Wood charcoal Charcoal briquettes have limited markets in the USA, but they can be readily manufactured from waste wood. A disadvantage is the difficulty in preventing high rates of air pollution in charcoal manufacture.

Wood pellets Wood pellets are made from dry wood residues, and, optimally, they are made from wood with a minimum of bark. Pellets are a desirable form of wood fuel, and modern stoves and furnaces for burning pellets have automatic feed and control modules. Pellets may therefore be burned without undue exertion. Moreover they are usually cost-effective, and the combustion units are reliable. Usually there is little ash, especially if excessive amounts of bark in pellet manufacture are avoided.

Animal Bedding

When wood is placed in contact with soil, the action of bacteria in the decomposition of the soil traps much of the soil nitrogen. This can cause a condition known as 'nitrogen starvation' for plants growing in the soil. An attractive solution for this problem is to use the wood as animal bedding prior to spreading it on the soil. Wood bedding reduces manure runoff and helps to control odors.

Dry wood, especially that from planer shavings, tends to get dusty and is good for poultry bedding and some other domestic animal bedding.

Although the smell of cedar makes it a preferred species for use in home pet care, other species may be used. The freedom from splinters and the clean smell of aspen and cottonwood make them desirable for some animals, including mink that are raised for fur production.

See also: **Non-wood Products**: Energy from Wood. **Packaging, Recycling and Printing**: Paper Recycling Science and Technology. **Wood Use and Trade**: Environmental Benefits of Wood as a Building Material.

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Drying

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History of Wood Drying

Evidence exists in furniture, carvings, and artwork that survive from millennia ago that the importance of drying and how wood responds to changing ambient conditions has long been recognized. Until the turn of the twentieth century, however, only limited quantities of wood were artificially (kiln) dried. Natural (air) drying was generally sufficient because the practice of heating all rooms in a house was not common. The smoke kiln was developed in Europe 200 to 250 years ago. As the name implies, a fire burned under a perforated floor and the wood was stacked above the floor. In the late nineteenth century, humidity was added to help control the drying rate. A few smoke kilns were still in use in the United States in 1926, but they had disappeared in Europe.

The lumber dry kiln as we know it today has its origins in the late nineteenth and early twentieth century. By the time of World War I, drying methods had been established and texts from the 1920s have much the same basic information as those written today. Since that time our understanding of what happens at the cellular level has advanced, improvements have been made in the equipment, and techniques have been developed for many species. The advancement of other types of dryers, for example veneer and particle dryers, was in parallel with the development of these industries during the twentieth century.

Why Wood is Dried

It is generally desirable for the shrinkage associated with moisture loss to occur before products are produced. For example, furniture parts will not fit together if they change moisture content after manufacturing. It is most desirable to dry the wood to the moisture content it will eventually achieve in service. This depends on relative humidity at the location of installation and varies from summer to winter, but ranges from 5% to 15% for indoor applications. In temperate climates, 7% to 9% is a common indoor equilibrium moisture content.

As wood dries, some defects such as splitting and warping are likely to happen in some pieces. It is desirable for these to occur prior to using the wood in an appearance application.

In some cases wood is dried to improve its ability to accept adhesives, paints, preservative treatments, or finishes. Moisture content is critical for adhesive penetration and most surface coatings need to be applied over dry wood. The quality of a machined surface will not be good if the moisture content is not correct for the machine tools. The strength of wood increases as it is dried. This allows dry wood to be assigned higher strength properties than green wood in some applications. If green wood is used at the dry wood design values, excessive deflection or even failure might result before it has a chance to dry in service.

When sufficiently high temperatures are used, insects and their eggs are killed as are some fungi. The temperatures normally used in kiln drying are sufficient to accomplish this as well as set the pitch. When the wood is at 20% or less in moisture content, fungal attack is prevented and most insects lose interest in the wood. Setting the pitch means that the wood resins no longer flow at in-service temperatures. For some species the drying process gives a desirable color to the wood, for example in walnut (*Juglans* spp.), maple (*Acer* spp.), and red alder (*Alnus rubra*). Drying also reduces the shipping weight.

