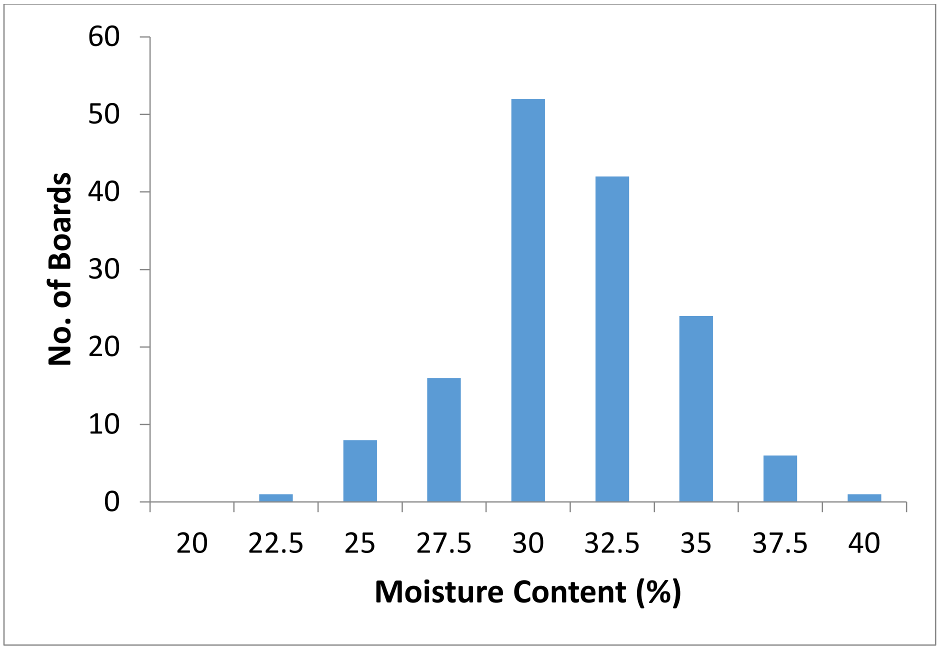

Figure 23. *This graph shows what the moisture content distribution might look like for a load of 150 air-dried boards. In this example, I chose to use a species (black cherry) where the sawyer probably slabs off most of the sapwood, so the individual board MCs probably started out more similar than a mixed heartwood-sapwood pack. The average MC in this plot is 30%.*

Your challenge as a hardwood drying supervisor or kiln operator is to accept lumber with a range of moisture contents (as above, perhaps) and reduce not only it's moisture content but also the *variability* of its moisture content. As you finish drying, your goal will probably be to have the moisture content of every board within 1% of your target MC. If your target MC was 7%, your final moisture distribution should look something like Figure 24:

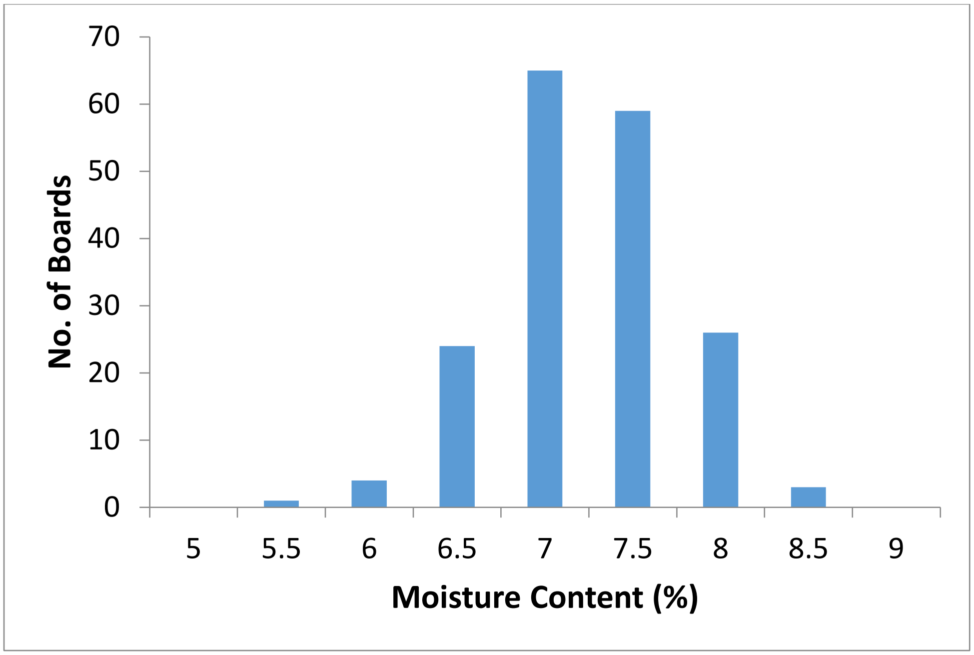

Figure 24. *A final moisture content distribution similar to this ought to be the goal of every hardwood dry kiln operator. For this illustration, I assumed that the target average moisture content was 7%, with an allowable tolerance of ±1% moisture content. With very few exceptions, the lumber falls within the range of 6-8% moisture content.*

EQUILIBRIUM MOISTURE CONTENT

Equilibrium moisture content (EMC) varies from place to place according to the environmental conditions. Wood kept indoors will achieve a lower moisture content than wood that is kept under a roof outdoors, and wood stored under a roof will dry more than wood that is left exposed to the elements without protection. Given similar storage conditions, wood kept outdoors in the desert will become (and stay) drier than wood that is kept outdoors along the Gulf Coast as well. To further complicate things, our indoor environment is often affected by a furnace or an air conditioner. For manufacturers and consumers in many parts of the United States, a wood moisture content of between 6% and 8% MC is often specified.

Wood EMC is affected by both the temperature and the relative humidity, but it's more sensitive to the relative humidity. You can change both the RH and the temperature in different combinations to get the same EMC. That's useful information to know for running a dry kiln, because the drying rate can be adjusted using temperature while the same EMC is maintained. In other words, you can get the same EMC at two different combinations of temperature and RH, but the combination that uses the higher temperature will change the moisture content more quickly.

There's a complete table of EMC conditions (temperature and RH combinations) in the *Wood Handbook* and many other drying publications. In the portion of the table below (Table 2), I marked the cell you would refer to if you wanted to look up the EMC for a location maintained at 70°F and 40% RH. The EMC would be 7.7%, so your lumber would probably be at a reasonable MC for woodworking.

***Table 2**. EMC values for wood. At 70°F and 40% RH the EMC will be 7.7% EMC. (*Source: *Wood Handbook, Table 4-2)*

Temperature		Moisture content (%) at various relative humidity values																		
(°C	(°F))	5%	10%	15%	20%	25%	30%	35%	40%	45%	50%	55%	60%	65%	70%	75%	80%	85%	90%	95%
−1.1	(30)	1.4	2.6	3.7	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.4	11.3	12.4	13.5	14.9	16.5	18.5	21.0	24.3
4.4	(40)	1.4	2.6	3.7	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.4	11.3	12.3	13.5	14.9	16.5	18.5	21.0	24.3
10.0	(50)	1.4	2.6	3.6	4.6	5.5	6.3	7.1	7.9	8.7	9.5	10.3	11.2	12.3	13.4	14.8	16.4	18.4	20.9	24.3
15.6	(60)	1.3	2.5	3.6	4.6	5.4	6.2	7.0	7.8	8.6	9.4	10.2	11.1	12.1	13.3	14.6	16.2	18.2	20.7	24.1
21.1	(70)	1.3	2.5	3.5	4.5	5.4	6.2	[illegible]	7.7	8.5	9.2	10.1	11.0	12.0	13.1	14.4	16.0	17.9	20.5	23.9
26.7	(80)	1.3	2.4	3.5	4.4	5.3	6.1	6.8	7.6	8.3	9.1	9.9	10.8	11.7	12.9	14.2	15.7	17.7	20.2	23.6
32.2	(90)	1.2	2.3	3.4	4.3	5.1	5.9	6.7	7.4	8.1	8.9	9.7	10.5	11.5	12.6	13.9	15.4	17.3	19.8	23.3
37.8	(100)	1.2	2.3	3.3	4.2	5.0	5.8	6.5	7.2	7.9	8.7	9.5	10.3	11.2	12.3	13.6	15.1	17.0	19.5	22.9
43.3	(110)	1.1	2.2	3.2	4.0	4.9	5.6	6.3	7.0	7.7	8.4	9.2	10.0	11.0	12.0	13.2	14.7	16.6	19.1	22.4
48.9	(120)	1.1	2.1	3.0	3.9	4.7	5.4	6.1	6.8	7.5	8.2	8.9	9.7	10.6	11.7	12.9	14.4	16.2	18.6	22.0
54.4	(130)	1.0	2.0	2.9	3.7	4.5	5.2	5.9	6.6	7.2	7.9	8.7	9.4	10.3	11.3	12.5	14.0	15.8	18.2	21.5
60.0	(140)	0.9	1.9	2.8	3.6	4.3	5.0	5.7	6.3	7.0	7.7	8.4	9.1	10.0	11.0	12.1	13.6	15.3	17.7	21.0
65.6	(150)	0.9	1.8	2.6	3.4	4.1	4.8	5.5	6.1	6.7	7.4	8.1	8.8	9.7	10.6	11.8	13.1	14.9	17.2	20.4
71.1	(160)	0.8	1.6	2.4	3.2	3.9	4.6	5.2	5.8	6.4	7.1	7.8	8.5	9.3	10.3	11.4	12.7	14.4	16.7	19.9
76.7	(170)	0.7	1.5	2.3	3.0	3.7	4.3	4.9	5.6	6.2	6.8	7.4	8.2	9.0	9.9	11.0	12.3	14.0	16.2	19.3
82.2	(180)	0.7	1.4	2.1	2.8	3.5	4.1	4.7	5.3	5.9	6.5	7.1	7.8	8.6	9.5	10.5	11.8	13.5	15.7	18.7
87.8	(190)	0.6	1.3	1.9	2.6	3.2	3.8	4.4	5.0	5.5	6.1	6.8	7.5	8.2	9.1	10.1	11.4	13.0	15.1	18.1
93.3	(200)	0.5	1.1	1.7	2.4	3.0	3.5	4.1	4.6	5.2	5.8	6.4	7.1	7.8	8.7	9.7	10.9	12.5	14.6	17.5
98.9	(210)	0.5	1.0	1.6	2.1	2.7	3.2	3.8	4.3	4.9	5.4	6.0	6.7	7.4	8.3	9.2	10.4	12.0	14.0	16.9
104.4	(220)	0.4	0.9	1.4	1.9	2.4	2.9	3.4	3.9	4.5	5.0	5.6	6.3	7.0	7.8	8.8	9.9			
110.0	(230)	0.3	0.8	1.2	1.6	2.1	2.6	3.1	3.6	4.2	4.7	5.3	6.0	6.7						
115.6	(240)	0.3	0.6	0.9	1.3	1.7	2.1	2.6	3.1	3.5	4.1	4.6								
121.1	(250)	0.2	0.4	0.7	1.0	1.3	1.7	2.1	2.5	2.9										
126.7	(260)	0.2	0.3	0.5	0.7	0.9	1.1	1.4												
132.2	(270)	0.1	0.1	0.2	0.3	0.4	0.4													

A similar table in the *Dry Kiln Operator's Manual* [9] is based on the equipment and controls that come with your dry kiln, so it ought to be more useful for operators of small kilns. It has the advantage of being set up so you can determine the RH and the EMC from the ***Dry Bulb Temperature*** and the ***Wet Bulb Depression***-you don't have to know the RH before you can determine the EMC like you have for Table 2. The dry bulb temperature is the ordinary measurement of the ambient air temperature, while the ***wet bulb temperature*** is measured by a thermometer with a wet cotton wick over the sensor bulb. Air flowing over the wet wick cools the thermometer, and since drier air will absorb more evaporated water than humid air a wet bulb will cool more in dry air-thus indicating the relative humidity. The difference between the dry bulb and the wet bulb is called the wet bulb depression. This table also has smaller gaps between the temperatures so it should be helpful if your equipment has difficulty precisely reaching or maintaining a desired temperature or RH condition.

What exactly is a wet bulb, anyway? It's nothing more than an ordinary thermometer or sensor with a wet piece of cotton wrapped around the bulb. Think about the cotton bandanna that we wrap around our sweaty foreheads when we work outdoors. When a breeze comes along the sweat evaporates, making us feel cooler, and the amount of evaporation is related to the relative humidity in the air. There's less evaporation on a muggy (or rainy) afternoon than there is on a dry afternoon, because the air is more nearly saturated with water already. The ability of the air to take up additional moisture is really what relative humidity means, anyway, so the difference between

[9] Simpson, William T., Editor. 1991. *Dry Kiln Operator's Manual*. USDA Agricultural Handbook Number 188. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 274 p. See Table 1-6. https://www.fpl.fs.fed.us/documnts/usda/ah188/ah188.htm

the dry bulb temperature and the wet bulb temperature can be used to determine the relative humidity. The wet bulb depression is merely the difference between the dry bulb and the wet bulb temperatures.

To show what this looks like, I've included part of the table from the *Dry Kiln Operator's Manual* with the entry points for the previous example marked as before (Table 3). Much more of this table is included as Appendix B.

Table 3. Relative humidity and equilibrium moisture content for some specified dry bulb temperatures and wet-bulb depressions. For each dry bulb temperature, the bold-font data in the first row are relative humidity values and the italicized numbers in the second row are the EMC values. (Source: *Dry Kiln Operator's Manual*, Table 1-6)

DB °F	WB Depression (°F)																						(Relative humidity (%) in bold font, *EMC (%) in italics*)
	1	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*	*10*	*11*	*12*	*13*	*14*	*15*	*16*	*17*	*18*	*19*	*20*	*21*	*22*	*23*
60	**94**	**89**	**83**	**78**	**73**	**68**	**63**	**58**	**53**	**48**	**43**	**39**	**34**	**30**	**26**	**21**	**17**	**13**	**9**	**5**	**1**	-	-
	-	*19.9*	*17.4*	*15.6*	*13.9*	*12.7*	*11.6*	*10.7*	*9.9*	*9.1*	*8.3*	*7.6*	*6.9*	*6.3*	*5.6*	*4.9*	*4.1*	*3.2*	*2.3*	*1.3*	*0.2*	-	-
65	**95**	**90**	**84**	**80**	**75**	**70**	**66**	**61**	**56**	**52**	**48**	**44**	**39**	**36**	**32**	**27**	**24**	**20**	**16**	**13**	**8**	**6**	**2**
	-	*20.3*	*17.8*	*16.1*	*14.4*	*13.3*	*12.1*	*11.2*	*10.4*	[illegible]	[illegible]	*8.3*	*7.7*	*7.1*	*6.5*	*5.8*	*5.2*	*4.5*	*3.8*	*3*	*2.3*	*1.4*	*0.4*
70	**95**	**90**	**86**	**81**	**77**	**72**	**68**	**64**	**59**	**55**	**51**	**48**	**44**	**40**	**36**	[illegible]	[illegible]	**25**	**22**	**19**	**15**	**12**	**9**
	-	*20.6*	*18.2*	*16.5*	*14.9*	*13.7*	*12.5*	*11.6*	*10.9*	*10.1*	*9.4*	*8.8*	*8.3*	*7.7*	*7.2*	*6.6*	*6*	*5.5*	*4.9*	*4.3*	*3.7*	*2.9*	*2.3*
75	**95**	**91**	**86**	**82**	**78**	**74**	**70**	**66**	**62**	**58**	**54**	**51**	**47**	**44**	**41**	**37**	**34**	**31**	**28**	**24**	**21**	**18**	**15**
	-	*20.9*	*18.5*	*16.8*	*15.2*	*14*	*12.9*	*12*	*11.2*	*10.5*	*9.8*	*9.3*	*8.7*	*8.2*	*7.7*	*7.2*	*6.7*	*6.2*	*5.6*	*5.1*	*4.7*	*4.1*	*3.5*

Start at the line for 70°F and look right until you find 40% in the RH data in the same row. Notice that the same EMC as noted earlier (7.7%) is listed in the line directly below 40% RH. If you look at the column label above this pair of values you will see that the difference between the dry bulb and wet bulb temperatures (*i.e.*, the wet bulb depression) would be 14°F. For this example, when the DB is 70°F and the WB depression is 14°F the wet bulb reading will be (70-14)=56°F.

There are a number of inexpensive digital relative humidity meters on the market that you can use to monitor the conditions in a shed or retail area. Digital meters are more accurate than the analog dial type. Wireless digital sensors are also available.

If you want to verify a meter's calibration for relative humidity, put it in a plastic baggie with a small container of table salt and water, thoroughly stirred, with enough of a surplus of salt that not all of it dissolves. Close the baggie and wait; after 24 hours the meter should read 75% RH.

DIMENSIONAL CHANGES

As mentioned previously, living tree cells contain water both in the lumens, the hollow spaces in the cell centers, and in the cell walls. Physics dictates that water will evaporate from large cell openings more readily than it will from within the cell walls, but the loss of water from the lumens doesn't cause any shrinkage because it's only excess water that serves to keep the cell walls saturated. Lumber can lose any amount of water from the unseasoned (green) moisture condition to the ***fiber saturation point (FSP)*** and not change dimensions at all. It is only when water starts to leave the cell wall that shrinkage begins. (Of course, the reverse is true as well: if water is added to dry wood, swelling will only occur until the MC reaches the FSP point.)

The FSP apparently varies somewhat from species to species, but in general most people are content to think of it as occurring at around 30% MC. This means that all wood shrinkage occurs as wood dries from 30% to 0% moisture content. End grain (where the cell lumens are exposed) will dry out faster than wood in the middle of a log or board; the end grain will try to shrink before the wood closer to the middle of the board can approach the FSP, and this causes stresses across the grain that can result in end checks or end splits.

Attention to the exposure conditions of logs and air-drying lumber is essential, and a coating is often applied to help prevent moisture loss and attendant defects on end grain (sometimes even on logs before sawing). Several types of coatings could be used, but most sawyers apply a type of water-based wax emulsion. One well-known brand is called ANCHORSEAL®, sold by U-C Coatings. Thin coatings, whether brushed on or sprayed, aren't going to be sufficient to prevent moisture loss from the end grain; thicker coatings work much better, and valuable thick stock ought to get two coats. Each gallon will cover roughly 100 square feet of end grain.

Shrinkage in boards is nonuniform. Boards actually shrink very little along their length (just 0.1%-0.2% on average for most wood). The shrinkage across the width and thickness of the boards, though, depends on how the boards are cut from the log. Shrinkage is greatest in the tangential plane (parallel with the bark surface and the growth rings) (about 6%–8%), but in the radial direction (the path between the pith and the bark), the shrinkage is about half of that (about 3%–4%). (Refer to Figure 11, repeated below.)

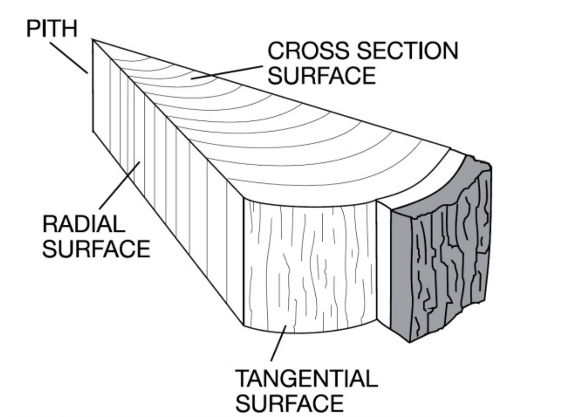

Figure 11, repeated. *This sketch labels the three wood faces on a wedge of wood. Ray sides will look like ribbons on radial faces, and the ray ends will look like short lines on tangential faces. Rays will also be visible on the cross-section extending from the direction of the pith towards the bark, in the radial direction.*

The surface of quartersawn lumber exposes a radial face, so it's sometimes preferred for flooring installations. The wide face exposes a radial surface, so the shrinkage will be about one-half as much as a flatsawn board whose surface is more generally cut across a tangential plane.

In general, denser wood tends to shrink more than less-dense wood. This means that species such as oak and hickory will shrink more than yellow-poplar, for instance. This is particularly noticeable across the grain.

HOW DRYING PROGRESSES

Lumber drying doesn't progress at a constant rate. Think about squeezing out that wet kitchen sponge: it's easy to get rid of the water in the large open cells and pressing harder will remove water from the smaller cells, but the rate of water loss quickly slows. After all the water in the sponge pores has been removed, all that is left is the water saturating the cellulose itself. This water will evaporate given the right conditions, but the water will leave at a slower rate than squeezing produced. Removing water from a piece of wood is similar; liquid water will evaporate from larger cell pores more readily than it does from small pores, and it will take more energy and more time to evaporate a unit of water from those smaller pores than from the larger ones. Drying the cell wall itself takes even more energy and time to vaporize the bound water and to transport it as vapor to the wood surface where it can be carried away by warm air.

Higher temperatures speed up the heat transfer, facilitating vaporization of water below the wood surface; increasing the wet bulb depression (lowering the relative humidity) speeds up the rate at which water can be removed from the surface. You might think of it like this: a pot full of room temperature water gets hotter when you increase the burner heat and steam will form above the surface. Practically no evaporation occurs unless the lid is off, though, because the air inside the pot quickly gets saturated with water vapor. Once you lift the lid, the steam is exposed to a lower relative humidity environment and the water vapor escapes the pot seeking to reach an equilibrium with the less-saturated air. Evaporation goes faster at lower relative humidities.