How Water Moves in Wood

For wood with a wet surface, a boundary layer of air near the surface of the wood limits the drying rate. Increased airflow reduces the thickness of the boundary layer and lower relative humidity increases the driving force for mass transfer across it. This boundary layer is most important for small pieces of wood, such as particles or veneer, for which the internal resistance to drying is minimal and when the moisture content is high.

Moisture moves from wetter areas to dryer areas. Within the wood, free (liquid) water can move through the capillary structure if the wood is permeable enough. This can keep the surface wet and the drying rate high. This mode of mass transfer is important in fast-drying woods such as the pines (*Pinus* spp.). Capillary forces, and to a certain extent heating of the wood, cause pressure gradients which result in free water movement. Smaller capillaries tend to pull water from large capillaries so that evaporation from pits near the surface can pull water from the interior of the wood. Once some cells lose most of the free water, a continuous pathway of water is no longer present and moisture cannot move as a liquid.

Water can also diffuse through the wood as a vapor or in the bound state. Vapor diffusion requires a continuous gaseous pathway such as open vessels or cell lumens connected by unaspirated pits. Bound water diffusion occurs through the cell wall material. While vapor diffusion coefficients are much greater than bound water diffusion coefficients, the pathways for vapor diffusion are small compared with those for bound water. Therefore, bound water diffusion dominates moisture movement at low moisture contents. The difference between the equilibrium moisture content and the wood moisture content is often used as the driving force for diffusion at moisture contents below fiber saturation. Diffusion rates increase with increasing temperature, moisture content, and wood permeability. High temperatures (70°C and higher) are used as the wood gets low in moisture content to prevent prolonged drying times.

All modes of moisture movement may be occurring simultaneously at different locations within a piece of wood. Near the center of a piece the moisture content might be high enough for free water movement to occur. At some plane the moisture content is too low to support free water movement and the liquid water evaporates. From there it can move to the surface in the vapor or bound phase.

Lumber

Lumber refers to wood that is typically greater than 5 mm in thickness and sawn. It is either air dried, kiln dried, or dried by a sequence of these. In either type of drying the wood is stacked so that there is airflow around each piece. In developing regions, lumber may be air dried by leaning the pieces almost vertically against a support. In industrial facilities, it is common to lay the pieces horizontally and use narrow strips of dry wood as spacers (**Figure 1**). These are called stickers or fillets. Almost all kiln drying is done on stickers which range from 12 to 24 mm in thickness and 36 to 100 mm in width. Wider stickers are used on heavy woods with low basic density to reduce crushing. The wood is stacked in cuboid packages so the air can move horizontally, perpendicular to the long axis of the wood.

Quality Considerations

Maintaining product quality is a major concern in lumber drying. Stains (chemical or biological) need to be prevented by rapid drying; however, slow drying is often needed to prevent structural damage. Water evaporating from the surface can create enough capillary force to cause the cells to collapse early in the drying process (**Figure 2**). As the surface dries below the fiber saturation point and shrinks, surface checks may appear on the face of the board. These are splits which may be from one to several centimeters in length and from very narrow to a millimeter or two in width (**Figure 3**). The likelihood of surface checking decreases as the wood gets drier. They are most likely to appear in the rays on the bark side of wide, flat sawn pieces.

Early in drying while the shell of the wood has tensile stress, the core of the piece has compressive stress. The tension in the shell prevents it from shrinking as much as a stress-free section. The compression in the core causes it to decrease slightly

Figure 1 Lumber is stacked in cuboid packages with the layers separated by stickers so air can move between the layers.

Figure 2 Capillary forces, especially in low density species with high moisture content, can result in collapse. Wood can be steamed to recover minor collapse if no cracks have occurred.

Figure 3 Surface checks can occur if the surface of the board shrinks too much or too quickly compared to the center. This can happen early in lumber drying and the checks close part way through the drying cycle. They are still considered a defect after they close.

in size due to creep and mechanosorptive effects. Later in drying, the core begins to dry below the fiber saturation point and shrink. However, it has already changed size somewhat and the additional size change due to shrinkage causes the stress state in the wood to reverse. After the core begins to shrink there is tensile stress in the core and a compressive stress in the shell. Surface checks close and internal checks, called honeycomb, can form on the inside of the piece (**Figure 4**).

At the end of drying, even if there is no moisture content difference between the shell and the core, there is still tensile stress in the core and compressive stress in the shell. The term 'casehardening' has been applied to this even though the shell is no harder than the core. If the lumber is not resawn or machined extensively, this is not a defect. In many products, however, internal stress will cause warp in pieces that are resawn or machined. Casehardening is relieved at the end of drying with a conditioning step, a process in which the moisture content of the wood is raised by exposing it to using a high relative humidity at a high enough temperature ($>70°C$). The degree of casehardening in wood is determined by the prong test or a similar method (**Figure 5**). The prong test should be evaluated 24 h after cutting to allow for moisture and mechanical equilibrium.

Pieces of lumber can change shape during drying (**Figure 6**). The difference in tangential and radial shrinkage results in diamonding and cup. Differences in longitudinal shrinkage from one side or face of the board to the other results in crook or bow. Spiral grain in the tree leads to twist in lumber. These defects are worsened by drying to low moisture

Figure 4 Honeycomb can occur if the internal tensile stress is high enough. This occurs when the core of the piece is near or below the fiber saturation point. These cracks would not be visible on the end of the piece.

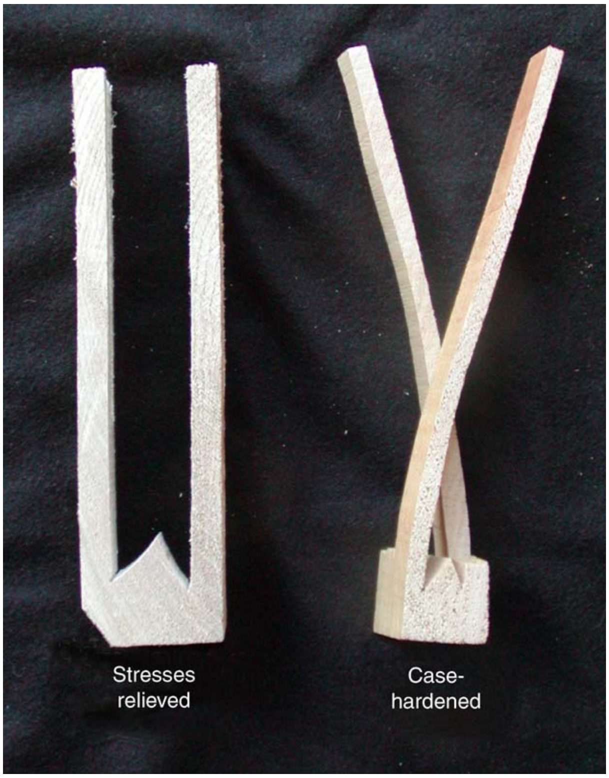

Figure 5 Casehardening can be detected by the prong test. In some regions it is more common to saw the board into two pieces rather than cutting prongs.

contents. Stacking boards so they are restrained by the boards above them helps to minimize warp. In some regions it is common to put concrete or steel weights on top of the stacks to reduce warp.