WHY KILN TEMPERATURES GET CHANGED DURING DRYING. Kilns start out at low temperatures because it doesn't take much energy to evaporate water that's on (or close to) board surfaces. Air bubbles within the wood cells expand as they're heated and help push liquid water to the surface at the same time that water is pulled to the surface by wicking to replace the water that evaporates. Driving the so-called "wet line" below the surface too quickly can cause the surface to attempt to shrink before it's strong enough to resist drying-induced stresses, and defects such as checks will result. As the bulk of the wood starts to dry out and strengthen and the remaining water is contained within small pores and the cell wall, kiln operators can raise the heat in increments to finish drying the wood.

Let's examine how wood dries in more detail.

PREHEATING THE LUMBER. Wood starts to dry as soon as its surface is exposed to an EMC condition that's lower than the MC of its surface (which is essentially saturated in freshly-cut green lumber). Nonetheless, if you're placing wood in a warmer environment like a kiln, it will have to warm up a bit before drying can really get going; a cold piece of lumber will require more energy for liquid water to begin to change to vapor and evaporate from the surface.

WATER EVAPORATES FROM THE SURFACE AND LARGER PORES. The wood surface is wet in the early stages of drying. Water on the surface begins to evaporate, and its loss is fairly rapid. Free water flows from the inside of the wood towards the surface, especially through the lumens of cells with the larger diameters–hardwood pores, and the earlywood pores particularly in ring-porous species. Higher temperatures and lower relative humidities will hasten this evaporation. Internal water vapor pockets begin to form to replace the volume of the water lost to surface evaporation and push more free water to the surface where it can evaporate. During this stage of drying, the rate of water loss is essentially constant.

By the time that most of the water has left the larger cells, approximately one-third of the water will have evaporated from the lumber. Green white oak, for example, might have an average green MC of about 65%, so when the MC has dropped to about 44% or so you'd know you're beginning to evaporate water from the smaller pores. The drying rate is going to slow down. When water migrates more slowly from the interior than it evaporates, the wood surface starts drying out and shrinkage and stresses can start to occur.

STRESSES IN THE OUTER WOOD SURFACE. When a board starts to dry, the wood fibers on the surface drop below the FSP and come into equilibrium with the EMC conditions quickly. Continuing to dry the lumber "locks in" the original dimension of the wood near the surface; because of the moisture content drop the surface layer would normally shrink, but the wetter, swollen wood in the core prevents it from doing so. Because the shell is restrained from shrinking it goes into tension, this is known as ***tension set***; surface checks open up when the tensile stresses exceed the strength of the wood.

DEFECTS ARE CREATED DURING EARLY DRYING. Fast drying rates increase the moisture difference between the core and the surface and serve to increase the tension stress at the surface. For green wood especially, drying defects will occur if the tensile stress exceeds the wood strength.

Surface checks can open quickly in green lumber, so air drying yard managers and kiln operators need to monitor the drying progress to ensure that drying doesn't proceed too quickly. Slower drying can be accomplished by three things: 1) lower air speeds, 2) high relative humidities, and 3) low temperatures. Drying rates increase with air flow rates, and this is why low initial air speeds are essential for quality lumber drying operations. High RHs and low temperatures produce higher EMC conditions, resulting in slower drying.

When wood is exposed to both heat and humidity in a kiln, the combination weakens wood more than exposure to just one or the other–hot moisture (steam) is used to plasticize pieces of ash so they can be bent to make Windsor chair backs, for example. For this reason, kiln schedules start at low temperatures to keep wet lumber as strong as possible and kiln schedules are advanced to higher temperatures only when the lumber is drier and stronger. Weak wood is more likely to develop surface and end checks.

Drying will proceed most quickly at the edges of the stacks, and on air drying yards you will notice that uncovered top boards and lumber packs stored at different locations will dry at different rates. Controlling the drying rate of wet lumber is very important because checks can form readily during periods of rapid drying (such as high wind conditions). Even transporting uncovered green lumber from one location to another can be enough to initiate checks in species that are especially prone to checking (such as oaks).

Checks commonly form on end grain or adjacent to rays, so they will be most noticeable in flatsawn lumber. One problem with surface checks is that they can easily become more severe as drying progresses. Checks are sharp-pointed separations between wood cells, and it takes only a little more energy (shrinkage) to make them deeper.

Lumber that's cut with a circular saw or a dull saw is more likely to tear the wood than shear it cleanly, and this promotes surface checking as well; this is one reason why some firms that dry oak will presurface the lumber with a planer after sawing.

WATER EVAPORATES FROM SMALLER AND SMALLER PORES. As it dries, a moisture gradient forms within the lumber. Drying progresses from a dry surface towards the wet core, and in due course the rate of water transport from the interior of the lumber will slow down as the supply of easily-transported, easily-evaporable free water in large pores dwindles. The remaining free water is in smaller pores that give up their water less readily, and more heat is typically used to encourage this water to evaporate at a reasonable rate.

The thickness of the layer of dry wood will increase with time and the “wet line” will recede further and further towards the center of the board as drying progresses. As smaller and smaller capillaries are dried out some bound water will begin to be evaporated as well.

It takes time for the wet line to recede and for the shell to reach a moisture content below the FSP (where it begins to strengthen); this is why kiln schedules stay conservative even as the average MC begins to drop below 30%. It’s common to keep the initial kiln temperature fairly low until the wettest samples are at an average MC of 30%, and then to raise it only slightly; the RH is usually changed in small increments until about 30-35% MC as well (unless checks have been observed, in which case the RH is dropped a lesser amount or even maintained).

If the wood has been air-dried or partially kiln dried be careful not to rewet the wood surface or put the lumber in an environment where the ambient RH is going to add water to the wood (rain or a high RH kiln environment, for example), and don’t cycle wood conditions wet-dry-wet-dry etc. If you see new surface checks forming when the average MC approaches 30%, the lumber probably went through a wet-dry-wet-dry cycle.

When the surface of the wood is wet its temperature is about the same as the wet bulb temperature– after all, a piece of wood with a saturated surface is essentially the same thing as a thermometer bulb covered by a saturated wick. When the surface begins to dry out, however, the surface temperature will start to rise. Eventually the surface temperature will reach the kiln dry bulb temperature (see Figure 25).

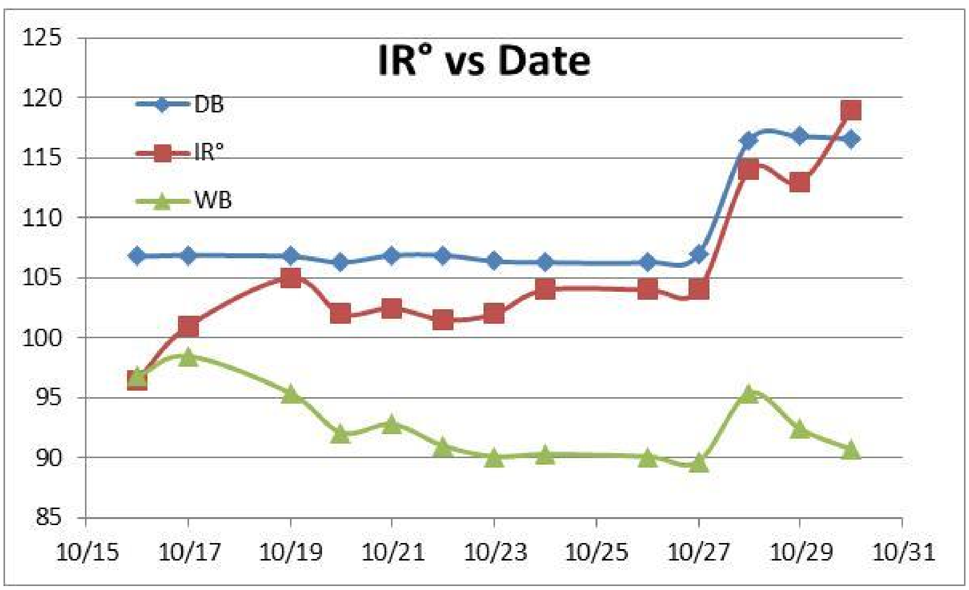

Figure 17. *Data from a commercial DH kiln run with hickory sapwood. The surface temperature readings taken with a handheld infrared thermometer approached the dry bulb temperature on October 24th. DB= dry bulb temperature (°F), WB = wet bulb temperature (°F), and IR° = the infrared thermometer reading (°F).The IR thermometer readings aren’t as precise as the kiln temperature readings, and so they appear to vary more than the kiln temperature readings.*

EVAPORATION OF WATER VAPOR FROM CELL WALLS. Wood structure is nonuniform, and it doesn't dry uniformly either; this means that some parts of the boards will be drier than others. Water will continue to evaporate from smaller and smaller capillaries; water in microcapillaries will move by diffusion through the cell walls to places where it can evaporate. When the free water is gone in any location the only remaining water will be the bound water in the cell walls. This too will evaporate, but additional heat and/or time will be needed to further dry the wood in these places.

Wood will begin to shrink when the moisture content drops below the fiber saturation point, but it's important to note that "moisture content" doesn't refer to the average moisture content of a piece of lumber–it refers to the moisture content at a specified location. This is why the shell will try to shrink (resulting in tension set) even though the core is wet enough to make the entire board have a moisture content over 30%.

When much of the wood is at a moisture content below the FSP (and therefore stronger), it's safe to start accelerating the drying schedule. The rate of water loss will be noticeably slower, and the dry bulb can be increased at the same time that the RH is lowered.

DRYING STRESSES IN DRIER LUMBER. When the core finally dries and shrinks, the stresses reverse! The drying shell will pull the shell inwards in all directions, closing any surface checks; the shell will now be in compression and the core will be in tension. Often those closed-up checks won't be discovered until boards are planed or stained. This can cause problems for kiln operators, because surface checks are often initiated during transport or air drying before the lumber ever enters the dry kilns–but *the kiln operator will still get the blame!*

DEFECTS CREATED AT THE END OF DRYING. Dry wood is much stronger than moist wood, so new defects are unlikely to occur regardless of the kiln settings (though high temperatures are often avoided to prevent darkening light-colored woods). There's one important exception to that statement: the defect known as ***honeycomb*** becomes visible (Figure 26). This is why preventing surface checks in the initial stage of drying is so important! You probably won't notice honeycomb until the lumber is cut or machined; this can cause product returns and headaches for the kiln operator.

Figure 26. *Honeycomb in red oak.*

I knew a kiln operator once who was asked to custom-dry some green 8/4 black walnut, and the client wanted it done as quickly as possible. The kiln operator, diligent but somewhat inexperienced, tried his best to accommodate the client, but he pushed his kiln schedule too quickly. When drying was completed the lumber was found to have extensive honeycomb. I leave it to you to imagine the discussions that ensued.

I mentioned earlier that you need to avoid ever rewetting partially-dried lumber. Adding water to the surface of wood will make the outer layer swell, creating a tensile stress in the center of the lumber. This will deepen any existing surface checks and cause honeycomb.

FINISHING DRYING. Kiln schedules prescribe low EMCs in the final stages of a drying schedule. These values are typically 2%–4% lower than the final target MC, and they are set this low to promote drying as the rate of water loss slows down. The final step in a hardwood drying schedule with a 7% target MC might set an EMC of about 4%, for example. **It's important to monitor the kiln sample with the lowest MC at this point to avoid over-drying the lumber**, as this can lead to all sorts of problems with machining, gluing and even finishing operations.

To avoid overdrying the lumber, watch for the point at which the driest moisture sample board reaches two percent below the bottom end of the target moisture content range. For example, if the moisture content target was 7%, then you should note when the driest sample board reached 5% MC. Not all of the lumber will be as dry as 5% MC, and some of it might still be at 9% MC or so – and that's too wet. The procedure used to bring all of the lumber into specification is called **equalization**. Equalization is followed by a stress relief procedure called **conditioning** that removes stresses from the lumber by putting it into a hot steamy environment for a few hours.

CONSIDERATIONS FOR DH KILN OPERATORS. If you're using a DH kiln you will find that the kiln conditions you can set are limited by the compressor operating range. This isn't going to be anything to concern yourself with until you come to the end of the drying schedule, because this is where temperatures get highest and relative humidities get lowest. Avoid trying to operate dehumidification units at a dry bulb over 160°F or with a wet bulb setting over 120°F; running the compressor with a wet bulb set for over 120° can damage the compressor and it should turn itself off at 132°F. You probably won't be drying at DBs over 160°F anyway, and I'll show you how to adapt schedules published for steam kilns to ones you can use in a DH kiln later in this manual.

EQUALIZING. To equalize the lumber, set an EMC condition within the kiln that is the same as the driest kiln sample (5% in this example). This will prevent the driest boards from getting any drier, and it will continue to encourage the wetter boards to reach the target MC range. (It's ok to dry some of the load below the target MC range at this point, because you'll add a little water back in during conditioning). Continue equalizing the lumber until the ***wettest*** sample board reaches the target MC - not the upper limit of the moisture range including the MC tolerance, but the target MC itself.

To continue the previous example, if the target MC is 7% with a ±1% MC tolerance (*i.e.*, 6%–8% MC range for all the lumber being dried), continue to equalize the lumber until the wettest sample board reaches 7% (not 8%). You now have a load of lumber which – if the sample boards were chosen well to begin with – contains lumber which is all within the range of 5%–7%. That's 1% lower than you ultimately want, but it's perfectly ok at this point.

Different parts of your kiln sometimes dry at different rates, and boards in the center of the pack often dry more slowly than the boards around the edges. The air entering the packs becomes less dry (perhaps even saturated) after flowing over several boards, and the drying for the interior boards will be delayed or slowed. This might be of particular concern if you are using a kiln where the air has to flow through several stacks of lumber, and variability in drying across the load will be more noticeable in kilns with low fan speeds. If this description resembles your kiln, consider using a longer equalizing period than would be indicated by the MCs of your sample boards. If you only have kiln samples in convenient retrieval locations you might misjudge the length of equalizing needed, no matter how carefully you selected the kiln samples. If you have a way to monitor the moisture content of boards in the interior of your packs (using electronic sensors, perhaps), that would be a good set of observations to pair with your sample boards.

CONDITIONING. *I mentioned earlier that* when the average moisture content reaches the target value there is tensile stress in the outer layer and compression stress in the core. This residual tension stress in the lumber core after drying is called **casehardening**.[10] Casehardening results in dried wood pinching a sawblade when it's machined, so it's very desirable to relieve these stresses before lumber is sold. ***Conditioning*** is a method used to relieve these drying stresses *by adding* a *very* small amount of *moisture back to the lumber under controlled conditions*. Conditioning raises the average moisture content slightly, which is why equalization target MCs are set a little lower than the final target moisture content (ex., 5% MC instead of 7% MC).

Adding steam to the kiln is a very effective way to reduce casehardening; the heat and water combine to plasticize the wood shell, relieving residual drying stresses. Water mist systems can also be effective, and are particularly popular with companies don't have a boiler on the premises (like most DH kiln operations). The length of time that lumber is conditioned depends upon the amount of drying stress and the kiln temperature among other things – higher temperatures result in shorter conditioning times. Lower density species condition more quickly than higher-density species as well, and thicker lumber takes more time than thinner lumber.

In many respects, air-drying conditions somewhat replicate the cyclic temperature and RH conditions experienced during solar drying, and air-dried lumber typically has less drying stress than green lumber with a similar moisture content that's been dried in a kiln. Each load of drying lumber may have a different drying history (and the species

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[10] Casehardening is a term from the metals industry that implies that the wood somehow harder on the surface – and this is <u>not</u> the case – but it's a historical term that has been used in our industry for well over 100 years.

and perhaps the thicknesses may be different as well), so each load *should* be checked *for drying stresses and treated* for casehardening *as needed*; there's no *"magic* recipe*"* that can be automatically repeated at the end of drying.

CONDITIONING IN CONVENTIONAL (STEAM) KILNS. To condition hardwood lumber when steam is available, a conventional procedure is to set the dry bulb to a temperature about 10°F higher than the equalizing temperature. Before raising the dry bulb temperature, though, set the wet bulb to a value that would give you an EMC of 4% higher than the target MC – steam contains a lot of heat and the dry bulb temperature in the kiln will increase from the steam alone. (For softwood lumber, set an EMC of 3% higher than the target MC.) To minimize the chances of exceeding the set point, turn off the heating coils or temporarily set a low dry bulb temperature to achieve the same result. Maintaining a set temperature might be difficult even with venting, however.

Besides venting, another way to address the problem of steam overheating the kiln is to purposely cool the kiln before starting to condition the load. When the kiln is turned back on, the operator still has to ensure that the target EMC has been reached, but the problem of steam overheating the kiln past the DB setting is lessened.

For the 7% target MC example, you'd set the wet bulb to give an EMC of 11%, and after the wet bulb temperature was reached you would then increase the dry bulb temperature. The most important point isn't that you have to be able to set the prescribed dry bulb and wet bulb temperatures – the most important point is that you have to be able to actually reach the correct EMC.

CONDITIONING IN OLDER STEAM KILNS. For various reasons, some older kilns may not be capable of reaching the desired conditioning set points. One common problem is leaks around the doors, vents, between panels and so forth. Fixing leaks will help you to achieve your set conditions throughout the kiln cycle, not just during conditioning. Leaks can sometimes be detected by steam plumes in extreme cases, but another way to discover leaks is to examine the kiln with an IR camera. If you can't borrow one from your local university or town engineer, you can buy one online starting at a couple of hundred dollars (as of 2017). If you have to live with a leaky kiln in the meantime, try for the highest dry bulb/wet bulb temperature combination that is both appropriate for the desired EMC and attainable.

CONDITIONING IN DEHUMIDIFICATION KILNS. DH kilns typically don't have boilers or access to steam, so traditional conditioning methods aren't available–which is why water mist systems are used. Steam conditioning proceeds more quickly, but fine water mists also work well and are relatively inexpensive to install and operate. Large DH kilns might use pressurized water at about 1000 psi (±200 psi), and they will spray somewhere between five pounds and ten pounds of water per hour for each 1000 board feet of lumber. (The water needs to be filtered to help prevent the fine nozzles from clogging.) Smaller kilns with less urgent time constraints might use lower pressures (around 100–125 psi) with slightly larger nozzle sizes.[11] The heat in the kilns will evaporate the water mist and increase the RH, thereby helping to relieve casehardening.

Mist systems appear to work well, but some people prefer steam because water mists don't release heat to the lumber like steam does. Of course, steam might also be preferred because dry kilns have used steam for decades and mist systems are relatively new to North America. People tend to prefer what they're familiar with.

[11] Phone conversation with Don Lewis, Nyle Systems, January 2017.

I have heard of kiln operators spilling buckets of water on the kiln floor or spraying packs of hardwood lumber with garden sprayers in attempts to "home brew" conditioning solutions when purpose-built mist or steam systems were not installed. Don't follow their example! Water puddles will evaporate too slowly to provide the quick boost in RH needed for stress relief, and rewetting the lumber with large water droplets from low-pressure sprayers will increase the likelihood of defects in the finished lumber. I've even heard of people using rice cookers to add steam to small dry kilns, but they can't begin to generate the amount of steam required. If for some reason a company running DH kilns didn't want to use a water mist system, commercial electric steam generators are available. High pressure steam is not required, but an appropriately-sized steam generator might cost you almost what you paid for the DH compressor setup. It might also require either 240 or 480 3-phase electrical connections. As an example, a 10 kW steam generator will produce roughly 35 pounds of steam per hour. This might be a reasonable starting point for a kiln with 4000 BF capacity based on the five to ten pounds of water per hour per 1000 BF rule of thumb mentioned above, but the size of the steam generator might need to be increased depending on the fraction of lumber volume to kiln volume.

Conditioning in a DH Kiln. DH kiln schedules for hardwoods usually terminate at an EMC of about 4%, but some DH kiln operators run their kiln with a final step-EMC of 5% so they can equalize while they're drying to the target MC. The driest boards are already restricted to drying below the EMC in the kiln, so their conditioning procedure might be to increase the dry bulb by 10° when the slowest-drying sample board reaches the target MC and then and to add water back to the kiln as a mist to provide the added moisture needed for conditioning.

Most of the Nyle-supplied schedules finish drying at 160°. If you use those schedules, you might think that you could just do the final drying and equalization at a lower temperature than the schedule calls for, slowing down the kiln a little bit and then boosting the kiln temperatures for conditioning at the higher RH required. This might not be practical because of compressor limitations.

Table 4 reproduces a sample schedule that Nyle provides to its customers for 4/4 to 6/4 red oak:

Table 4. *Nyle-provided drying schedule for 4/4, 5/4, and 6/4 red oak lumber*

RED OAK 4/4, 5/4, 6/4				
MC%	**DB °F**	**DEPRESSION °F**	**WB °F**	**EMC%**
Green to 50%	110	4	106	17.5
50 to 40%	110	5	105	16.2
40 to 35%	110	8	102	13.3
35 to 30%	110	14	96	9.9
30 to 25%	120	30	90	5.4
25 to 20%	130	40	90	3.8
20 to 15%	140	50	90	2.6
15% to Final	160	60	110	2.1
Equalize and Condition to Target MC%				

Could you wind up this run at 150°F instead of 160°F? If the target MC is 7%, you could use a 150°F dry bulb temperature with a wet bulb depression of 35°F (5.0% EMC at 31% RH) for equalizing, giving you a wet bulb temperature of 115°. That's within the operating parameters recommended for the compressor (maximum of 120°F or so or the wet bulb), so you'd be ok for equalizing.