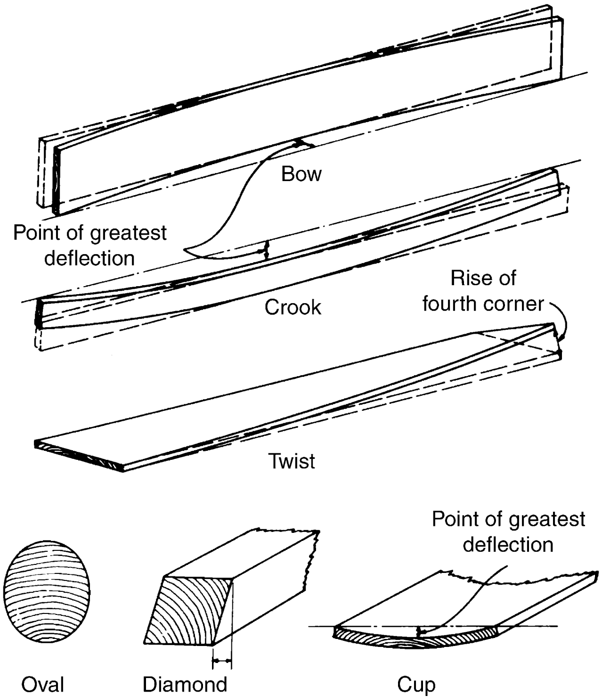

Figure 6 Lumber can distort due to differences in the amount of shrinkage in different locations of directions. From Simpson WT (ed.) (1991) *Dry Kiln Operator's Manual*. US Department of Agriculture.

Air Drying

Air drying is used on woods that need to be dried slowly to avoid defects such as collapse and surface checks. To dry slowly in a kiln is very expensive from a capital investment and energy standpoint. During air drying the wood is exposed to uncontrolled conditions and large losses in wood value can occur. For example, one day of hot, windy, dry, weather can cause oak (*Quercus* spp.) to check so badly that it cannot be used for a high-quality product. Conversely, extended humid weather with little wind can result in lumber that is stained.

Air drying is done in open areas with good airflow. The package arrangement is a trade-off to achieve good airflow, forklift access, and to maximize solar gain to promote faster drying. When slower drying is desired, the piles might be covered with a porous cloth to reduce airflow. In rare cases, water mists are used to raise the relative humidity so freshly sawn lumber does not dry too fast. Drier lumber is sometimes placed on the windward side of the yard and the fresh, wetter lumber on the cooler, more humid leeward side to reduce the drying rate and avoid degrade. The inventory in an air yard must be controlled so wood is removed when it reaches the appropriate moisture content.

For some outdoor applications, air drying alone is sufficient. However, the lowest moisture content that can be achieved is about 12% in most regions. This is too high for applications such as furniture and flooring. Also, as the wood approaches the ambient equilibrium moisture content it dries very slowly which would result in large inventories and much land area for drying. Therefore air drying is often followed by kiln drying.

Kiln Drying

Kiln drying occurs in a building with a way to control the temperature, humidity, and airflow (**Figure** 7). The temperature most often is controlled by steam in pipes or coils. The humidity is controlled by limiting how much water leaves the building through vents. If the wood is not losing moisture fast enough, live steam or a water mist might be used to raise the humidity. The air is circulated with fans. Modern kilns use electronic instrumentation and controls; however, pneumatic instrumentation is the norm in many parts of the world.

The packages of wood are loaded into the kiln by forklift (package kilns) or rolled in on tracks (track kilns). Package kilns are more common for species with longer drying times, making the turn around time between charges less important. Package kilns occupy less land area. Track kilns are more common for softwoods. There are some semicontinous track kilns; however, almost all kiln drying is done as a batch process. That is, the kiln is loaded with a charge of wet lumber, it is dried, then removed.

Lumber is kiln dried using a set of environmental conditions called a schedule (**Figure** 8). The schedule is highly dependent on the species and thickness and somewhat dependent on the width and the eventual product. The purpose of the schedule is to minimize defects in the product while also minimizing drying time and cost. Published schedules are available for most species and thicknesses of wood; however, in practice most mills have their own schedules.

While the wood is at high moisture content, the temperature in the kiln is kept low and the relative

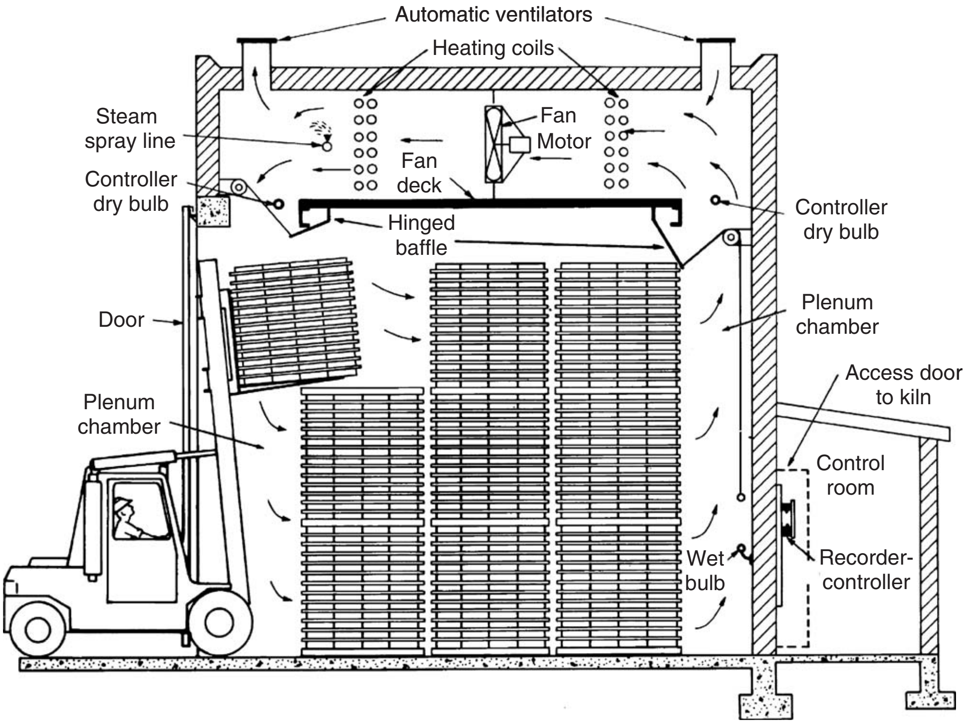

Figure 7 Package lumber kiln. From Simpson WT (ed.) (1991) *Dry Kiln Operator's Manual*. US Department of Agriculture.

Moisture content-based drying schedule					
Step	MC, %	T_{db}, °C	T_{wb}, °C	EMC, %	RH, %
1	above 35	43.3	41.1	17.6	87
2	35 – 30	43.3	40.6	16.3	84
3	30 – 25	48.8	44.4	13.5	77
4	25 – 20	54.4	46.6	10.1	65
5	20 – 15	60.0	43.3	5.8	38
6	15 – dry	82.2	60.0	3.5	26
Equalize and condition as necessary					

Time-based drying schedule					
Step	Time, hrs	T_{db}, °C	T_{wb}, °C	EMC, %	RH, %
1	0 – 12	76.7	73.3	14.1	86
2	12 – 24	76.7	71.1	11.4	78
3	24 – 48	79.4	71.1	9.1	69
4	48 – 72	82.2	71.1	7.7	62
5	72 – dry	82.2	60.0	4.5	36
Equalize and condition as necessary					

Figure 8 Drying schedules. The upper schedule is based on the moisture content of the wood in the kiln. The lower schedule is based on time. Moisture-based schedules are used for species that are difficult to dry. Time-based schedules are used for species that are easy to dry. EMC, equilibrium moisture content.

humidity high to restrict the drying rate. After the surface has dried and the wood has lost about one-third of its moisture, the relative humidity is gradually lowered. When the free water has evaporated from the center of the piece, the temperature is raised and the relative humidity reduced further. After some of the pieces reach the desired moisture content, the humidity is raised to prevent the driest pieces from getting even drier while the wetter pieces continue to lose moisture. This is known as an equalization step. Finally, after the moisture content distribution among the pieces is acceptable, a conditioning step may be employed to eliminate internal stress. The acceptable moisture content distribution depends on final moisture content and end use. For furniture, 7% plus or minus 0.5% to 1% might be necessary whereas for structural lumber 15% plus or minus 2% to 4% or more may be acceptable.