Next, though, there's the question of how to condition the lumber. If you plan to raise the conditioning temperature to 160°F the wet bulb would have to be set to a temperature of 149°F (an 11°F wet bulb depression yields an RH of 75% and an EMC of 11%). This is outside of the operating range for the compressor, but it doesn't make sense to run the compressor to extract moisture at the same time as you're trying to add humidity anyway. To reach these conditions you might shut off the compressor, monitor your wet bulb, and make adjustments as needed to maintain the RH at 75%–but you're still going to have to add moisture somehow. Raising the temperature from 150°F to 160°F is going to decrease the ambient RH, not raise it. You won't be able to make a 31% RH at 150°F increase to 75% RH at 160°F without evaporating more water from the lumber–and that's the last thing you want to do.

Here's a practical approach to conditioning in a DH kiln: Let the kiln cool down for an hour or so after equalization and then increase the RH to the prescribed EMC for conditioning using mist or steam as available. This can result in rapid moisture uptake and speedy conditioning. Keep an eye on the length of the conditioning period and make sure you don't add too much moisture back to the wood (see the descriptions below about monitoring this). Let the wood sit for a day or two afterwards to let the excess surface moisture evaporate.

USING PRONG TESTS TO DETERMINE DRYING STRESSES AND THE END OF THE CONDITIONING PERIOD. Stress relief has to be frequently monitored during conditioning. Residual drying stresses can be indicated by using a ***prong test*** at the end of equalization. For each prong test, a one inch thick piece of wood is cut across a board (like for a moisture section) to make prong test sections to judge the degree of casehardening. Prong test sections could be cut from the sample boards or any other lumber you select from the load being dried; movement of the prongs after cutting indicates residual stresses (assuming the moisture in the prongs is uniformly distributed). The manner of cutting prong test samples varies according to the board thickness as shown in Figure 27 below:

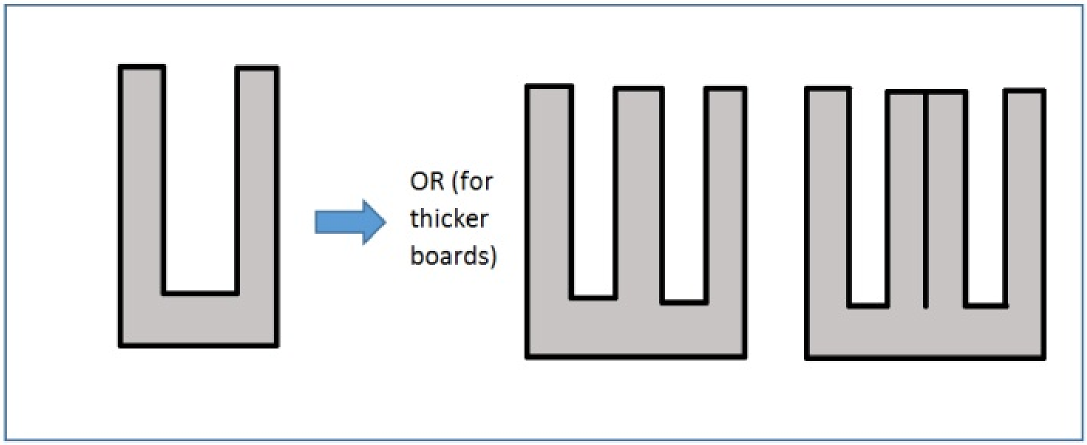

Figure 27. *A single pair of prongs is appropriate for 4/4 boards, but thicker boards are usually cut somewhat differently. You are looking at representations of the end grain in these diagrams. For 4/4 boards, the prongs should be about one-quarter of the board thickness.*

As an example, for 4/4 boards you would mark out two prongs about 6”-8” long or so depending on the width of the board(s). The prong thickness ought to be 3/8” of an inch thick – about a quarter of the board thickness is right because thinner prongs too strongly indicate the stresses at the surface and won’t provide reliable results. In the 4/4 board shown below, the core would be removed with a bandsaw leaving one-quarter of the thickness remaining at each surface (Figure 28).

Figure 28. *Cross-section of board showing wood to be removed for a prong test.*

Samples cut before conditioning starts will probably have the prongs turn inwards, indicating that casehardening is present (Figure 29).

Figure 29. *In casehardened lumber the prongs will bend inwards like this.*

There is one point that is ***essential*** to note for a valid prong test: you have to be sure that a moisture gradient isn't confounding the results. There are two ways to avoid this: 1) let the cut prongs sit for a few hours to allow any moisture gradients to even out (though this can increase the kiln residence time while you wait for the results); or 2) you can put the cut prongs into a microwave on high power (~1000 watts) for 15 seconds, and use this to even out any moisture gradients present. You have to let the prongs cool for a few minutes before examining them, but what you see after this short procedure will be identical to the results you'd see after letting the prongs sit for a few hours.

The prongs will continue to bend inwards as long as there's residual compression stress acting on the shell, and if you observe this happening then conditioning is not complete (*i.e.*, the lumber is still "casehardened"). As a kiln operator, your goal is to stop conditioning when the prongs stay straight – this might take anywhere from a few hours to more than a day, depending on the wood density, the lumber thickness and the kiln conditions (temperature particularly). (Refer to Appendix C for some helpful guidance about when to stop conditioning.) If a planer or moulder will remove the outermost part of the board (which has the most drying stress), it's probably ok to stop conditioning when the prongs bend slightly inwards (or maybe conditioning won't be required at all).

This is what a stress-free prong test sample should look like:

Figure 9*. In stress-free lumber the prongs will remain straight after the sample has cooled.*

Be careful: you can condition the lumber for too long (“***over-condition”*** the wood) and reverse the stresses again, in which case the prongs will move outwards. This is called ***reverse casehardening***. Reverse casehardening cannot be fixed.

If you’re interested in selling lumber to a European market, note that European markets make use of a standard designated as ENV 14464 (a “slicing test”) to determine the relief of drying stresses. See *Dried Timber – How to specify correctly.*

USING SAMPLE BOARD WEIGHTS AS AN ALTERNATIVE TO PRONG TESTS. If you choose not to use a microwave to hasten readings of prong tests, you have another option. Some mills weigh their sample boards before conditioning and continue to monitor these weights until the moisture contents are approximately 1½% higher than they started out. If you choose to try this, I recommend that you continue using prong tests as well until you are comfortable with this procedure.

FACTORS THAT AFFECT THE DRYING RATE: *TEMPERATURE, RH AND AIR FLOW*

The dry bulb temperature, relative humidity and the air flow all interact to influence the drying rate. Here's a table to help keep things organized:

Table 5. *Effects of temperature, relative humidity and air flow on the drying rate*

↑ ***Temperature***	↑	Increased drying rate, more uniform drying,
	↑	More warp, strength loss results in checks, honeycomb. Higher temperatures increase color change in white woods (ash, basswood, hard & soft maple, sap yellow-poplar)
↓ ***RH***	↑	Faster drying, more checking, more uniform drying
	↓	Less warp (wood stays flatter), less risk of discoloration
↑ ***Air Flow***	↑	Faster drying at high MCs (above 30-40%), more uniform RH and more uniform drying in the stack
		Under 20% MC, you can put the sample boards just about anywhere because air flow won't affect the drying.

AIR FLOW ON AIR DRYING YARDS. Airflow affects all stages of drying, even air drying, and the climate where you're located might affect how you handle your air drying yard. Consider the area surrounding The Dalles, a city in Oregon: the summers there are breezy, warm and dry. These conditions can cause lumber to dry too quickly, and sometimes it's desirable to slow things down. To do this, stacks of drying lumber might be moved closer together there than they would be in an area with less wind and more humidity.

STACKING. Be intentional about how you bolster and sticker your lumber, because the vertical spacing between stacks or layers of boards will affect the drying uniformity and drying rate. Larger spaces between layers of boards permit greater air volumes to pass in a given time, and this encourages more uniform drying. Air speed increases when the air is forced between narrower openings, and higher air velocities will dry lumber with a high moisture content more quickly.

In practice, the bolsters used between stacks of air drying lumber are most often 4” x 4”, and most people use ¾” thick stickers. You might find that a stacking jig made from steel U-Channel helps to keep the stickers in vertical alignment (see Figure 31), as this supports the layers of lumber and helps prevent warp induced by the weight of the lumber above. If you place stickers as close to the ends as practical you will find that any end checks that occur will stop growing when they reach the sticker.

Figure 31. *This is an example of a steel U-Channel stacking jig for 8’ lumber used at a small Kentucky sawmill. Boards and stickers are placed by hand.*

Make sure that tops of the air-drying pile foundations are at least 12” above the ground, and preferably 18” above the ground. This helps keep the bottom boards away from the higher relative humidity that occurs at ground level. Vegetation such as weeds and grass will promote the retention of humidity; remove it. Be careful to place a bolster directly beneath each line of stickers. Keeping the bolsters aligned with the stickers is another simple step you can take to help prevent warp.

Here’s a good example of how to stack air-drying lumber (Figure 32):

Figure 32. *This is a good example of how to stack air-drying lumber. The piles are supported by doubled bolsters and there is no vegetation. The fork truck operator placed the piles directly atop the bolsters and the stickers are nicely aligned with the bolsters and the packs above. At this location the lumber is drying under a shed roof, but stack covers could be used as well.*

Here’s an example of lumber with stack covers in the open air:

Figure 33. *This lumber is well stacked and the yard manager has added stack covers (made of weighted-down boards in this case) above the top layer of lumber to protect the lumber. Note the stickers used to keep the stack covers away from the top layer.*

Don't neglect your piles of air-drying lumber as shown in Figure 34:

Figure 34. *This lumber is too close to the ground, vegetation needs to be cleared and the area in front of the stacks collects water. None of this will help a sawmill dry high-quality lumber.*

AIR FLOW IN KILNS. Baffles are used in dry kilns to direct all of the air energy from your fans through (rather than over and around) the lumber. Whether you make them out of plywood, canvas, or metal, keep your baffles in good condition and repair them as needed, because good baffles will save you money and time. Get them close to the lumber, no more than 4" away. Leave a gap for air to circulate over the top layer of boards in your stacks.

The air speed you use might be dictated by your current equipment. I've observed the air speed to vary a lot in different types of dry kilns. Some small DH kilns that I've checked have had air flow rates in the range of 125–200 feet per minute through stickered lumber, whereas larger kilns have more fans with higher horsepower and their air speeds might be 300 fpm or more. Upgrading your fans may have advantages for some species and moisture contents. Hard and soft maple are difficult to check, for example, so if you're drying a lot of maple in a 4000 BF DH kiln you might put in a third fan to increase the air flow rate; you could probably go as high as 600 fpm without problems. On the other hand, it's very easy to check red oak, so you might stay with 200 fpm at high MCs.

In larger kilns, you could increase the horsepower of the fan motors and maybe even change the fan blades. Reversing fans are helpful if the air flows over packs of lumber more than twelve feet deep. Variable speed fans can be useful, but they run on 220V with 3-phase current. The motors are smaller than the 110V version with the same horsepower, and are generally cheaper, too.

AIR FLOW AND TEMPERATURE READINGS. The air speed in kilns affects not only the drying rate, but also (to a small extent) the wet bulb reading. Perhaps you remember (as I do) being told in high school science class to swing a sling psychrometer as fast as possible to get a reliable reading from the wet bulb thermometer, because faster air speeds drive down the wet bulb reading more than slow air speeds? How does air speed affect the reliability of our wet bulb measurements if our kiln air speeds are a bit on the slow side? I've read that the wet bulb readings don't stabilize until the air speed gets to about 600–800 fpm[12], but once the air speed exceeds 100 feet per minute of so the WB readings only change by fractions of degrees as the air speed increases. As a practical matter your WB readings are still perfectly adequate regardless of whether your kiln air speed is slow or fast.

I was told years ago that the kiln schedules used in the *Dry Kiln Operator's Manual* were developed using kilns that ran at about 300 fpm. Nowadays many hardwood kilns run fan speeds in the range of 200-400 fpm but some small DH kilns have less efficient fan setups, and I have measured some that only have 150 fpm air flow. At this air speed the WB might theoretically read just a little higher than it would at 300 fpm (by less than one-half degree Fahrenheit); my own experiments with a sling psychrometer showed negligible differences at room temperature conditions. Small temperature differences on this scale don't make any real difference to the EMC in the dry kiln. For a kiln set at 120°F dry bulb and 100°F wet bulb running at 150 fpm, the actual EMC in the kiln would only be about 0.1% EMC or less below what you're attempting to set. That small difference is obviously nothing to worry about.

The differences between 300 fpm WB readings and 600 fpm WB readings are even smaller than the ones I referred to above, so even if you use variable speed fans at their fastest setting you needn't concern yourself with differences between the EMCs you're trying to set and the EMCs that actually occur in the dry kiln. Very high air

[12] Threlkeld, James L. 1970. *Thermal Environmental Engineering*, second edition. Chapter 10: The Psychrometer and Humidity Measurement. See the lines in Figure 10.6 for unshielded thermometers.

velocities might require adjustments to the kiln conditions because of the more turbulent manner in which air interacts with lumber surfaces, but that's not because the wet bulb readings are inaccurate.

WET AND DRY BULB LOCATIONS. The placement of your wet bulb is important. First of all, put it in a location that's easily seen and accessible for maintenance. Make sure it's exposed to the main air flow and not tucked away behind a beam or too close to the wall or a piece of equipment. Ideally you'd like to put the dry bulb thermometer in the warmest part of your kiln (if you can locate it), but don't put it directly in front of a heated air stream because that won't be representative of the actual kiln temperature.

Putting both the wet bulb and dry bulb thermometers on brackets to keep them away from the wall is a good idea; for one thing, the temperature measurements will be less affected by the heat radiating from the kiln wall, and you'll be more likely to get good air flow over your wet bulb thermometer.

WET BULB MAINTENANCE. Here are a few common-sense things you can do to get the most accurate wet bulb readings:

1. Check the wet bulb wick prior to every load. Keep it clean and change it often– dirty wicks will not evaporate water properly, and this can lead to inaccurate wet bulb readings. Wet bulb temperatures are affected by both heat and mass (water vapor) transfer, so less evaporation will mean less cooling of the wick and a perception that your kiln is running at a higher RH than it is. Very dirty wicks may not even wick water from the reservoir efficiently.
2. Use distilled water whenever possible to minimize mineral buildup, and be sure that the wick completely covers the thermometer bulb.
3. Be sure your water reservoir is full (otherwise your wick might not stay wetted throughout the drying run.)
4. Be sure that there aren't any obstructions or barriers in the way of the air surrounding your WB thermometer so it can read as accurately as possible.

DRYING PROCEDURES

OKAY–YOU'VE BOUGHT SOME LOGS. The logs you buy may have been cut on your own property, they may be logs that you asked a logger to cut for you, or they might even be gatewood that someone brought to your doorstep asking if you wanted to buy them. Let's assume that you know how to scale them and that you have some idea about the quality and actual yield that you're going to get after sawing them so you can pay an appropriate price (good for you!). The question now is: what do you do with the logs now that you've got them?

END COATING. After the logs have been received at the sawmill (or preferably, right after they've been cut), think about coating the ends of the logs with ANCHORSEAL or a similar end coating ("end coat") to help prevent moisture loss and end checks.[13] If you don't put an end coating on the logs, put it on the lumber as soon as possible after sawing. End coating is particularly important for expensive and thicker lumber and for denser species (because drying shrinkage is generally greater for denser species). End checks can form quickly, and delaying end coating usually doesn't prevent any end checks already formed from getting larger and longer. Applying an end coating will dramatically decrease the likelihood of new end checks forming.

Good quality black walnut logs intended to be cut into 8/4 boards would be prime candidates for end coating, as end checks could significantly decrease the amount of saleable lumber – but end coating yellow-poplar isn't as cost-effective because it's less valuable. Yellow-poplar is also less dense than walnut, so the amount of shrinkage/checking should be less significant.

Different mills use end coating differently: one sawmill I know color-codes the logs with tinted end coatings indicating different species, while another occasionally uses different colors to indicate ownership (if they're custom-sawing) or the source. Some people prefer not to have any tint in the end coating at all; they feel that a transparent end coating helps the sawyer and that they can keep track of the logs another way.

No matter how you apply end coating, remember to put it on thick enough to do some good. Slather it on with a stiff brush, and give it two coats if the log's valuable. If you spray it on, be careful to maintain a good coverage or it won't be as effective (see Figure 35).

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[13] ANCHORSEAL is a water-based wax emulsion sold by U-C Coatings; sometimes people just call it "wax". I've seen some hobbyists and even a small business on occasion try to use latex paint as an end coating, but it's very porous and therefore ineffective.

Figure 35. *A sprayer was used to apply end coat to these* oak *boards, but the end coating wasn't applied carefully or heavily enough to be very effective. Notice the overspray and the many end checks. The stickers weren't placed close to the board ends either and that would have also helped to minimize the loss due to end checks.*

Some years ago I visited a company that does a lot of custom sawing and drying and noticed that they had a stack of non-end coated black walnut on their air drying yard. The amount of end checking made an impression on me because the checks were severe enough that many boards would have had to be trimmed back 6" from each end; I think the boards were ten feet long, so that amounted to a 10% loss! I remember asking the yard manager why the boards weren't end coated and he told me that "the customer didn't want to pay for it." I still think about what I saw; for one thing, I can't imagine why the yard manager didn't pointedly discuss the likelihood of drying degrade with the customer, and I also can't imagine the customer's reaction when he picked up the lumber. Surely it would have made the company look more professional had they priced the drying costs to include end coating.

TAG THE LOGS. This is optional, but consider putting a tag on one end of each log for inventory control. Recordkeeping will let you keep track of where and when you got each log, how much you paid for it, what you originally scaled it out as, how many board feet and what grade of lumber you actually ended up with, and so forth. Maintaining this information takes time, but it helps you analyze whether you're making or losing money on the logs you buy and will help you make better decisions in the future. It can also help you to identify where your best logs are coming from and vice-versa.

SAW AND STACK YOUR LUMBER. Treat logs like fresh fruit and use a FIFO (First In, First Out) handling procedure whenever possible. Logs will degrade over time and attract both insects and fungi, so minimize your inventory and saw, stack and dry the lumber as soon as possible.

Proper stacking is critical if you want to get flat lumber. You have to stack the lumber such that air can flow between the boards, and wooden spacers called **stickers** or **stacking sticks** are used for this purpose. Stickers are generally ¾" thick for hardwood lumber, and it's important for them to all be the same thickness so that your lumber stacks stay flat. Stickers are sometimes square, but more often they are rectangular (¾' x 1¼" or so) to increase their strength and the likely number of times they can be reused. Grooved or fluted stickers[14] and bolsters can be used to increase the airflow between the stickers and the lumber during drying (see Figure 36). Airflow around the stickers helps kiln operators avoid wet spots where the stickers are placed.

Figure 36. *This is a sample of a Breeze Dried™ sticker.*

One company I've worked with has cut 1½" PVC pipe in half lengthwise and used the resulting half-moon shaped pieces as stickers for light-duty locations where they aren't subjected to a lot of weight (*e.g.*, the top bundles in stacked cedar piles) (see Figure 37).

[14] See Breeze Dried™ stickers (http://www.breezedried.com/) for an example of a well-made commercially available grooved sticker.

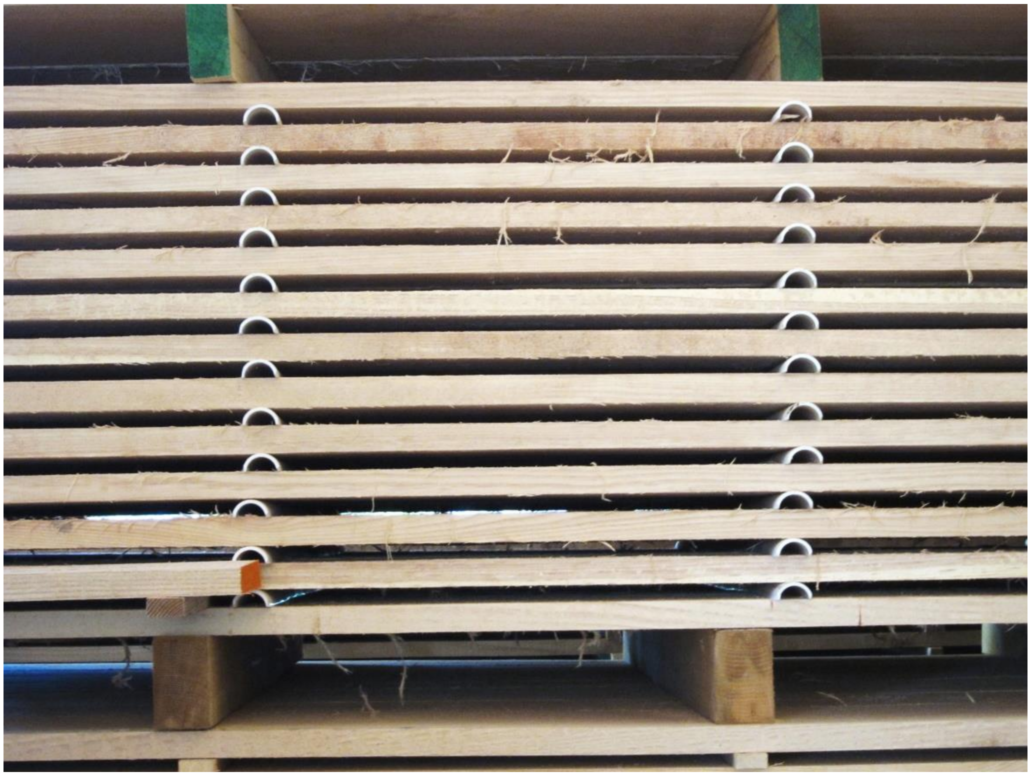

Figure 37. *Cut 1-1/2" PVC pipe can be used to make light-duty stickers with good air flow characteristics. The stickers should have been better aligned with the bolsters here.*

The likelihood of getting **sticker stain** (also known as **sticker shadow**) increases with older logs (see Figure 38). Sticker stain is a shadowy mark that occurs beneath stickers placed across sawn boards. It's caused by localized enzymatic activity where stickers make unventilated contact with wet lumber, slowing drying in those locations. Grooved or fluted stickers will improve the air flow and drying uniformity where they make contact with the lumber so the chance of sticker stain in light woods is reduced.

Sticker stain often doesn't show up until dry boards have been planed and it's difficult if not impossible to remove, depending on how deep it goes. It's most noticeable in light-colored species such as maple and ash.

Figure 38. *The dark stripe in the middle of this board resulted from the contact of the board with a stacking sticker and is commonly called sticker stain or sticker shadow.*

To help prevent sticker stain, stack your lumber immediately, or in the worst case no more than twelve hours after sawing in warm weather. Be sure the stickers are at least as long as your stacks of lumber are wide, otherwise you won't have good support across every layer.

Hopefully the entire package is made of lumber of the same thickness, but at a minimum be sure that all the boards in each layer are the same thickness. Boards in the same layer can be butted right up next to each other, though small gaps are acceptable; boards are going to shrink across their width anyway, so you don't need to add air gaps between the boards during stacking.

Some people put lower quality material in the top layers, and there are a couple of reasons to do this: 1) the lumber on the top surfaces of a pack might end up at the top of a lumber pile where it will be more prone to degrade from sun or rain, so putting lower-quality lumber on top makes sense. 2) if the piles aren't weighted above the top layers there will be less weight keeping the boards on the top layers flat, so it might make sense to keep the higher-quality boards closer to the bottom where there will be more weight on top of them. Some warp is inevitable, but it takes about 50 pounds/square foot – MINIMUM! – to keep boards flat. That value was determined for aspen, but species that are more prone to warp might require as much as three times that (*i.e.*, 150 pounds/square foot) based on some work with black gum.

Poorer quality boards are also sometimes placed on the edges of the stacks. The reasoning is that these locations are the most likely places to be exposed to rain or sun, and any resulting degrade will cost the operator more money if the higher-value boards aren't protected in the middle of the stack. Obviously, stacking like this is not practical for everyone.

HOW BIG SHOULD THE STACKS BE? Small companies generally set the height and width of their lumber packs not according to the size of their dry kiln(s) but by the capacity of their fork lifts. It's fairly common for lumber packages to be 4'-6' wide, but there's nothing to say that you can't use wider packs. There's no particular prescription for the height of the stack either: make the stacks whatever height seems practical to you. Four foot-wide stacks can get wobbly if they're too tall.

Use Stack Covers. Unless you can put your lumber under a shed roof, it's a good idea to put stack covers on the top load of stickered lumber if you're air-drying outdoors. Good stack covers can be made from corrugated sheet metal or any number of other materials. Weight them down or fasten them to keep them from blowing off or getting damaged. Put a sticker or bolster under the stack cover to ensure air flow over the top board.

How Far Apart Should the Stickers Be? The distance between the stickers needs to be the same for every layer. Putting a sticker every two feet often works well, though you might put stickers every 1' if you expect the species to twist a lot (beech or sycamore, for example) or if you're drying higher quality or 8/4 lumber that you really want to stay flat. If your lumber isn't all the same length, a mix of 7' and 8' boards for example, the stack will have a little more integrity if you box pile your lumber (stack the lumber with the ends of shorter lengths at alternate ends of the pile) (Figure 39[15]). It's important to put stickers close to the ends of your boards because placing stickers there will help to minimize end checking.

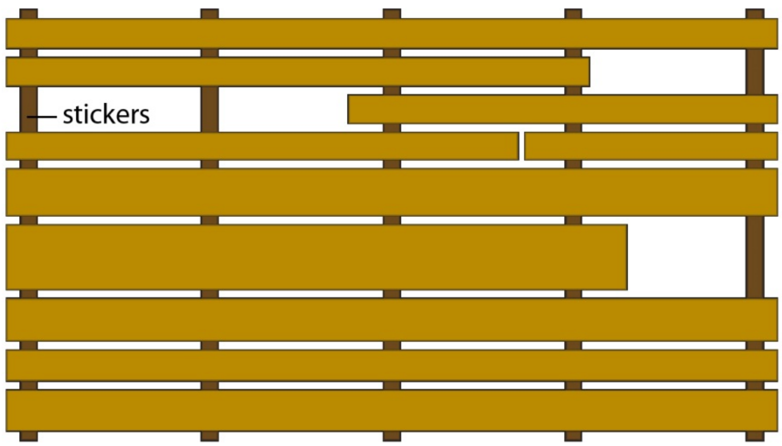

Figure 39*. This is a top-down view of box piling. Notice the full-length boards placed along the front and back edges of the pile; shorter boards get placed in the middle.*

Put stickers in place to support ends of shorter lumber – this means that your piles will have stickers at the ends as well as one foot in for 7' lumber. Think about making a place for sample boards as you stack.

What Species Should the Stickers Be? The short answer is: It generally doesn't matter as long as the stickers won't discolor the lumber. Oak stickers are strong and last a long time, though some users have found that they aggravate sticker stain in maple. A good rule of thumb would be to use a sticker species that is similar to the wood being dried. Don't make your own stickers out of southern pine plywood, though, because these will leave marks.

How Dry Should the Stickers Be? It's important for the stickers to be dry because dampness increases the chance for sticker stain; air dry stickers are ok (around 12% MC or so is good; remember to keep stickers under cover when not in use). Wet stickers are candidates for infection by fungi, and placing infected stickers between

[15] Stelzer, H.E. 2011. *Air-Drying Hardwood Lumber*. Publication G5550, University of Missouri Extension. http://extension.missouri.edu/p/G5550

layers of lumber will only spread the infection. On the other hand, stickers that are too dry can cause reverse sticker stain and can actually leave lighter color wood underneath the sticks!

How About the Bolsters? Think of the bolsters as wide stickers. Bolsters also need to be dry and at least as long as your packs of lumber are wide. They need to be placed directly in line with your stickers to provide support for the layers of lumber above, so make sure the fork truck operator is trained to do this correctly. Bolsters can cause sticker shadow too (only wider), so some people nail stickers to the tops and bottoms of their bolsters (or use grooved bolsters) to minimize the contact area with the lumber. Treated bolsters are sometimes used to avoid insect problems at ground level (Figure 40).

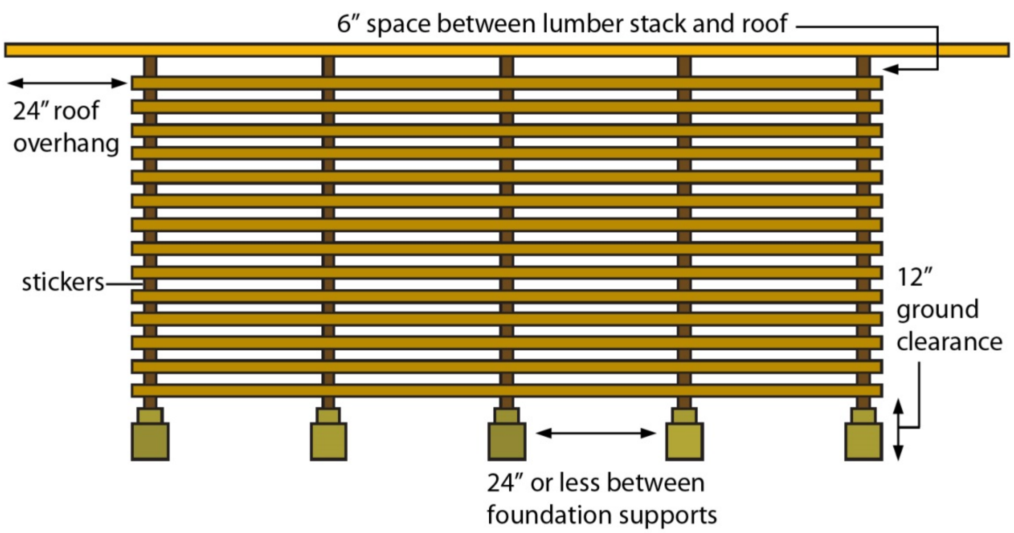

Figure 40. *Side view of a well-stacked pile of hardwood lumber.*

Preserving Color in Light-Colored Species. Many companies air dry their hardwood lumber before it goes into the kiln unless there's a special order, or unless there's some particular quality specification that is best addressed by controlling the drying conditions in a kiln. Air drying is generally cheaper and decreases the time needed in the kiln. Maple is one of those species that often goes directly into a kiln; maple's value is enhanced by its whiteness, and immediate drying increases the brightness of the dried lumber. During warm months many sawmills turn away maple logs on Fridays (because they know they won't get around to sawing them on Monday) and Mondays (because they know that the logs were cut before the weekend. Unsightly color changes are more readily visible in light-colored species; for example, holly will blue stain very quickly and some people are cautious about ash, too.

PREPARING TO DRY YOUR LUMBER. Lumber starts to dry as soon as it comes off the saw, and the options for most small sawing and dry kiln operations include 1) air drying on an air drying yard; 2) shed drying; and 3) kiln drying. Air drying and shed drying environments are similar; drying sheds are typically pole buildings with foundations and roofs but no sides. Shed drying offers the potential to control rain and slow down drying with screen-like curtains around the perimeter of the shed (one such product is called Shade-Dri®). Compared to immediate kiln drying, both air drying and shed drying are less controlled and have more potential for lumber damage but your costs will usually be lower. If you truck green lumber to another location without tarping it you definitely have the potential for drying defects due to the air flow on the exposed surfaces.

In general, for most species except white woods like maple or yellow-poplar sapwood, you should try to minimize your kiln drying expenses by getting your wood dry enough from air/shed drying to finish the drying in the kiln within 10 to 14 days. This is difficult to time, so check the moisture content of the lumber in your stacks periodically. In general, well air-dried lumber will have a moisture content of 20 to 30%.[16] The amount of time needed to air dry lumber varies with its thickness and the time of year that it gets stacked, but it could take the better part of a year to air dry lumber satisfactorily if it's stacked in cold weather. Some species (yellow-poplar, for instance) will, of course, dry more quickly than others.

In 2015 dollars, you should plan on making at least $25–30/1000 board feet (BF) of lumber in the kiln per day (gross profit). Increasing the number of times you can turn the lumber in your kiln helps your bottom line. More time spent on the air drying yard or shed means less time spent in the dry kiln – and potentially more money in your pocket.

Your kiln costs will increase if you start with green lumber and your drying profit per board foot will decrease, though some of that profit loss might get offset by increased quality. You may have higher handling costs if the lumber doesn't go directly into a kiln.

SAMPLE BOARDS. Just as you can't measure the weights of every pebble in a gravel driveway, you can't monitor the weight of every board in a pack of lumber. Not only is it impractical, it doesn't make sense when you can use sampling to get the information you need. That raises a really important question: What exactly ***is*** the information that you need? You need to know the range of moisture contents in the lumber throughout the drying cycle! Every board is different in the beginning but, as I showed earlier, the moisture contents will get more similar as drying progresses.

Wood is a natural material, so in any charge of lumber we know that:

- Different boards will have differing moisture contents;
- There will be variability in the densities of the boards, even from a single log;
- The moisture contents of the heartwood and sapwood will likely be different;
- The drying rates of heartwood and sapwood will be different;
- The drying rates of high grade boards will be different from boards with more knots;
- The drying rates of flatsawn, riftsawn and quartersawn boards will be different;
- Thick boards will dry more slowly than thin boards.

Since all of these types of boards might be present in a lumber pack or kiln charge (and sometimes with the added challenge of mixed species in your kiln), it should be obvious that there will be a range of moisture contents and drying rates represented by the boards at the beginning of drying. Your challenge is to get all the boards to the same degree of dryness, and to do it within the specifications your customer requires (perhaps 7% MC plus or minus 1%, for example).

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[16] Don't partially air dry lumber (*i.e.*, don't stop air drying at MCs above 30%), as this can lead to color differences within the wood when it's kiln dried. In maple, for example, the drier part of the wood will be white when a cross-section is cut, but the wetter core will turn darker when it is dried at the higher temperatures to which it is subjected in a dry kiln. This can create all sorts of problems between the seller and the buyer.

Sample boards are equally useful in the air drying yard and the dry kiln, so it's appropriate to select and cut them when you stack the lumber. You can use the samples to determine when air dry lumber is ready to go into the kiln.

CHOOSING SAMPLE BOARDS. Your drying quality will improve a lot if you take the time to select sample boards carefully and use them well. The boards going into your kiln have a range of initial moisture contents; some boards will dry more slowly or more quickly than the rest during drying, either because of their position in the stack or because there was something about those boards that made them dry at a different rate. Even if you are starting with green lumber, you need to have a good handle on the moisture variability in your lumber to run a kiln properly.

The question that arises, then, is this: what types of boards are present in the load, and which are important to track during drying? You're going to need to *sample* the boards in your drying packs, so it's important that your samples are appropriate. Sample boards are shorter sections cut from full-length boards that you intentionally select from the load. Don't choose the lousiest looking boards because you think that you're going to lose money cutting your better-looking boards! It's important to have the *range* of boards represented; *range* might mean quality, moisture content, grain orientation (plain or quartersawn), heartwood and sapwood, species (in a mixed charge), and (hopefully not, but it sometimes happens) thickness.

To select good sample boards, you need to be able to identify those boards that represent the extremes of the boards in your charge:

- Identify boards that will dry faster as well as those that will dry slower than the rest;
  - You need to sample more slow-drying boards than fast-drying boards, because these are the boards that will dictate how quickly you can speed up the drying conditions.
  - You need to sample the fastest-drying boards too, because these are the boards that will help you to know when to set the kiln conditions to finish drying.

- Identify boards that are wetter or drier than the rest.
  - Some air-dried lumber will be wetter or drier just because of its position in the stack.
  - Boards closer to the ground or closer to the center of the stack will probably have slightly higher moisture contents.
  - Some boards were wetter than others when they were sawn.

Boards that don't represent either the driest or the wettest boards in your load as drying progresses won't give you any information you would use to control the kiln.

Remember Figure 23 showing the simulated moisture distribution for a pack of air-dried cherry heartwood lumber? The graph shows what the moisture content distribution might look like for a load of 150 air-dried black cherry heartwood boards. The average MC in this plot is 30%.

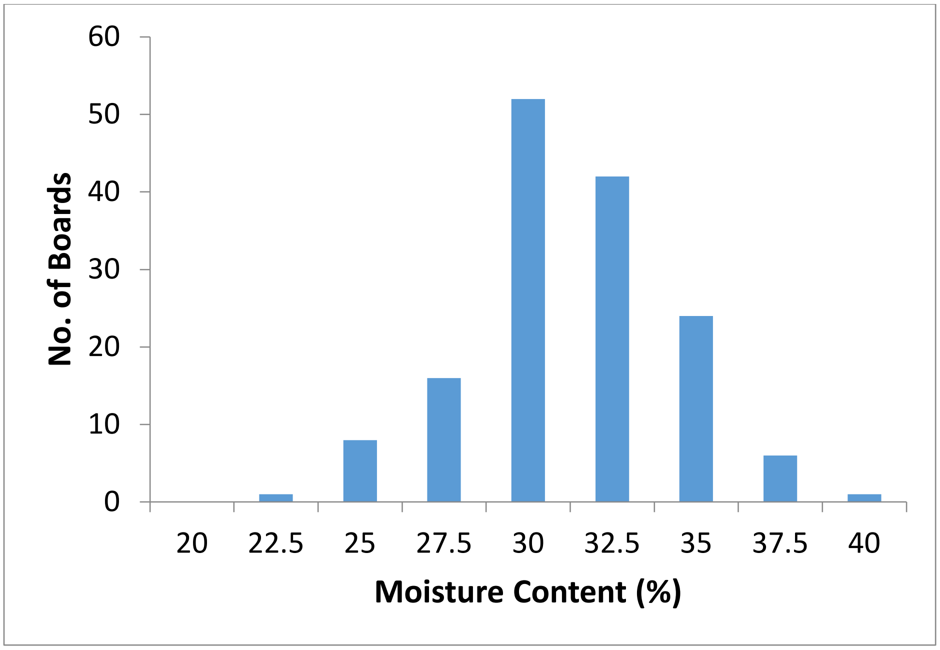

Figure 23 (repeated)*. What the moisture content distribution might look like for a load of 150 air-dried black cherry heartwood boards. In this example, I chose to use a species (black cherry) where the sawyer probably slabs off most of the sapwood, so the individual board MCs probably started out more similar than a mixed heartwood-sapwood pack. The average MC in this plot is 30%.*

If you wanted to know what the highest moisture content was with a high degree of certainty you could take a lot of samples – or you could be smarter and think more about the lumber variability and the moisture variability due to the positions of the boards in the pack.

Choose the kinds of boards to look for according to the criteria in Table 6:

Table 6. Criteria for choosing sample boards

BOARDS THAT WILL DRY MORE QUICKLY	BOARDS THAT WILL DRY MORE SLOWLY
Flatsawn boards will dry about 15% faster than quartersawn boards but will surface check lots more than quartersawn boards	Quartersawn boards
Sapwood, though it's usually wetter than heartwood	Heartwood, though it's usually drier than sapwood
Thin boards	Thick boards (8/4 lumber will dry 2½ times slower than 4/4 lumber)
Low density species	High density species
Red oak dries faster than white oak[17]	White oak dries slower than red oak
Upland oaks (growth rings narrower than ¼- ½") (Appalachian oaks are usually in this category)	Lowland oaks (wider, wavy growth rings, higher proportion of fibers)
End grain and round knots	Face and edge grain
Higher grade lumber	Lower grade lumber (dried more slowly to avoid lowering quality)

- It's particularly important to select boards that represent different species (if for some reason you mixed your load), the heartwood/sapwood in the charge, typical flatsawn/riftsawn/quartersawn boards, and any variation in lumber thickness.

- For small kilns, look for several samples that will dry the most slowly, and make at least one sample from a board that you expect will dry the fastest.

Different people use different length sample boards, though in general longer boards give you a better representation of the moisture content; two-foot sample boards are the shortest you should use. Keep in mind that you might want to recut a sample board later in the kiln run to verify that the estimated MC is correct, so it's going to be to your advantage to use longer sample boards.

[17] Don't mix air dry red oak and white oak in the dry kiln. If they both go in at the same MC, white oak will dry slower throughout the kiln run, delaying the time to complete the drying.

Cutting Sample Boards. It's important to take your sample boards from the ***center*** of the boards that you choose to represent your drying lumber. If you take the samples from the ends, they might be drier than the overall board average. Some small sawmills and dry kiln companies choose to saw and dry only 8' lumber, and if that's the case you're kind of stuck with some "shorts" from the board ends. Don't be tempted to cut corners and choose a lower-quality board or to make shorter sample boards than you might need; think to yourself, "which is going to be more expensive: the loss of a few boards, or the downgrading of the value of the entire kiln charge due to poor drying control?"

If you cannot cut a board and still leave a merchantable piece, at least attempt to cut your sample away from the end of the board. If the entire load has a lot of knotty wood ("character wood"), it's probably a good idea to sample some knotty boards, but avoid them otherwise–customers will just cut around the knots anyway, so it doesn't make sense to use these as samples.

Once you have selected and cut your sample boards, cut a one-inch moisture section from each end so you can estimate the moisture content of the entire sample board; if you use a 32" sample board, that would leave you with a 30" sample board plus your two moisture sections. Each moisture section needs to be sound and free of bark and knots. See Figure 41[18].

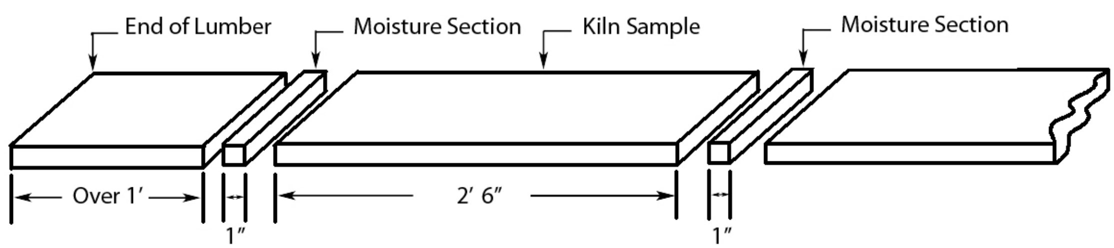

Figure 41. *Cut your moisture sections and kiln samples like this. Redrawn from Drying Hardwood Lumber.*

How Many Sample Boards Should You Use? This is a pretty common question. The number of samples chosen could be influenced by a lot of things: the value of the load, the degree to which the kiln operator is familiar with the species, the thickness and the drying schedule, the confidence the operator has in his samples, whether or not the load contains multiple species or different board thicknesses, etc. A kiln filled with narrow boards will contain more pieces than the same kiln filled with wide boards, and this might influence the operator's judgement regarding the number of samples to use as well.

Small kiln charges have fewer boards than larger kilns, but the moisture content variation is likely to be similar. That's important to remember when you're thinking about the number of kiln samples to select. Dry kiln operators running kilns of roughly 60 MBF capacity frequently use six samples (and sometimes eight), distributed at different locations in the kiln–front and back, and probably at different heights. Even using eight samples isn't going to be enough to get a good determination of the wettest lumber unless the samples are chosen deliberately and

[18] Denig, Joseph; Wengert, Eugene M.; Simpson, William T. 2000. *Drying Hardwood Lumber*. Gen. Tech. Rep. FPL–GTR–118. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 138 p. http://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr118.pdf. See Figure 7.4.

thoughtfully. A kiln operator would have to use over a dozen samples (and perhaps as many as two dozen samples) chosen randomly to find samples that represent the wettest and slowest-drying boards in the charge.

Even for small kilns, I recommend that you use at least four sample boards. Use good judgement when you select your samples –selecting the right sample boards is more important than having the right number of sample boards. Take most of your samples from the slowest-drying, wettest stock and sample the quickest-drying stock as well to be able to monitor what's happening to the lumber in the kiln throughout the run.

Your kiln probably has places that dry differently from the rest. If you have a new kiln, think about cutting extra sample boards so you can find those spots. After you know how your kiln performs you can distribute your sample boards in the slowest- and fastest-drying locations intentionally.

Determining the Moisture Contents of Sample Boards.

1) Cut your moisture sections (one inch along the grain) and kiln sample boards as shown in Figure 41.

2) Remove any loose wood and immediately weigh each of them on your low-capacity, more sensitive balance (0.1 gram sensitivity). Record their weights in a notebook and write the weights on each piece with a permanent marker as well. Put the moisture sections into an oven to dry at about 215°F.

    - If you like, speed up the drying by putting the moisture sections in a microwave oven for a couple of minutes before you put them into a convection oven. To ensure accuracy, I recommend that you not attempt to dry them to completion using only a microwave oven!

3) Don't wait for sample boards to dry out. Thickly coat both ends of your sample boards immediately with an end coating made for sample boards, such as B.O.S.S.® (Bright Orange Sample Sealer) made by ANCHORSEAL. This coating doesn't melt off at dry kiln temperatures, so if you put on a thick coating then the sample boards won't dry out any faster than the other boards in the charge.

    After applying the end coating, weigh each sample board to the nearest 5 grams (0.01 pound) or better. You will need to use your higher-capacity balance for this, because these boards might weigh 5–10 pounds (more or less, depending on the species, moisture content and size of the board).

4) Record the weights of each sample board and write these original weights directly on the boards with permanent markers as you did with the moisture sections. Because the sample boards are so heavy, the added weight of the end coating is disregarded in any weighings or calculations–accounting for the end coating weight will only change the moisture content calculation by a very small amount. Put the sample boards in a stack of lumber; for green wood especially, be sure to put them in a sample pocket where the temperature and air flow are similar to that of the rest of the lumber. This ensures that they will dry at the same rate as the rest of the lumber.

5) Ovendry the moisture sections in an oven until the weights are unchanging; remember, the oven needs to be at least 212°F to evaporate all the moisture in the sample. Calculate the MC for each section independently using Equation [3] or Equation [5] (repeated below). The moisture contents of the two moisture sections are rarely identical, though they should be similar; if they aren't, reconsider whether you made a good selection when you chose that sample board. You might have to resample your lumber.

$$MC\% = \left(\frac{Initial\ Wood\ Weight}{Ovendry\ Wood\ Weight} - 1\right)\ x\ 100\% \quad [5]$$

6) Once the MC is determined for each of the moisture sections, calculate the expected ovendry weight of your sample boards. I used a little algebra to rearrange the moisture content formula in Equation [5].

$$Ovendry\ Weight\ of\ Sample\ Board = \frac{Original\ Weight\ of\ Sample\ Board}{\left(1 + \frac{Average\ MC\%\ of\ moisture\ sections}{100}\right)} \quad [7]$$

Here's an example:

You cut two moisture sections from one sample board; moisture section #1 weighs 125 grams, and moisture section #2 weighs 163 grams. When they are dried, the weights are 80.5 grams and 104.2 grams. The calculated moisture contents are 55.2% and 56.5%, respectively, so the average MC of the moisture sections is 55.8%. You can use this value to estimate the ovendry weight of the larger sample board from which these pieces were cut.

If the weight of the sample board is 3810 grams, the ovendry weight would be estimated from Equation [7] as follows:

$$Ovendry\ Weight\ of\ Kiln\ Sample = \frac{3810\ grams}{\left(1 + \frac{55.8}{100}\right)} = 2445\ grams$$

This calculated ovendry weight should now be recorded - write it on the sample board itself with a permanent marker to be sure you don't misplace it! As the wood dries, every subsequent weighing will use this calculated dry weight to estimate the current moisture content of the sample board without actually drying it out.

For example, if at some point in your drying cycle this sample board weighed 3100 grams, you could use Equation [5] to calculate the current moisture content this way:

$$MC\% = \left(\frac{Initial\ Wood\ Weight}{Ovendry\ Wood\ Weight} - 1\right) x\ 100\% \qquad [5]$$

$$MC\% = \left(\frac{3100\ grams}{2445\ grams} - 1\right) x\ 100\% = 26.8\%$$

Using Sample Boards. At this point, you should have a record of your sample boards, their initial moisture contents and their predicted ovendry weights. Rank the boards according to their MCs; you will control your kiln conditions according to a schedule that is based on the average MC of the wettest half of your samples through most of the drying cycle. Do not make changes to your schedule based on the average moisture content of *all* your sample boards, because you can change kiln conditions too quickly and create defects in a significant portion of the kiln charge.

If you only have a few sample boards or if you didn't get a sample board from the middle of an air-dried stack, I suggest that you set your kiln conditions based on the wettest sample by itself. This is a more conservative approach, but it might more realistically give you an indication of how wet many of your boards actually are. The driest sample isn't used until close to the end of drying, where it is accounted for to avoid overdrying the load.

Placement of Sample Boards. If unseasoned sample boards are going to dry at the same rate as the lumber they represent, they need to be dried in the same conditions as the rest of the lumber. The best place to put sample boards is inside the lumber pack, but unless you have electronic kiln sample monitoring that's not a practical option because you'd have to be able to retrieve them for periodic weighing. Instead, make pockets for the sample boards; these are empty spaces long enough for your sample boards, and they're best placed along the pack sides so you can access them easily. Make the sample board pockets when you're stacking the lumber.

Sample board pockets are gaps in a layer of lumber created by shorter lengths of lumber at either end of the same row. For example, in a stack of ten-foot lumber you might have a four-foot long board and a 2' board in a layer resulting in a four foot gap where you could put a sample board. Keep the shorter lengths of lumber stickered to keep them flat; you need to put stickers below your kiln sample boards as well, but these are only going to be used to maintain the same air flow conditions as the rest of the boards. You should use shorter stickers across the pile above the sample board, because this makes it easier to pull the sample boards out and replace them. See Figure 42 below.

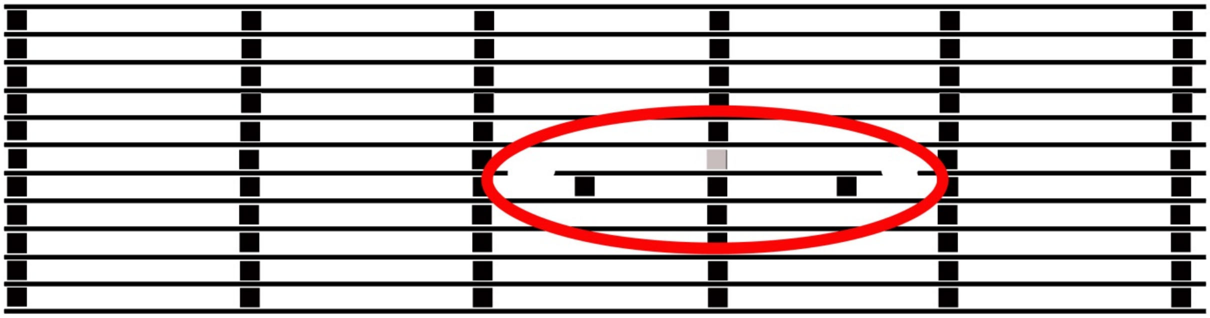

Figure 42. *This diagram shows a kiln sample pocket in a stack of ten-foot lumber. The gray sticker above the sample board should be shorter than the rest to make it easy to remove and replace the sample board. The stickers supporting the ends of the sample boards can be shorter than the rest.*

Sample boards need to be in a location where the air flow is going to be similar to the rest of the lumber, particularly for lumber above 30% MC. Mark both the sample boards as well as the surrounding lumber so you can put the sample boards back in the original locations after weighing– don't shift them around. If you know that your kiln dries differently in different locations you should take that into account as well, though a better practice would be to figure out why the drying is nonuniform and fix any issues you find.

If your kilns is built to hold only eight- or ten-foot lumber you will find that at least one of the boards on the end of the pile next to your sample board is pretty short (as in the figure above). It's tempting to put sample boards in between stacks (between the bolsters) instead of making sample pockets and short boards but the air flow and overall exposure is going to be different from what it is inside the stack.

Some people use short stickers to cantilever sample boards off the sides of previously air-dried lumber stacks for easy stacking and easy access (Figure 43). This is not a good practice for green lumber being dried in a kiln or for lumber which is being air-dried, but if you are putting well air-dried lumber (below 20–25% MC or thereabouts) into a dry kiln the placement of sample boards is less critical.

Figure 43. *Cantilevered sample boards used for lumber that has been previously air-dried.*

USING THE AIR-DRYING YARD AND/OR SHED. Air drying takes time, and it's intuitive that drying will progress faster in the summer months than in the winter months. In hot, windy conditions drying can progress too quickly for species that check easily (such as oak), so you have to be attentive.

If the lumber is drying too quickly, consider moving the lumber stacks closer together. Sometimes different parts of the air-drying yard have higher humidity than others, so if that's the case you have options for stack locations. Shade-Dri® screening cools the lumber and protects it from small gravel on the air drying yard, and many find it very useful for restricting the air flow in sheds as well. Stack alignment might affect the drying rate; one study found that aligning the boards parallel with the predominant wind direction actually gave the best airflow through the lumber.

Be cautious with slow-drying lumber. It's easy to overlook a stack of lumber that dries slowly, and one day you might find it's sprouting mushrooms. To avoid this problem, be sure that your lumber sits on a well-drained location, atop bunks that support the lumber 12"–18" above the ground (use the higher figure for sites with poor air flow or for sites with so-so drainage). Aim for enough air flow beneath the stack that the ground moisture levels won't create a biological minefield.

Make sure that vegetation is kept clear from around the base of these piles. Plants cut down the air flow and let the humidity build up under the lumber.

Finally–and this is **important**!–, remember that this lumber may be sitting in one place for several months – when you put a pile of lumber on the yard, make sure that the bunks and the stickers all line up with each other and that the stacks are level. See Figure 44.

Figure 44. *There are several problems with this stack of lumber. The stack isn't high enough off the ground, the lumber isn't supported properly all across the load, the yard is weedy, the sticker alignment could be improved and the lumber isn't all a uniform length.*

Put some sort of cover on top to keep the rain and sun off (Figure 45).

Figure 45. *Don't position your stacks like this! In spite of the obvious problem with this pile of lumber, this yard has tried to do things right. The piles have stack covers, the yard looks well-drained and free of vegetation, and the lumber is placed on double bunks to raise it off the ground.*

HOW LONG WILL AIR DRYING TAKE? The time needed for air drying depends on the species, the date and the location where the lumber is stacked. Red oak 4/4 lumber stickered in Madison, WI in January took 100 days to come to 25%, but when it was stickered in May it only took 50 days to arrive at the same MC. This should give you an idea of the variations in the length of time required, but you can refer to Table 8 in *Air Drying of Lumber* for more detailed estimates for different species in different parts of the country. The length of the effective air drying season increases the farther south you go.

The air drying rate can be controlled to some extent by moving the stacks closer or farther apart; the lumber will dry slower when the piles are closer together. If you have a large air drying yard, the stacks closest to the center often dry quickest because there aren't the obstructions blocking air flow that are commonly found close to property boundaries.

DON'T USE MOISTURE METERS TO MONITOR DRYING PROGRESS. Some drying supervisors and dry kiln operators try to use moisture meters instead of weighing sample boards when the MC drops below 30%. Moisture meters could certainly speed up the process but (like all tools) they can be used incorrectly and that can create some expensive problems. Take the time to weigh your sample boards!

Both resistance (pin type) and dielectric (pinless) moisture meters can be used inappropriately. For example, I've seen resistance meters used to measure the moisture content at board edges in air drying stacks, but I disagree with this procedure. For one thing, moisture meters aren't accurate with wet lumber. Another consideration is that the moisture content won't be symmetrical across the width of the board at the edge of the stack of lumber due to the different drying conditions on the two edges–the side of the lumber exposed to the wind, sun and rain will dry differently from the opposite edge. Erroneous readings can easily result. About all that you could reliably determine is that you will get "snake bites" along the board edges from the meter pins.

Don't use resistance meters during a dry kiln run. Resistance meters will read inaccurately unless temperature corrections are applied conscientiously, and it's very important to make corrections according to the manufacturer's recommendations.

Boards often dry nonuniformly because of grain or density differences or the presence of knots. It's always a safer and more certain practice to avoid using moisture meters to monitor lumber drying. Use sample boards.

Dielectric meters require careful application as well. I visited a fellow one day who used his dielectric moisture meter as his sole means of tracking the drying progress of lumber in his kilns. He'd been having some problems, and he asked me why he was getting different readings with the meter oriented parallel to the grain and perpendicular to the grain. The answer was pretty obvious once I took a look at his lumber. It turned out that the lumber he was working with was slightly cupped, and the amount of contact between the wood and the sensor plate differed depending on the meter orientation. I took the photos in Figures 46–48 using one of my own meters on one of his sample boards (after it had been sitting in my office for a month or so, which is one reason the meter readings are so low):

Figure 46. *Different readings with a dielectric moisture meter on the same (cupped) board. The meter is parallel to the grain in the left-hand photo and turned at 90° to the grain in the right-hand photograph.*

Dielectric meters cannot sense moisture accurately when the wood doesn't make full contact with the sensor plate (Figures 47 and 48 depict the same board used in Figure 46). It doesn't matter whether the meter and the grain orientation are aligned or not.

Figure 47. *Dielectric moisture meters cannot make an accurate reading if the electrode plate can't make full contact because the lumber is cupped. In this photo the meter is perpendicular to the grain.*

Figure 48. *Dielectric moisture meter oriented parallel to the grain on the same board as in the previous figure. Poor contact between the board and the meter electrode plate will prevent accurate moisture readings.*

FOLLOWING AND CREATING DRYING SCHEDULES

As the lumber dries in the air drying yard or kiln, the moisture content is tracked using the sample boards you prepared. There are a lot of details yet to be discussed, but in general, running a dry kiln is a lot like following a baking recipe where you start the oven at a low temperature, subsequently increase it, wait awhile and then check for doneness. For lumber, you start up the kiln at one temperature and relative humidity (a starting EMC condition), and when certain conditions are reached (a specified lower MC as determined from your wettest sample boards), the EMC is lowered (by raising the temperature and/or lowering the RH). This cycle is repeated several times.

Defect prevention and drying rate are intertwined, which is why people have created lumber drying schedules to dry different species successfully. If you kiln dry wood too quickly or too slowly you can create various defects (especially if you're drying green lumber), so both kiln companies and the USDA Forest Products Laboratory have published schedules to help. Most hardwood dry kiln operators use a moisture content-based schedule to dry their lumber, though time-based schedules are often used in the softwood lumber drying industry.

Table 7 shows what a hardwood drying schedule looks like. The following example is a schedule for 4/4 hard maple from *Drying Hardwood Lumber* (Table 7.8).

Table 7. *Drying schedule for 4/4 hard maple*

Moisture Content (%) at Start of Step	Dry Bulb (°F)	Wet Bulb (°F)	Depression (°F)	RH (%)	EMC (%)
Over 40%	130	125	5	86	16
40	130	123	7	81	14.0
35	130	119	11	71	11.5
30	140	121	19	56	8.4
25	150	115	35	35	5.1
20	160	115	45	25	3.7
15	160	115	45	25	3.7

Note that the temperature does not get very high until the end of the kiln run. Higher temperatures cause wet wood to change color and lose brightness, and brightness can be an important factor affecting the value of hard maple lumber. (This is why it's best to either air-dry maple completely or to saw it and put it into the dry kiln immediately.) There are variations on this schedule that have been worked out by different investigators, and I've included them as Appendix D in this manual.

Both *The Dry Kiln Operators Manual* and *Drying Hardwood Lumber* contain a variety of schedules for common species and thicknesses. They also describe how to compile a schedule for a wide variety of North American species, but the procedure can be a little confusing when you first look at it. I recommend that you use the schedules in *Drying Hardwood Lumber* in preference to those in the *Dry Kiln Operator's Manual.* The schedules in *Drying Hardwood Lumber* are more recent and take into account the lower quality and narrower boards that are commonly dried nowadays.

Another publication that you should know about is *Dry Kiln Schedules for Commercial Woods – Temperate and Tropical*[19]; it contains schedules for about 500 different North American and tropical species that you might refer to for less common species.

Special schedules have been formulated for achieving the whitest hard maple possible, for drying both upland and lowland red oak, for drying weak, bacterially-infected oak and so forth. These schedules work reliably, but understanding what's happening with your lumber will help you avoid the sort of problems you get when all you know is how to follow the "cookbook." Understanding how drying procedures and drying defects are related will also help you to understand and explain what happened when you receive a load of air-dried lumber from someone else that turns out to have a lot of surface checks or stain!

The schedules in both books were developed with operators of steam kilns in mind. I'll demonstrate how to modify these schedules to take advantage of the lower drying temperatures possible with DH kilns in the next section.

HOW DO CONVENTIONAL AND DEHUMIDIFICATION KILN SCHEDULES COMPARE?

You can run conventional steam kilns and dehumidification kilns on identical schedules, within the upper temperature limits of the DH equipment, but it's sometimes useful for brightness considerations to be able to take advantage of the lower temperature at which you can start to dry in a DH kiln.

To convert a conventional kiln schedule to one suitable for a dehumidification kiln, lower the starting temperature to something you're comfortable with but keep the RH% the same. If you consult the EMC chart you will find that this changes the kiln EMC very slightly (see the first lines for conventional and DH kiln schedules in Table 8 for an example). Use your common sense to increase the temperature as your sample boards dry, keeping the EMCs roughly the same as the conventional schedule you're using as a reference.

Table 8 compares a conventional steam kiln schedule with a possible DH kiln schedule for 4/4 and 5/4 upland red oak (including Appalachian red oak). (These schedules would be followed by equalization and conditioning as needed.). The DH schedule shown starts at a lower dry bulb than the conventional kiln; the RH and EMC values for each MC step are about the same as the conventional schedule until the wood is nearly dry.

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[19] Boone, R. Sidney; Kozlik, Charles J.; Bois, Paul J.; Wengert, Eugene M. 1988. *Dry kiln schedules for commercial woods-temperate and tropical*. General Technical Report FPL-GTR-57. Madison, WI: U.S. Department of Agriculture, Forest Service, Forest Products Laboratory. 158 p. http://www.fpl.fs.fed.us/documnts/fplgtr/fplgtr57.pdf

Table 8. *Conventional kiln schedule for 4/4 and 5/4 Appalachian red oak*[20]

Moisture Content	Dry Bulb (°F)	Wet Bulb (°F)	Depression (°F)	RH%	EMC
Conventional kiln					
>50	110	106	4	87	17.5
50-40	110	105	5	84	16.2
40-35	110	102	8	75	13.3
35-30	110	96	14	60	9.9
30-25	120	90	30	31	5.4
25-20	130	90	40	21	3.8
20-15	140	95	45	19	3.4
<15	160	115	45	25	3.7
DH kiln					
>50	90	86	4	85	17.3
50-40	90	85	5	81	15.9
40-35	95	88	7	75	13.9
35-30	100	87	13	59	10.1
30-25	110	82	28	30	5.4
25-20	120	82	38	19	3.7
20-15	130	90	40	21	3.8
<15	140	90	50	14	2.6

[20] Lamb, Fred M. and Eugene M. Wengert. 1990. *Techniques and procedures for the quality drying of oak lumber*. Proceedings of the Western Kiln Drying Association, pages 16–21. http://ir.library.oregonstate.edu/xmlui/bitstream/handle/1957/5242/Techniques_Procedures_ocr.pdf?sequence=1

Small DH kilns often have lower air velocities than conventional kilns, and this decreases the drying rate of green lumber. If this is the case for your kiln, you might cautiously decrease the RH in your kiln schedules to compensate for the reduced drying rate in the initial drying stages. This has the potential to create defects, so be careful.

There are some species which are not listed in any publication. For example, what would you do if you want a schedule for mulberry? And what should you do if your kiln cannot match the temperature or RH requirements of a schedule that was originally formulated for a steam kiln?

WOOD GROUPS FOR DH KILNS

Different species have different densities and different green moisture contents, and they dry safely at different rates. Lower density species tend to dry without defects more readily than high density species, for example. This means that the species, the moisture content, the amount of lumber, and the desired moisture reduction rate all have to be considered when designing and constructing a dry kiln. In conventional kilns the rate of water removal from the kiln is largely restricted by the amount of steam heat available and the size of the vent openings, but in DH kilns the water removal rate is constrained by the auxiliary heater and the compressor capacity. Undersized compressors will not be able to remove water vapor quickly enough for the kiln relative humidity to decrease as water is evaporated, and mold and mildew can result if the relative humidity climbs above 70% or so.[21] This means that the initial moisture content, the volume of lumber in the kiln and the ease of water removal from that species must all be considered in kiln design (particularly with regard to the size of the compressor) and subsequent use.

Oversized compressors are less efficient than properly-sized compressors, so DH kiln manufacturers usually recommend compressors that will work for most kiln charges even if they are slightly undersized for drying full loads of some species at high moisture contents. Many hardwood lumber charges fall into one of three categories: 1) they have a middling green moisture content; 2) they are initially air-dried; or 3) they have to be dried fairly slowly to avoid defects. Water removal rates for loads such as these will be moderate and DH kilns will not require high-capacity compressors. On the other hand, some low-density hardwood species and some softwood species such as the pines can be readily dried with few defects, but these species have high green moisture contents and give up their water quickly. To dry green lumber from these species while keeping the RH below 70% you have only two options: you either have to buy a larger compressor than you'd buy for drying air-dried oak or you have to load the DH kiln with a smaller volume. If these aren't typical loads it makes sense to downsize the kiln charge for fast-drying high moisture content hardwoods instead of increasing the compressor size.

The ease with which water can be removed (and the potential for stain and/or mildew) is the basis for the idea of **wood groups** (as used by Nyle, a major manufacturer of DH kiln equipment).

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[21] Pearl, Virginia. 1996. *How to prevent and remove mildew*. University of Florida IFAS Extension. FCS3042. Found online at http://edis.ifas.ufl.edu/pdffiles/HE/HE63300.pdf.

Here's a summary of some different species in wood groups (these are for 4/4 lumber):

Group 1: Pine, fir, cedar, and low-density hardwoods such as basswood, cottonwood, poplar (including yellow-poplar), and aspen that can be dried quickly

Group 2: Ash, beech, birch, black cherry, American and red elms, black gum, sweet gum, hard and soft maples, walnut.

Group 3: Rock elm, red and white oaks

LOADING DH KILNS ACCORDING TO WOOD GROUPS. For Group 3 species, a compressor size of about 1/2 HP per 1000 board feet is sufficient to dry at a good rate, but for species that depend on fast drying to minimize stain or mold you'll need to downsize the kiln charge. For example, 4000 bf of a Group 3 species could be dried with a two horsepower compressor, but you should downsize the load to 2500–3000 board feet for Group 2 species and to 1500 board feet for Group 1 species. This increases the efficiency of the compressor and increases the drying rate per board foot per day while comfortably controlling the kiln relative humidity.

Because some mills saw uncommon species for craft and custom furniture makers, sometimes you have to make your own best estimate of how to load the kiln. As an example, I'd guess that holly probably should be in either Group 1 or Group 2 because it stains readily unless dried very quickly after sawing, though there are conflicting reports about whether it is due to a blue stain fungus or a chemical reaction. Reports from some wood turners suggest that it can be dried as quickly as maple.

MAXIMUM MOISTURE LOSS PER DAY

In the manual which accompanies their dry kilns, Nyle states that "Drying Group 1 woods at a rate of less than 5% per day may result in mold or staining of the lumber. Drying Group 3 woods at a rate greater than 3.5% per day may result in checking or other degrade to the lumber." That's excellent advice.

Two tables have been published to help you determine if you are drying at a safe rate. The first list of species and thicknesses was published by Dr. Gene Wengert and has been reproduced in numerous publications since at least 1980. His recommendation for 8/4 walnut has become slightly more conservative over time, and the latest version of his recommendations is published in *Drying Hardwood Lumber (*See Table 9).

Table 9. *Safe drying rates for North American hardwoods*

SPECIES	MAXIMUM RATE OF MC LOSS PER DAY (%)	
	4/4 LUMBER	8/4 LUMBER
Ash, White	10.4	4.1
Beech	4.5	1.8
Birch, yellow	6.1	2.4
Cherry	5.8	2.3
Elm, American (White)	10.4	4.1
Maple, hard	6.5	2.6
Maple, soft (sapwood)	13.8	5.5
Oak, red, upland	3.8	1.5
Oak, red, lowland	1.0–3.8	–
Oak, white, upland	2.5	1.0
Sweet gum	5.3	2.1
Tupelo/Black gum	10.9	4.3
Walnut	8.2	3.3
Yellow-poplar	13.8	5.5

Nyle started with Dr. Wengert's list and expanded it for a number of northeastern species (see the far right column in Table 10)[22]. A good starting point might be to try to get about 75% of the listed maximum moisture losses per day. Aim for a slightly lower maximum loss rate for lower quality or more variable wood. This table is for 4/4 lumber; to estimate the maximum moisture content loss per day for other thicknesses, Nyle suggests multiplying the maximum MC loss per day from this table by 0.6 for 6/4 lumber and by 0.4 for 8/4 lumber.

Use your fastest-drying samples to compare your drying rate to the table above. Most kiln operators running DH kilns never attempt to dry at the maximum rates listed in this table. Trying to dry lumber too quickly only increases the chances for drying problems.

Table 10. *Useful species information, with acceptable maximum moisture content (%) loss per day for northeastern 4/4 lumber*

Softwoods					
SPECIES	**OVENDRY WEIGHT #/MBF**	**AVE. GREEN MC%**	**GREEN WEIGHT #/MBF**	**# WATER LOST PER 1% MC**	**MAX. MC% LOSS PER DAY**
Cedar, eastern white	1578	93	3046	16	11
Fir, balsam	1739	118	3790	17	20
Hemlock, eastern	2161	111	4558	22	20
Larch, eastern	2532	52	3849	25	20
Pine, red (Norway)	2051	83	3747	21	15
Pine, eastern white	1950	90	3705	20	12
Spruce, black	2110	80	3798	21	20
Spruce, red	2000	89	3781	20	20
Spruce, white	1840	115	3967	18	20

[22] http://www.nyle.com/downloads/L200Manual_Web.pdf, pages 2-5 and 2-6

Hardwoods					
SPECIES	**OVENDRY WEIGHT #/MBF**	**AVE. GREEN MC%**	**GREEN WEIGHT #/MBF**	**# WATER LOST PER 1% MC**	**MAX. MC% LOSS PER DAY**
Ash, white	3055	45	4431	31	10.4
Basswood	1899	107	3933	19	12
Beech	3114	63	5089	31	4.5
Birch, white	2692	73	4659	27	10
Birch, yellow	2954	69	4996	30	6.1
Cherry, black	2633	58	4161	26	5.8
Elm, rock	3165	50	4760	32	3.5
Elm, white	2692	93	5207	27	10.4
Hickory	3325	64	5452	33	6
Maple, hard	3165	68	5317	32	6.5
Maple, soft	2692	93	4389	27	13.8
Oak, northern (upland)	3277	74	5703	33	3.8
Oak, white (upland)	3518	70	5981	35	2.5
Oak, southern red (lowland)	3092	80	5567	31	3.8
Sweetgum	2740	100	5480	27	5.3
Walnut, black	2851	85	5274	29	8.2
Yellow-poplar, Cottonwood	1899	154	4819	19	13.8

WHAT SHOULD YOU DO WHEN DRYING APPEARS TO SLOW DOWN OR STOP?

If you're paying attention to your sample boards, you'll notice that the drying rate slows down as they approach 20%–25% moisture content or thereabouts. Don't panic. This is perfectly normal.

If your wettest sample board is still losing moisture, your kiln is operating correctly. People sometimes get flustered when the average rate of MC change starts to slow down (but you shouldn't be controlling the kiln based on the average MC of all the sample boards in any event).

The slowdown you observe occurs because of the rates of water removal for free water and bound water are different. The wetter boards have more free water initially, so the rate of water loss is faster than for drier boards, which have mostly bound water. The overall daily average MC change might be slight, but the kiln is still drying.

TROUBLESHOOTING A DRYING SLOWDOWN. What would you do if you found that your wettest sample board is only losing 0.5%-0.75% per day? If you don't think your kiln charge is drying as quickly as it should, the first thing to do is to double-check your equipment. It's possible that your kiln conditions aren't really what you think they are.

1. **Check the wet bulb wick**, making sure it's clean and well-moistened, has good air flow, and is properly connected.
2. **Check your dry bulb thermometer** and its connections as well; if you have a reliable, calibrated backup hygrometer, use it to verify the readings you're getting with your primary equipment.
3. **Check your fans** to be sure they are turning properly; at this moisture level the air flow isn't as important to your drying rate as at higher MCs, but if the fans or baffles have problems your wet bulb may not be getting enough air flow to respond properly.
4. **Verify that your baffles are in place**.
5. **Take a look at your sample boards** if everything else looks good so far: maybe your wettest sample board is in a slow-drying part of your kiln.
6. **Consider if you might have made a mistake with the sample boards**; could your original MC or calculated dry weight be in error? It's not uncommon to have a board that looks like an outlier when you only use a few sample boards to control the kiln, but if the kiln starts to slow down and you can't figure out what's going on, it would make sense to confirm that the sample board(s) you're using to monitor the kiln is really at the MC you think it's supposed to be.

POTENTIAL SAMPLE BOARD PROBLEMS. Sometimes sample boards aren't handled with the attention they require – phone calls, customers, all sorts of things might interrupt you. Occasionally these normal business activities result in sample boards being put aside to await a "better" time, or maybe the way you handle them just gets hurried up a bit. What could go wrong?

Besides getting the original or calculated dry weights recorded incorrectly, I've observed that sample board handling problems generally fall into just a couple of categories: 1) the board ends don't get coated thickly enough with B.O.S.S.®. They dry out faster and consequently the boards have a less uniform MC from end to end compared to the rest of the kiln charge; 2) boards sometimes get set aside after they're cut or in-between weighings once the kiln has been started up.

In both of these cases, you run the risk of your boards drying faster than the rest of the charge. Depending on how bad the problem is, you might advance the kiln conditions too quickly for the load, causing drying defects.

The biggest reason to coat sample board ends with B.O.S.S.® is to make the sample board moisture loss rate mimic that of your full-length boards (whether end coated or not). Even so, if you start noticing lumber drying defects starting to develop but your sample boards aren't drying at a worrisome rate, start investigating.

INTERMEDIATE MOISTURE CHECKS. The only way to find out if your sample boards are at the moisture content you think they are is to perform an intermediate moisture content check. You might be able to use a moisture meter, but the best thing to do would be to cut a new moisture wafer from the sample board and dry it to find out how close your calculations have been.

Try this: If the end coat on your sample board failed it's possible that there's a moisture gradient between the ends and the middle of the board. Cut a new moisture wafer roughly one-third of the distance from one of the board ends to the center. In other words, if the original sample board was 30" long, then cut a new moisture wafer 5" from one end. A wafer taken at that location ought to represent the average moisture content of the board. If you don't have a moisture gradient then it wouldn't matter which position the new moisture wafer came from, but that's still a good location. Slather the cut end of the remaining sample board with B.O.S.S.® and reweigh it.

Ovendry the wafer at 215°F until it reaches a constant weight and redo your moisture calculations for the ovendry weight of your shortened sample board. If the sample is drier than you thought, the ends of your sample board probably dried out faster than the rest of your sample. This means that the remainder of the sample board isn't typical of the rest of the load anymore, and you need to disregard that sample for the remainder of the drying run.

You might decide to cut and prepare new sample boards from other boards in the charge. If you do, take as much care in picking new sample boards as you did earlier. Quartersawn boards are still probably the slowest-drying boards in your load, but it's hard to predict whether sapwood boards (that started out wetter) or heartwood boards (that started out drier) have the higher moisture content at this point. Remember to think about where the wettest boards might be in your kiln, and try to resample from that location if possible.

"FIXING" A SLOW-DRYING LOAD OF LUMBER (ACCELERATING A DRYING SCHEDULE). If the drying rate is slow but you've proven to yourself that your equipment is working correctly and that your sample boards are adequate, what options do you have? Probably the best thing to do would be to adjust the schedule a little. You might raise the dry bulb temperature by a few degrees for example (though this weakens the wood and might cause problems if your moisture content is high). Raising the dry bulb temperature increases the rate of heat transfer, but you have to mind the wet bulb setting as well. If you keep the size of the WB depression the same, raising the dry bulb temperature will increase both the RH and the EMC–and since the EMC controls the drying rate, the kiln will actually run more slowly. (You can see this for yourself by referring back to Table 3.)

You're going to need more information than is found in other dry kiln manuals to make these changes, so I calculated the RH and EMC values for combinations of dry bulb temperatures from 115° to 160° and for wet bulb depressions from 20–50°. Table 11 shows only a portion of this table (DB from 120°–130°F). RH values are integers and are shown in bold type, and the EMC values are given to tenths of a percent moisture content and are shown in italics. Only the even dry bulb temperatures are shown, but you will find that there is seldom a significant change in EMC due to a 2°F dry bulb change. You could always interpolate if you think it's necessary. **(*See Appendix E for the table displaying the wider temperature range.*)**

Here's an example of how to use this table based on the schedule for red oak in Table 7. Let's assume that you are drying with a 120°F dry bulb and that your wet bulb is 82°F (a depression of 38°). This is equivalent to an RH of 19% and an EMC of 3.7%. If you wanted to increase your drying rate slightly you might change the dry bulb to 124°F; if you kept a 38° depression (an 86°F wet bulb) , your RH would now be 21% and your EMC would be 3.9% (see the highlighted boxes). IF you controlled the kiln this way, you'd actually be slowing the kiln down! If you had kept your wet bulb set at 82°F, however, your new wet bulb depression would be greater than formerly (42°); your new RH would be 16% and your new EMC would be 3.0% and drying will speed up.

Table 11. *RH and EMC table for a selected range of dry bulb temperatures and wet bulb depressions. (See Appendix E for the complete table.)* The text example is highlighted.

	WB Depression (°F) (Relative humidity (%) in bold font, *EMC* (%) in italics)																													
DB °F	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50
120	49	47	45	44	42	40	38	36	35	33	31	30	28	27	25	24	22	21	19	18	17	16	14	13	12	11	10	8	7	6	5
	7.9	7.7	7.4	7.2	6.8	6.6	6.3	6.1	5.8	5.6	5.4	5.3	5.0	4.9	4.6	4.5	4.2	4.0	3.7	3.5	3.3	3.2	2.9	2.7	2.6	2.3	2.3	1.8	1.6	1.3	1.1
122	50	48	46	44	42	41	39	37	35	34	32	31	29	27	26	25	23	22	20	19	18	17	15	14	13	12	11	9	8	7	6
	7.9	7.7	7.4	7.2	6.8	6.6	6.4	6.2	5.9	5.7	5.4	5.3	5.1	4.8	4.7	4.5	4.3	4.1	3.8	3.6	3.4	3.2	2.9	2.8	2.6	2.4	2.2	1.9	1.7	1.5	1.3
124	51	49	47	45	43	41	39	38	36	34	33	31	30	28	27	25	24	23	21	20	19	17	16	15	14	13	12	11	9	8	7
	7.9	7.7	7.5	7.2	6.9	6.7	6.4	6.2	5.9	5.7	5.5	5.2	5.1	4.9	4.7	4.5	4.4	4.2	3.9	3.7	3.5	3.2	3.0	2.9	2.7	2.6	2.4	2.2	1.8	1.6	1.5
126	51	49	47	45	44	42	40	38	37	35	34	32	31	29	28	26	25	23	22	21	20	18	17	16	15	14	13	12	10	9	8
	8.0	7.8	7.5	7.3	6.9	6.7	6.5	6.3	6.0	5.8	5.5	5.3	5.2	4.9	4.8	4.6	4.4	4.1	4.0	3.8	3.6	3.3	3.2	3.0	2.9	2.7	2.5	2.4	2.0	1.8	1.6
128	52	50	48	46	44	43	41	39	37	36	34	33	31	30	28	27	26	24	23	22	20	19	18	17	16	15	14	12	11	10	9
	8.0	7.8	7.6	7.3	7.0	6.8	6.5	6.3	6.0	5.8	5.6	5.5	5.2	5.1	4.8	4.7	4.5	4.2	4.1	4.0	3.7	3.5	3.4	3.2	3.0	2.9	2.7	2.3	2.2	2.0	1.8
130	52	50	48	47	45	43	41	40	38	37	35	34	32	31	29	28	26	25	24	23	21	20	19	18	17	15	14	13	12	11	10
	8.0	7.8	7.6	7.3	7.0	6.8	6.6	6.4	6.1	5.9	5.6	5.5	5.3	5.2	4.9	4.8	4.6	4.4	4.2	4.1	3.8	3.7	3.5	3.4	3.3	3.0	2.8	2.6	2.4	2.2	2.0

"SHOCKING THE KILN". For over 100 years some people have thought that kiln slowdowns are due to pushing the kiln a little too fast while liquid water is evaporating. If the surface dries out while water remains in the center, the pathways used to transport water to the surface become interrupted and ineffective – or so the thinking goes. Drying actually isn't "interruptible"; kiln slowdowns *must* happen as the wood dries, even with a very gentle drying schedule. At some point the wet line will recede below the surface no matter what kiln conditions are in use. If the kiln operator is controlling by the wettest sample(s) and not by the average MC, and if the kiln control mechanisms and sample boards have checked out, then, according to the laws of thermodynamics, the lumber must still be drying!

"Shocking" the kiln is a procedure that some people use to induce a higher drying rate after a slowdown, typically in the range of 15 to 20% moisture content. This is exactly where we normally expect drying to proceed at a slower rate, but if drying slows at this point some advocate for turning the compressor off, raising the dry bulb to 150°F, and adding water to the kiln (as a fine spray or even as a wash on the floor). The RH and EMC conditions increase according to the amount of water added to the kiln chamber. These high temperature-higher humidity conditions are maintained for a day or so before the dry bulb is lowered again. Practitioners state that the drying rate increases after this type of treatment.

Shocking the kiln doesn't increase the drying rate for the reasons that people think. What's happening is that the lumber is being heated to a much hotter dry bulb than formerly and, since a higher dry bulb increases the amount of water vaporized, a greater amount of water is removed from the sample boards when the compressor is turned back on.

There are good reasons not to add water during drying. Tiemann[23] noted that steaming lumber during kiln drying didn't increase the overall drying rate and in fact sometimes caused checking and warping in oak. Additionally, if a dry lumber surface is rewetted while the interior is wet, it's possible for the surface swelling stresses to exceed the wood strength and honeycomb will result. This is the reason why it's important not to increase the EMC during the kiln schedule.

All in all, if the drying rate slows down to an unacceptable rate, it's far better to raise the dry bulb temperature and adjust the kiln schedule as described previously than to add water back into the dry kiln!

[23] Tiemann, H.D. 1917. *The Kiln Drying of Lumber*, 2nd edition. J.B. Lippincott Company, Philadelphia. 318 pages.

STARTING THE DRY KILN: A STEP-BY-STEP GUIDE

"80% of kiln drying problems are developed before the lumber ever goes in the kiln." – Joe Denig

AIR-DRIED LUMBER: As my friend Joe indicated, a lot of lumber quality problems originate in the air-drying yard. Look over your lumber for drying problems (such as surface- or end-checking) before transferring your lumber to the dry kiln. If you see problems, try to learn from your mistakes so you don't repeat them. End checks, for example, might be caused by placing stickers too far from the ends of the boards, or maybe the end coating you applied wasn't put on thickly enough.

1. Select a drying schedule according to the species and thickness of the lumber you plan to dry. Don't use the schedules in the Dry Kiln Operator's Manual; we tend to put more lower-quality lumber in our dry kilns today than dry kiln operators did in the past, and those schedules can be too aggressive for modern lumber. Use a schedule from *Drying Hardwood Lumber* - or select a schedule provided by your kiln manufacturer. Plan to decrease the severity of your schedule if you see checking or if you suspect the lumber has been mishandled in some manner. How you change the schedule is up to you, but you could choose to modify the schedule by starting out at a lower temperature with a smaller depression or you could change the EMC conditions more slowly, for example.

2. Measure the surface moisture content of your lumber with a pin-type moisture meter; put the pins in only as far as you need to get decent contact (about 1/16") and take the reading of the shell MC. Remember to orient the pins according to the manufacturer's directions. Measure about 20 pieces to get a good feel for what the surface moisture content really is. Expect to see a variation of up to 5% or so. To avoid rewetting the lumber, your kiln's starting EMC has to be set lower than the shell MC, so take your time and get good readings.

3. Take a moment to be sure that your wet bulb and dry bulb thermometers or sensors are in good condition, then do a quick check on the fans. Load the dry kiln and make sure that the baffles direct the air flow through the stacks of lumber; baffle placement is especially important for wet lumber.

4. Check on the locations of your sample boards. It might help to mark the location with a bit of fluorescent chalk or something similar if you have them in sample pockets. Make sure your sample boards are numbered; it's convenient to number them in a logical sequence, left to right perhaps, because you want to replace them in the same locations they came from after you weigh them.

5. Start the dry kiln at an EMC condition that is 1% to 2% drier than the surface MC.

6. Over the next day or so, gradually work your way up to the settings in your schedule.

LET'S WORK THROUGH AN EXAMPLE. Say you want to kiln dry some air-dried 4/4 red oak. Let's assume that you are running a 4000 BF kiln with only a few sample boards and that (based on moisture sections) your sample boards have MCs of 16%, 19%, 21% and 22%. Red oak is a Group 3 species, so you can fill a DH kiln completely.

Four well-chosen sample boards may be enough for most drying runs in small kilns. With only a few sample boards, though, you have a higher risk of undersampling your lumber than if you used a greater number. In this example, I would have to assume that 22% truly represents a significant portion of the lumber. Because it's wetter than the others, use that sample's MC to set your kiln conditions unless or until it becomes drier than one of the others; if that happens, switch to the newly-wettest sample for controlling your kiln conditions.

There are a number of good reasons why you might want to use more than just a few sample boards. For example, you might be running a larger kiln and want a better handle on moisture variation or you might know that your kiln dries unevenly in different locations. You might also be drying a species that you have less familiarity with, you could be drying a load of mixed species or boards with a high variation in the amount of sapwood and heartwood, or the lumber is thicker or more valuable. These are all good reasons to use more sample boards. If any of these situations apply and you choose to increase the number of sample boards you use, you could calculate your controlling MC by taking the average moisture content of the wettest half of your sample boards. (That's the moisture content that the kiln schedules are based on.)

In this example, since I assumed that the lumber is in a small kiln I am going to be conservative and use 22% as representative of the wettest half of the lumber. The next thing to do is to figure out which schedule to use and what conditions I should use at startup.

Use the schedule for 4/4 red oak in Table 12 (Table 7.12, *Drying Hardwood Lumber*).

Table 12. Kiln schedule for 4/4 and 5/4 red oak*

Table 7.12—Kiln schedules for green, air-dried, or predried red oak—northern, Appalachian, or upland[a]

	4/4 and 5/4 (T3–D2)			6/4 and 8/4 (T3–D1)		
Initial MC (%)	Dry-bulb temperature (°F)	Wet-bulb depression (°F)	Wet-bulb temperature (°F)	Dry-bulb temperature (°F)	Wet-bulb depression (°F)	Wet-bulb temperature (°F)
>50	110	4	106	110	3	107
50	110	5	105	110	4	106
40	110	8	102	110	6	104
35	110	14	96	110	10	100
30	120	30	90	120	25	95
25	130	40	90	130	40	90
20	140	45	95	140	45	95
15	160	45	115	160	45	115
Equalize	170	43	127	170	43	127
Condition	180	10	170	180	10	170

[a]For all oak species, 6/4 stock is usually dried by the 8/4 schedule.

* Source: *Drying Hardwood Lumber*, Table 7.12.

The first thing to do is to compare the MC of the wettest sample board MC (22%) to the MCs in the schedule. The 22% sample board is between 25% and 20%; it isn't quite down to the 20% level yet, so you would enter the schedule for 4/4 red oak at the 25% line (see the box in Table 12) to identify the first set of prescribed conditions: a dry bulb of 130°F with a depression of 40° (a 90° F wet bulb) This corresponds to a 21% RH and an EMC of 3.9% (Appendix D). Since this is air-dried lumber we're putting in the kiln, we ought to check to be sure that we aren't going to rewet the lumber surface. This is the time to take pin meter readings of the outermost wood. Let's assume you've done that and the *average* moisture reading was 12%. That's the normal sort of reading you should expect for air-dried lumber, and that means that you're all set! The kiln EMC is going to be lower than the MC of the shell moisture content, and that's what's important.

You don't have to (and maybe even shouldn't) put the lumber into the kiln and immediately use the prescribed schedule condition; this is one of the places where the *art* of lumber drying enters the picture.

GETTING TO THE RECOMMENDED DRY BULB AND WET BULB CONDITIONS. What's the wood temperature on your air drying yard? Does it makes sense to you to take wood that's been sitting there and heat it up to 130°F right away? Since the surface MC is at 12% perhaps you're more comfortable getting to the set point in smaller steps instead of exposing the lumber to the stress of a 3.8% EMC right away. Maybe you think you might have trouble getting your kiln to the prescribed temperature and RH conditions for some reason.

The most important thing to know is this: you have options. There's several things you could do to adjust your schedule.

Dehumidification kiln compressors won't work unless the kiln chamber is at least 80°F, so if the lumber is cold you should use some auxiliary heat source (like an indirectly-aimed torpedo heater or electric heater) to warm up the lumber in the kiln before you turn on the compressor. Conventional (steam) kilns have to get over 100°F to get much water to vaporize (which is then removed by venting). The significance of this comparison is that you can begin to dry at lower temperatures in a DH kiln, and that's good for lumber quality. If you have a DH kiln, therefore, you might choose to use a lower dry bulb temperature to begin with. The kiln controls will let you start out with a depression of just a few degrees if you need to, but regardless of the dry bulb temperature a small depression would result in too high an EMC value for this example–it's very important to avoid rewetting the lumber surface.

You'll be okay with any starting kiln EMC that's lower than the surface moisture content, but remember that the 12% surface MC reading given in the example was an *average* value. To avoid rewetting the lumber you should assume that you have a significant amount of lumber with a surface MC that's a bit drier (ex., one to two percent lower), so it's best to start the kiln at an EMC that's below that 12% average MC. You always have options, but you might start the kiln at something like a 100°F dry bulb and a 13° depression (87° wet bulb, 59% RH) (EMC=10.1%) and gradually work the temperature up as you increase the depression.[24]

What will your target DB/WB settings actually be? Once again, you have options! You could choose a 130°F dry bulb with a 30° WB depression (100°F WB) for your intended setting instead of the prescribed 40° depression in the above schedule (5.6% EMC instead of a 3.8% EMC). That 5.6% EMC is just a bit higher than the EMC value you'd probably use to equalize your lumber (5%) anyway. There's nothing wrong with this, but you have to be comfortable with the drying delay that will result compared to the more assertive schedule. If there's something about the load that suggests that you ought to be a little more conservative, there's no reason not to set your dry bulb to 120°F instead – it's all up to you!

[24] The lowest wet bulb temperature you can set on a Nyle DH kiln is 68° F, and the highest wet bulb you can safely use is 120° F.

Even though you're changing the kiln conditions slowly, the lumber is drying the whole time. After a day or so your wettest sample board might be down to 20% - maybe. You're going to have to check it to find out. (Weigh ***all*** of your sample boards to make sure you've got a good handle on what your highest MC is among your sample boards. Remember: Don't use a moisture meter, rely on actual weights.) When your wettest sample board gets to 20% MC the schedule says that you can go up to 140°F dry bulb and 3.4% EMC. Keep changing the kiln settings according to the schedule as the sample boards and the lumber dry; the wood gets stronger as it dries so you can increase the severity of the conditions safely. It won't hurt to go slowly if that's your preference, but keep an eye on that driest sample board, because that's the one that's going to tell you when to wrap up the drying phase and move onto moisture equalization and drying stress relief (conditioning).

GREEN LUMBER

1. Start the kiln according to the moisture content of the sample boards. If it's green lumber, you probably will be initiating the kiln conditions at the beginning of the schedule. Most of the procedures are going to be the same as for air-dried lumber, but for green lumber it is much more important that the sample boards are located in places where the air flow is similar to that of the stickered lumber.

APPENDIX A: A FEW MOISTURE CONTENT CALCULATION PROBLEMS FOR PRACTICE

1. Original weight = 101.74 grams
   Dry weight = 63.27 g
   Calculate the moisture content.

   Use equation [3] or equation [5].
   Answer = 60.8%

2. Original weight = 21.62 g
   Dry weight = 18.56 g
   Calculate the moisture content.

   Use equation [3] or equation [5].
   Answer = 16.5%

3. Original weight = 251.03 g
   Dry weight = 150.61 g
   Calculate the moisture content.

   Use equation [3] or equation [5].
   Answer = 66.7%

4. Original weight = 79.23 g
   Dry weight = 50.19 g
   Calculate the moisture content.

   Use equation [3] or equation [5].
   Answer = 57.9%

5. Original weight = 67.45 g
   Dry weight = 52.20 g
   Calculate the moisture content.

   Use equation [3] or equation [5].
   Answer = 29.2%

6. Original weight = 3101.7 g
From moisture sections, the MC=24.6%
What's the ovendry weight?

Use equation [7].
Answer = 2489.3 g

7. Original weight = 5405 g
From moisture sections, the MC=41.6%
What's the ovendry weight?

Use equation [7].
Answer = 3817.1 g

8. Original weight = 4261.1 g
From moisture sections, the MC=30.7%
What's the ovendry weight?

Use equation [7].
Answer = 3260.2 g

9. Original weight = 7195 g
From moisture sections, the MC=46.0%
What's the ovendry weight?

Use equation [7].
Answer = 4928.1 g

10. Original weight = 6310 g
From moisture sections, the MC=21.9%
What's the ovendry weight?

Use equation [7].
Answer = 5176.4 g

APPENDIX B: RH AND EMC TABLE FOR A RANGE OF DRY BULB TEMPERATURES AND WET BULB DEPRESSIONS

	WB Depression (°F) **(Relative humidity in bold font,** *EMC in italics***)**																						
DB °F	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***	***21***	***22***	***23***
30	**89**	**78**	**67**	**57**	**46**	**36**	**27**	**17**	**6**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
	-	*15.9*	*12.9*	*10.8*	*9*	*7.4*	*5.7*	*3.9*	*1.6*	*-*	*-*	*-*	*-*	*-*	*-*	*-*	*-*	*-*	*-*	*-*	*-*	*-*	*-*
35	**90**	**81**	**72**	**63**	**54**	**45**	**37**	**28**	**19**	**11**	**3**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
	-	*16.8*	*13.9*	*11.9*	*10.3*	*8.8*	*7.4*	*6*	*4.5*	*2.9*	*0.8*	*-*	*-*	*-*	*-*	*-*	*-*	*-*	*-*	*-*	*-*	*-*	*-*
40	**92**	**83**	**75**	**68**	**60**	**52**	**45**	**37**	**29**	**22**	**15**	**8**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
	-	*17.6*	*14.8*	*12.9*	*11.2*	*9.9*	*8.6*	*7.4*	*6.2*	*5*	*3.5*	*1.9*	*-*	*-*	*-*	*-*	*-*	*-*	*-*	*-*	*-*	*-*	*-*
45	**93**	**85**	**78**	**72**	**64**	**58**	**51**	**44**	**37**	**31**	**25**	**19**	**12**	**6**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
	-	*18.3*	*15.6*	*13.7*	*12*	*10.7*	*9.5*	*8.5*	*7.5*	*6.5*	*5.3*	*4.2*	*2.9*	*1.5*	*-*	*-*	*-*	*-*	*-*	*-*	*-*	*-*	*-*
50	**93**	**86**	**80**	**74**	**68**	**62**	**56**	**50**	**44**	**38**	**32**	**27**	**21**	**16**	**10**	**5**	**-**	**-**	**-**	**-**	**-**	**-**	**-**
	-	*19*	*16.3*	*14.4*	*12.7*	*11.5*	*10.3*	*9.4*	*8.5*	*7.6*	*6.7*	*5.7*	*4.8*	*3.9*	*2.8*	*1.5*	*-*	*-*	*-*	*-*	*-*	*-*	*-*
55	**94**	**88**	**82**	**76**	**70**	**65**	**60**	**54**	**49**	**44**	**39**	**34**	**28**	**24**	**19**	**14**	**9**	**5**	**-**	**-**	**-**	**-**	**-**
	-	*19.5*	*16.9*	*15.1*	*13.4*	*12.2*	*11*	*10.1*	*9.3*	*8.4*	*7.6*	*6.8*	*6*	*5.3*	*4.5*	*3.6*	*2.5*	*1.3*	*-*	*-*	*-*	*-*	*-*

60	**94**	**89**	**83**	**78**	**73**	**68**	**63**	**58**	**53**	**48**	**43**	**39**	**34**	**30**	**26**	**21**	**17**	**13**	**9**	**5**	**1**	**-**	**-**
	-	*19.9*	*17.4*	*15.6*	*13.9*	*12.7*	*11.6*	*10.7*	*9.9*	*9.1*	*8.3*	*7.6*	*6.9*	*6.3*	*5.6*	*4.9*	*4.1*	*3.2*	*2.3*	*1.3*	*0.2*	-	-
65	**95**	**90**	**84**	**80**	**75**	**70**	**66**	**61**	**56**	**52**	**48**	**44**	**39**	**36**	**32**	**27**	**24**	**20**	**16**	**13**	**8**	**6**	**2**
	-	*20.3*	*17.8*	*16.1*	*14.4*	*13.3*	*12.1*	*11.2*	*10.4*	*9.7*	*8.9*	*8.3*	*7.7*	*7.1*	*6.5*	*5.8*	*5.2*	*4.5*	*3.8*	*3*	*2.3*	*1.4*	*0.4*
70	**95**	**90**	**86**	**81**	**77**	**72**	**68**	**64**	**59**	**55**	**51**	**48**	**44**	**40**	**36**	**33**	**29**	**25**	**22**	**19**	**15**	**12**	**9**
	-	*20.6*	*18.2*	*16.5*	*14.9*	*13.7*	*12.5*	*11.6*	*10.9*	*10.1*	*9.4*	*8.8*	*8.3*	*7.7*	*7.2*	*6.6*	*6*	*5.5*	*4.9*	*4.3*	*3.7*	*2.9*	*2.3*
75	**95**	**91**	**86**	**82**	**78**	**74**	**70**	**66**	**62**	**58**	**54**	**51**	**47**	**44**	**41**	**37**	**34**	**31**	**28**	**24**	**21**	**18**	**15**
	-	*20.9*	*18.5*	*16.8*	*15.2*	*14*	*12.9*	*12*	*11.2*	*10.5*	*9.8*	*9.3*	*8.7*	*8.2*	*7.7*	*7.2*	*6.7*	*6.2*	*5.6*	*5.1*	*4.7*	*4.1*	*3.5*
80	**96**	**91**	**87**	**83**	**79**	**75**	**72**	**68**	**64**	**61**	**57**	**54**	**50**	**47**	**44**	**41**	**38**	**35**	**32**	**29**	**26**	**23**	**20**
	-	*21*	*18.7*	*17*	*15.5*	*14.3*	*13.2*	*12.3*	*11.5*	*10.9*	*10.1*	*9.7*	*9.1*	*8.6*	*8.1*	*7.7*	*7.2*	*6.8*	*6.3*	*5.8*	*5.4*	*5*	*4.5*
85	**96**	**92**	**88**	**84**	**80**	**76**	**73**	**70**	**66**	**63**	**59**	**56**	**53**	**50**	**47**	**44**	**41**	**38**	**36**	**33**	**30**	**28**	**25**
	-	*21.2*	*18.8*	*17.2*	*15.7*	*14.5*	*13.5*	*12.5*	*11.8*	*11.2*	*10.5*	*10*	*9.5*	*9*	*8.5*	*8.1*	*7.6*	*7.2*	*6.7*	*6.3*	*6*	*5.6*	*5.2*
90	**96**	**92**	**89**	**85**	**81**	**78**	**74**	**71**	**68**	**65**	**61**	**58**	**55**	**52**	**49**	**47**	**44**	**41**	**39**	**36**	**34**	**31**	**29**
	-	*21.3*	*18.9*	*17.3*	*15.9*	*14.7*	*13.7*	*12.8*	*12*	*11.4*	*10.7*	*10.2*	*9.7*	*9.3*	*8.8*	*8.4*	*8*	*7.6*	*7.2*	*6.8*	*6.5*	*6.1*	*5.7*
95	**96**	**92**	**89**	**85**	**82**	**79**	**75**	**72**	**69**	**66**	**63**	**60**	**57**	**55**	**52**	**49**	**46**	**44**	**42**	**39**	**37**	**34**	**32**
	-	*21.3*	*19*	*17.4*	*16.1*	*14.9*	*13.9*	*12.9*	*12.2*	*11.6*	*11*	*10.5*	*10*	*9.5*	*9.1*	*8.7*	*8.2*	*7.9*	*7.5*	*7.1*	*6.8*	*6.4*	*6.1*
100	**96**	**93**	**89**	**86**	**83**	**80**	**77**	**73**	**70**	**68**	**65**	**62**	**59**	**56**	**54**	**51**	**49**	**46**	**44**	**41**	**39**	**37**	**35**
	-	*21.3*	*19*	*17.5*	*16.1*	*15*	*13.9*	*13.1*	*12.4*	*11.8*	*11.2*	*10.6*	*10.1*	*9.6*	*9.2*	*8.9*	*8.5*	*8.1*	*7.8*	*7.4*	*7*	*6.7*	*6.4*

105	**96**	**93**	**90**	**87**	**83**	**80**	**77**	**74**	**71**	**69**	**66**	**63**	**60**	**58**	**55**	**53**	**50**	**48**	**46**	**44**	**42**	**40**	**37**
	-	*21.4*	*19*	*17.5*	*16.2*	*15.1*	*14*	*13.3*	*12.6*	*11.9*	*11.3*	*10.8*	*10.3*	*9.8*	*9.4*	*9*	*8.7*	*8.3*	*7.9*	*7.6*	*7.3*	*6.9*	*6.7*
110	**97**	**93**	**90**	**87**	**84**	**81**	**78**	**75**	**73**	**70**	**67**	**65**	**62**	**60**	**57**	**55**	**52**	**50**	**48**	**46**	**44**	**42**	**40**
	-	*21.4*	*19*	*17.5*	*16.2*	*15.1*	*14.1*	*13.3*	*12.6*	*12*	*11.4*	*10.8*	*10.4*	*9.9*	*9.5*	*9.2*	*8.8*	*8.4*	*8.1*	*7.7*	*7.5*	*7.2*	*6.8*
115	**97**	**93**	**90**	**88**	**85**	**82**	**79**	**76**	**74**	**71**	**68**	**66**	**63**	**61**	**58**	**56**	**54**	**52**	**50**	**48**	**45**	**43**	**41**
	-	*21.4*	*19*	*17.5*	*16.2*	*15.1*	*14.1*	*13.4*	*12.7*	*12.1*	*11.5*	*10.9*	*10.4*	*10*	*9.6*	*9.3*	*8.9*	*8.6*	*8.2*	*7.8*	*7.6*	*7.3*	*7*
120	**97**	**94**	**91**	**88**	**85**	**82**	**80**	**77**	**74**	**72**	**69**	**67**	**65**	**62**	**60**	**58**	**55**	**53**	**51**	**49**	**47**	**45**	**43**
	-	*21.3*	*19*	*17.4*	*16.2*	*15.1*	*14.1*	*13.4*	*12.7*	*12.1*	*11.5*	*11*	*10.5*	*10*	*9.7*	*9.4*	*9*	*8.7*	*8.3*	*7.9*	*7.7*	*7.4*	*7.2*
125	**97**	**94**	**91**	**88**	**86**	**83**	**80**	**77**	**75**	**73**	**70**	**68**	**65**	**63**	**61**	**59**	**57**	**55**	**53**	**51**	**48**	**47**	**45**
	-	*21.2*	*18.9*	*17.3*	*16.1*	*15*	*14*	*13.4*	*12.7*	*12.1*	*11.5*	*11*	*10.5*	*10*	*9.7*	*9.4*	*9*	*8.7*	*8.3*	*8*	*7.7*	*7.5*	*7.2*
130	**97**	**94**	**91**	**89**	**86**	**83**	**81**	**78**	**76**	**73**	**71**	**69**	**67**	**64**	**62**	**60**	**58**	**56**	**54**	**52**	**50**	**48**	**47**
	-	*21*	*18.8*	*17.2*	*16*	*14.9*	*14*	*13.4*	*12.7*	*12.1*	*11.5*	*11*	*10.5*	*10*	*9.7*	*9.4*	*9*	*8.7*	*8.3*	*8*	*7.8*	*7.6*	*7.3*
140	**97**	**95**	**92**	**89**	**87**	**84**	**82**	**79**	**77**	**75**	**73**	**70**	**68**	**66**	**64**	**62**	**60**	**58**	**56**	**54**	**53**	**51**	**49**
	-	*20.7*	*18.6*	*16.9*	*15.8*	*14.8*	*13.8*	*13.2*	*12.5*	*11.9*	*11.4*	*10.9*	*10.4*	*10*	*9.6*	*9.4*	*9*	*8.7*	*8.4*	*8*	*7.8*	*7.6*	*7.3*
150	**98**	**95**	**92**	**90**	**87**	**85**	**82**	**80**	**78**	**76**	**74**	**72**	**70**	**68**	**66**	**64**	**62**	**60**	**58**	**57**	**55**	**53**	**51**
	-	*20.2*	*18.4*	*16.6*	*15.4*	*14.5*	*13.7*	*13*	*12.4*	*11.8*	*11.2*	*10.8*	*10.3*	*9.9*	*9.5*	*9.2*	*8.9*	*8.6*	*8.3*	*8*	*7.8*	*7.5*	*7.3*
160	**98**	**95**	**93**	**90**	**88**	**86**	**83**	**81**	**79**	**77**	**75**	**73**	**71**	**69**	**67**	**65**	**64**	**62**	**60**	**58**	**57**	**55**	**53**
	-	*19.8*	*18.1*	*16.2*	*15.2*	*14.2*	*13.4*	*12.7*	*12.1*	*11.5*	*11*	*10.6*	*10.1*	*9.7*	*9.4*	*9.1*	*8.8*	*8.5*	*8.2*	*7.9*	*7.7*	*7.4*	*7.2*

APPENDIX C: IDENTIFYING THE END OF CONDITIONING

The following table may prove useful. It originated with Jim Steen of Pike Lumber Company, Akron, Indiana, who gave a copy to Dr. Daniel Cassens of Purdue. It should be useful to help identify casehardening and moisture gradient problems based on the prong test.

Remember that “casehardened movement” occurs when the prongs in a prong test move inwards; “reverse casehardened movement” occurs when the prongs move outwards. This table was originally published in Cassens, D.L. 2002. Quality control in lumber purchasing: Lumber stress/casehardening. Purdue University Forestry and Natural Resources Timber Processing Publication FNR-132. 4 pages.

1. **Immediate Observation:** No Movement
   - a. **Delayed Observation:** No Movement. (No stress or moisture gradient problems.)
   - b. **Delayed Observation:** Movement Occurs.
     - i. Casehardening Movement. (Indicates that the core moisture content is higher than shell moisture content, which could indicate that the piece was stress relieved before the core reached the target moisture content and the subsequent movement is a result of the inside surface of the prong test shrinking.) This type of movement also occurs early in the drying cycle when the shell has started to set but the core has not.
     - ii. Reverse Casehardening Movement. (Indicates that the shell moisture content was higher than that of the core, and that it was offsetting the effect of reverse casehardening.) This type of situation would be rare, but in theory, it is possible.
2. **Immediate Observation:** Casehardened Movement.
   - a. **Delayed Observation:** No Further Movement. (Indicates that casehardening exists, and there is no moisture gradient.) This is caused by not conditioning or not fully conditioning a kiln charge of lumber.
   - b. **Delayed Observation:** Further Movement Occurs.
     - i. Further Casehardening Occurs. (Indicates that in addition to casehardening that the core was of higher moisture content than the shell.) This can occur when the final target moisture content was not reached in the core of the piece, and then it was either improperly or not at all conditioned.
     - ii. Casehardening Eases. (Indicates that although there is some failure to properly condition the piece, part of the initial movement is the result of the shell being of higher moisture content than the core.) This is common and is usually caused by improper storage somewhere in combination with inadequate conditioning.
     - iii. Casehardening Disappears. (Indicates that the shell is of higher moisture content than the core.) More than likely, this is the result of poor storage conditions.
3. **Immediate Observation:** Reverse Casehardening Movement.
   - a. **Delayed Observation:** No Further Movement. (Indicates that reverse casehardening has occurred and that there is not a problem with moisture gradient.) This usually results from over conditioning of the piece.
   - b. **Delayed Observation:** Further Movement Occurs.
     - i. Further Reverse Casehardening Occurs. (Indicates that shell moisture content was greater than core moisture content.) A scenario would be that over conditioned lumber was stored for an undetermined period in a higher than 6-8 percent moisture content area.
     - ii. Reverse Casehardening Eases. (Indicates that core moisture content was higher in the core than in the shell and at the same time over conditioned.) This could occur if lumber that was over conditioned was moved to a drier than 6-8 percent moisture content area for an undetermined amount of time before testing.
     - iii. Reverse Casehardening Disappears. (Indicates that the moisture content of the core was higher than the shell for some reason.) A scenario might be that correctly conditioned lumber was stored for an undetermined period in a place drier than 6-8 percent moisture content.

APPENDIX D: HARD MAPLE DRYING SCHEDULES FOR WHITE WOOD

Besides the Dry Kiln Operator's Manual, other investigators have published schedules for drying hard maple when the whitest possible wood is desired.

Here's a schedule from Joe Denig, which he stated is good for both 4/4 and 5/4 lumber:

MC%	Dry Bulb (°F)	Wet Bulb (°F)	EMC%
>40%	105	95	12.0
40-35	108	95	10.4
35-20	108	90	8.3
20-16	115	90	6.4
16-12	125	90	4.6
<12	160	105	2.9

Here's another version, from some research done at the USDA Forest Products Laboratory in the 1970s[25]

Table 1.—Kiln schedule to produce whitest 4/4 and 5/4 sugar maple

Moisture content at start of step	Dry-bulb temperature[1]	Wet-bulb depression[2]	Wet-bulb temperature
Pct	°F	°F	°F
A—FOR INITIAL MOISTURE CONTENT 50 PERCENT OR LOWER			
Above 28	105	10	95
28	108	13	95
24	108	18	90
20	108	23	85
16	115	35	80
13	125	45	80
10	160	55	105
Conditioning[3] ±12 hrs.	170	16	154
B—FOR INITIAL MOISTURE CONTENT 51 PERCENT OR HIGHER			
Above 40	105	10	95
40	108	13	95
35	108	18	90
30	108	23	85
26	108	28	80
20	115	35	80
16	125	45	80
12	160	55	105
Conditioning[3] ±12 hrs.	170	16	154

[1] If wet-bulb depressions stated cannot be obtained at these temperatures, raise the dry-bulb temperatures just enough to obtain the depressions.

[2] Air-dried stock below 24 pct moisture content that has undergone surface moisture regain by rain or prolonged high humidity should be run 12 to 16 hours on a 10° to 13°F wet-bulb depression, then shifted to the depression corresponding to the moisture content.

[3] These conditions are for a final moisture content of 5 pct. If a different final moisture content value is desired, the kiln operator should adjust wet-bulb depressions. A 7 pct moisture content was attained with 4/4 stock by 4 hours at 165°F, 15°F wet-bulb depression, followed by 6 hours at 170°F, 7½° wet-bulb depression.

[25] McMillen, John M. 1976. Control of reddish-brown coloration in drying maple sapwood. USDA Forest Service Research Note FPL 0231.

APPENDIX E: RH AND EMC TABLE FOR A SELECTED RANGE OF DRY BULB TEMPERATURES AND WET BULB DEPRESSIONS

	WB Depression (°F)																													**(Relative humidity in bold font, *EMC in italics*)**
DB °F	***20***	***21***	***22***	***23***	***24***	***25***	***26***	***27***	***28***	***29***	***30***	***31***	***32***	***33***	***34***	***35***	***36***	***37***	***38***	***39***	***40***	***41***	***42***	***43***	***44***	***45***	***46***	***47***	***48***	***49***	***50***
115	**48**	**46**	**44**	**42**	**40**	**38**	**36**	**34**	**33**	**31**	**29**	**27**	**26**	**24**	**23**	**21**	**20**	**18**	**17**	**16**	**14**	**13**	**12**	**10**	**9**	**8**	**7**	**5**	**4**	**3**	**2**
	7.8	*7.6*	*7.3*	*7.0*	*6.7*	*6.5*	*6.2*	*5.9*	*5.6*	*5.4*	*5.2*	*4.9*	*4.7*	*4.5*	*4.4*	*4.1*	*3.9*	*3.6*	*3.4*	*3.2*	*2.9*	*2.7*	*2.5*	*2.1*	*1.9*	*1.7*	*1.5*	*1.1*	*0.8*	*0.6*	*0.4*
116	**48**	**46**	**44**	**42**	**40**	**38**	**36**	**35**	**33**	**31**	**30**	**28**	**26**	**25**	**23**	**22**	**20**	**19**	**17**	**16**	**15**	**13**	**12**	**11**	**10**	**8**	**7**	**6**	**5**	**4**	**3**
	7.8	*7.6*	*7.3*	*7.0*	*6.7*	*6.5*	*6.2*	*5.9*	*5.6*	*5.4*	*5.2*	*5.0*	*4.8*	*4.7*	*4.4*	*4.3*	*4.0*	*3.8*	*3.5*	*3.2*	*3.0*	*2.6*	*2.5*	*2.3*	*2.2*	*1.8*	*1.6*	*1.3*	*1.1*	*0.8*	*0.5*
118	**49**	**47**	**45**	**43**	**41**	**39**	**37**	**36**	**34**	**32**	**30**	**29**	**27**	**26**	**24**	**23**	**21**	**20**	**18**	**17**	**16**	**14**	**13**	**12**	**11**	**10**	**8**	**7**	**6**	**5**	**4**
	7.9	*7.7*	*7.4*	*7.2*	*6.8*	*6.6*	*6.3*	*6.1*	*5.8*	*5.6*	*5.4*	*5.2*	*4.9*	*4.8*	*4.6*	*4.4*	*4.1*	*4.0*	*3.6*	*3.4*	*3.2*	*2.9*	*2.7*	*2.5*	*2.4*	*2.2*	*1.8*	*1.6*	*1.4*	*1.2*	*1.0*
120	**49**	**47**	**45**	**44**	**42**	**40**	**38**	**36**	**35**	**33**	**31**	**30**	**28**	**27**	**25**	**24**	**22**	**21**	**19**	**18**	**17**	**16**	**14**	**13**	**12**	**11**	**10**	**8**	**7**	**6**	**5**
	7.9	*7.7*	*7.4*	*7.2*	*6.8*	*6.6*	*6.3*	*6.1*	*5.8*	*5.6*	*5.4*	*5.3*	*5.0*	*4.9*	*4.6*	*4.5*	*4.2*	*4.0*	*3.7*	*3.5*	*3.3*	*3.2*	*2.9*	*2.7*	*2.6*	*2.3*	*2.3*	*1.8*	*1.6*	*1.3*	*1.1*

122	**50**	**48**	**46**	**44**	**42**	**41**	**39**	**37**	**35**	**34**	**32**	**31**	**29**	**27**	**26**	**25**	**23**	**22**	**20**	**19**	**18**	**17**	**15**	**14**	**13**	**12**	**11**	**9**	**8**	**7**	**6**
	7.9	*7.7*	*7.4*	*7.2*	*6.8*	*6.6*	*6.4*	*6.2*	*5.9*	*5.7*	*5.4*	*5.3*	*5.1*	*4.8*	*4.7*	*4.5*	*4.3*	*4.1*	*3.8*	*3.6*	*3.4*	*3.2*	*2.9*	*2.8*	*2.6*	*2.4*	*2.2*	*1.9*	*1.7*	*1.5*	*1.3*
124	**51**	**49**	**47**	**45**	**43**	**41**	**39**	**38**	**36**	**34**	**33**	**31**	**30**	**28**	**27**	**25**	**24**	**23**	**21**	**20**	**19**	**17**	**16**	**15**	**14**	**13**	**12**	**11**	**9**	**8**	**7**
	7.9	*7.7*	*7.5*	*7.2*	*6.9*	*6.7*	*6.4*	*6.2*	*5.9*	*5.7*	*5.5*	*5.2*	*5.1*	*4.9*	*4.7*	*4.5*	*4.4*	*4.2*	*3.9*	*3.7*	*3.5*	*3.2*	*3.0*	*2.9*	*2.7*	*2.6*	*2.4*	*2.2*	*1.8*	*1.6*	*1.5*
126	**51**	**49**	**47**	**45**	**44**	**42**	**40**	**38**	**37**	**35**	**34**	**32**	**31**	**29**	**28**	**26**	**25**	**23**	**22**	**21**	**20**	**18**	**17**	**16**	**15**	**14**	**13**	**12**	**10**	**9**	**8**
	8.0	*7.8*	*7.5*	*7.3*	*6.9*	*6.7*	*6.5*	*6.3*	*6.0*	*5.8*	*5.5*	*5.3*	*5.2*	*4.9*	*4.8*	*4.6*	*4.4*	*4.1*	*4.0*	*3.8*	*3.6*	*3.3*	*3.2*	*3.0*	*2.9*	*2.7*	*2.5*	*2.4*	*2.0*	*1.8*	*1.6*
128	**52**	**50**	**48**	**46**	**44**	**43**	**41**	**39**	**37**	**36**	**34**	**33**	**31**	**30**	**28**	**27**	**26**	**24**	**23**	**22**	**20**	**19**	**18**	**17**	**16**	**15**	**14**	**12**	**11**	**10**	**9**
	8.0	*7.8*	*7.6*	*7.3*	*7.0*	*6.8*	*6.5*	*6.3*	*6.0*	*5.8*	*5.6*	*5.5*	*5.2*	*5.1*	*4.8*	*4.7*	*4.5*	*4.2*	*4.1*	*4.0*	*3.7*	*3.5*	*3.4*	*3.2*	*3.0*	*2.9*	*2.7*	*2.3*	*2.2*	*2.0*	*1.8*
130	**52**	**50**	**48**	**47**	**45**	**43**	**41**	**40**	**38**	**37**	**35**	**34**	**32**	**31**	**29**	**28**	**26**	**25**	**24**	**23**	**21**	**20**	**19**	**18**	**17**	**15**	**14**	**13**	**12**	**11**	**10**
	8.0	*7.8*	*7.6*	*7.3*	*7.0*	*6.8*	*6.6*	*6.4*	*6.1*	*5.9*	*5.6*	*5.5*	*5.3*	*5.2*	*4.9*	*4.8*	*4.6*	*4.4*	*4.2*	*4.1*	*3.8*	*3.7*	*3.5*	*3.4*	*3.3*	*3.0*	*2.8*	*2.6*	*2.4*	*2.2*	*2.0*
132	**53**	**51**	**49**	**47**	**45**	**44**	**42**	**40**	**39**	**37**	**36**	**34**	**33**	**31**	**30**	**29**	**27**	**26**	**25**	**23**	**22**	**21**	**20**	**19**	**17**	**16**	**15**	**14**	**13**	**12**	**11**
	8.0	*7.8*	*7.6*	*7.3*	*7.0*	*6.8*	*6.6*	*6.4*	*6.1*	*5.9*	*5.6*	*5.4*	*5.3*	*5.1*	*4.9*	*4.8*	*4.6*	*4.4*	*4.2*	*4.0*	*3.9*	*3.7*	*3.6*	*3.5*	*3.2*	*3.1*	*2.9*	*2.7*	*2.5*	*2.3*	*2.1*
134	**53**	**51**	**49**	**48**	**46**	**44**	**43**	**41**	**39**	**38**	**36**	**35**	**33**	**32**	**31**	**29**	**28**	**27**	**25**	**24**	**23**	**22**	**20**	**19**	**18**	**17**	**16**	**15**	**14**	**13**	**12**
	8.0	*7.8*	*7.6*	*7.3*	*7.0*	*6.8*	*6.6*	*6.4*	*6.1*	*5.9*	*5.7*	*5.6*	*5.3*	*5.2*	*5.0*	*4.8*	*4.7*	*4.5*	*4.3*	*4.1*	*3.9*	*3.8*	*3.5*	*3.4*	*3.3*	*3.2*	*3.0*	*2.8*	*2.6*	*2.4*	*2.2*
136	**54**	**52**	**50**	**48**	**46**	**45**	**43**	**42**	**40**	**38**	**37**	**35**	**34**	**33**	**31**	**30**	**29**	**27**	**26**	**25**	**24**	**22**	**21**	**20**	**19**	**18**	**17**	**16**	**15**	**14**	**13**
	8.0	*7.8*	*7.6*	*7.3*	*7.1*	*6.9*	*6.6*	*6.4*	*6.2*	*6.0*	*5.7*	*5.5*	*5.4*	*5.2*	*5.0*	*4.9*	*4.7*	*4.5*	*4.3*	*4.2*	*4.0*	*3.7*	*3.6*	*3.5*	*3.4*	*3.2*	*3.1*	*2.9*	*2.7*	*2.5*	*2.4*
138	**54**	**52**	**50**	**49**	**47**	**45**	**44**	**42**	**41**	**39**	**38**	**36**	**35**	**33**	**32**	**31**	**29**	**28**	**27**	**25**	**24**	**23**	**22**	**21**	**20**	**19**	**18**	**17**	**16**	**15**	**14**
	8.0	*7.8*	*7.6*	*7.3*	*7.1*	*6.9*	*6.6*	*6.4*	*6.2*	*6.0*	*5.8*	*5.5*	*5.4*	*5.2*	*5.1*	*5.0*	*4.8*	*4.6*	*4.4*	*4.1*	*4.0*	*3.9*	*3.8*	*3.6*	*3.5*	*3.3*	*3.2*	*3.0*	*2.8*	*2.6*	*2.5*
140	**54**	**53**	**51**	**49**	**48**	**46**	**44**	**43**	**41**	**40**	**38**	**37**	**35**	**34**	**32**	**31**	**30**	**29**	**27**	**26**	**25**	**24**	**23**	**22**	**20**	**19**	**18**	**17**	**16**	**15**	**14**
	8.0	*7.8*	*7.6*	*7.3*	*7.1*	*6.9*	*6.6*	*6.4*	*6.2*	*6.0*	*5.8*	*5.7*	*5.4*	*5.3*	*5.1*	*5.0*	*4.8*	*4.7*	*4.4*	*4.3*	*4.1*	*4.0*	*3.9*	*3.8*	*3.5*	*3.4*	*3.2*	*3.1*	*2.9*	*2.8*	*2.6*

142	55	53	51	50	48	46	45	43	42	40	39	37	36	34	33	32	30	29	28	27	26	24	23	22	21	20	19	18	17	16	15
	8.0	7.8	7.6	7.3	7.1	6.9	6.6	6.4	6.2	6.0	5.8	5.5	5.4	5.2	5.1	5.0	4.8	4.6	4.4	4.3	4.1	3.9	3.8	3.7	3.6	3.4	3.3	3.1	3.0	2.8	2.7
144	55	54	52	50	48	47	45	44	42	41	39	38	36	35	34	32	31	30	29	27	26	25	24	23	22	21	20	19	18	17	16
	8.0	7.8	7.6	7.3	7.1	6.9	6.6	6.4	6.2	6.0	5.8	5.7	5.4	5.3	5.1	4.9	4.8	4.6	4.4	4.2	4.1	4.0	3.9	3.7	3.6	3.5	3.3	3.2	3.0	2.9	2.7
146	56	54	52	51	49	47	46	44	43	41	40	38	37	36	34	33	32	30	29	28	27	26	25	24	22	21	20	19	18	17	17
	8.0	7.8	7.5	7.3	7.1	6.9	6.7	6.4	6.2	6.0	5.8	5.5	5.4	5.3	5.2	5.0	4.9	4.6	4.5	4.3	4.2	4.1	3.9	3.8	3.6	3.5	3.3	3.2	3.0	2.8	2.8
148	56	54	53	51	49	48	46	45	43	42	40	39	37	36	35	34	32	31	30	29	27	26	25	24	23	22	21	20	19	18	17
	8.0	7.8	7.5	7.3	7.1	6.9	6.7	6.4	6.2	6.0	5.8	5.7	5.4	5.3	5.2	5.1	4.9	4.7	4.5	4.4	4.2	4.1	3.9	3.8	3.7	3.6	3.4	3.3	3.1	3.0	2.8
150	57	55	53	51	50	48	47	45	44	42	41	39	38	37	35	34	33	32	30	29	28	27	26	25	24	23	22	21	20	19	18
	8.0	7.8	7.5	7.3	7.1	6.9	6.7	6.4	6.2	6.0	5.8	5.5	5.4	5.3	5.2	5.0	4.9	4.8	4.5	4.4	4.2	4.1	4.0	3.8	3.7	3.6	3.5	3.3	3.2	3.0	2.9
152	57	55	53	52	50	49	47	46	44	43	41	40	38	37	36	35	33	32	31	30	29	27	26	25	24	23	22	21	20	19	18
	8.0	7.8	7.5	7.3	7.1	6.9	6.7	6.4	6.2	6.0	5.8	5.7	5.4	5.3	5.2	5.1	4.9	4.7	4.5	4.4	4.2	4.0	3.9	3.8	3.7	3.6	3.5	3.4	3.2	3.1	3.0
154	57	56	54	52	51	49	48	46	45	43	42	40	39	38	36	35	34	33	31	30	29	28	27	26	25	24	23	22	21	20	19
	8.0	7.8	7.5	7.3	7.1	6.9	6.7	6.4	6.2	6.0	5.8	5.6	5.4	5.4	5.2	5.1	4.9	4.8	4.5	4.4	4.2	4.1	4.0	3.9	3.8	3.6	3.5	3.4	3.3	3.1	3.0
156	58	56	54	53	51	49	48	46	45	44	42	41	39	38	37	36	34	33	32	31	30	29	27	26	25	24	23	22	21	21	20
	7.9	7.7	7.4	7.2	7.0	6.8	6.7	6.4	6.2	6.0	5.8	5.7	5.5	5.3	5.2	5.1	4.9	4.7	4.6	4.4	4.3	4.2	4.0	3.9	3.8	3.7	3.5	3.4	3.2	3.2	3.1
158	58	56	55	53	51	50	48	47	45	44	43	41	40	39	37	36	35	34	32	31	30	29	28	27	26	25	24	23	22	21	20
	7.9	7.7	7.4	7.2	7.0	6.8	6.7	6.4	6.2	6.0	5.8	5.6	5.5	5.4	5.2	5.1	4.9	4.8	4.6	4.4	4.3	4.2	4.0	3.9	3.8	3.7	3.6	3.5	3.4	3.2	3.1
160	58	57	55	53	52	50	49	47	46	44	43	42	40	39	38	37	35	34	33	32	31	30	29	27	26	25	24	24	23	22	21
	7.9	7.7	7.4	7.2	7.0	6.8	6.7	6.4	6.2	6.0	5.8	5.7	5.5	5.3	5.2	5.1	4.9	4.8	4.6	4.5	4.3	4.2	4.1	3.9	3.8	3.7	3.6	3.6	3.5	3.3	3.2

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