The above schedule description is for species that are prone to defects which result from fast drying, such as oak and eucalyptus (*Eucalyptus* spp.). Many species dry quite easily and the drying schedules are very simple. For example, *Pinus taeda* and *P. radiata* can be dried rapidly with little defect. In easy-to-dry species the kiln is often brought up to the final temperature as rapidly as practical, then the relative humidity is lowered to achieve a high drying rate.

Initial kiln conditions for difficult-to-dry woods may be as low at 35°C with a relative humidity of 85% while easy-to-dry species may be dried with initial temperatures of 120°C or occasionally higher. At the end of drying and before equalization, most dry kiln schedules for difficult-to-dry species call for a temperature greater than 70°C but generally not higher than 85°C. Air velocity varies from 2 to 8 m s^{-1} through the sticker spaces with the greater values used for rapid drying. Kiln drying takes from 16 h to 60 days, depending on the species and thickness.

Sorting the lumber into groups with similar drying properties is desirable prior to drying. Wood is almost always sorted by species and thickness. Some other possible sorting criteria include: initial moisture content, length, width, heartwood content, sawing pattern, or grade. The equipment at the mill and the number of kilns limit how much sorting can practically be accomplished. It is also possible to sort wet pieces after drying and before planing and redry them. This reduces the overall kiln time required to produce a given quantity of dry lumber, reduces the number of overdried pieces, and eliminates the problem of wet pieces in the final product.

Veneer

Veneer is cut with a knife and ranges from 1 to 5 mm in thickness. Some veneer, most likely from a slicing process, is dried in the same manner as lumber, i.e., placed on stickers and loaded into a kiln. Several veneer layers are left together when dried in this way.

More commonly, however, veneer is dried in a conveyor dryer. The veneer is placed on rollers or wire mesh at one end of the dryer and moves through. There may be multiple decks of veneer vertically and three to five zones of different temperature along the dryer length. Rolls or mesh hold the veneer flat and play a significant role in heat transfer to the wood. A moisture meter at the end of the dryer automatically identifies wet pieces which are then redried. The moisture meter is also used to control the speed of the veneer through the dryer and hence its moisture content.

The airflow in older veneer dryers, called longitudinal dryers, is parallel to the surface veneer. Because veneer is thin, the external boundary layer is more significant than internal resistance to moisture movement and newer dryers (called jet or impingement dryers) have manifolds above and below the veneer that direct the airflow perpendicular to it. The temperatures in veneer dryers are limited to approximately 200–260°C because visible hydrocarbon emissions would be generated at higher temperatures. The highest temperatures are found in the early zones where evaporation keeps the wood cool. High wood temperature can inactivate the veneer's surface and prevent the adhesive from wetting the wood and penetrating. Overdried pieces may reach too high a temperature and show surface inactivation. The relative humidity is necessarily low because the dryers are operated at ambient pressure and well above the boiling point of water. Because of this, an attempt is made to minimize the amount of intake air and operate with a high absolute humidity.

Particles

Rotary dryers are often used for particulate material. Particles and hot air are continually fed to the drum. These large rotating drums have lifting flights which carry the particles upward as the drum rotates. The particles leave the lifting flight near the top of the drum and fall through the air stream. Heat is transferred to the particles both from the air and from contact with the dryer. The drums may have concentric sections so that the particles and air traverse the length of the drum up to three times. Residence time is on the order of minutes. Friable material, such as wafers or flakes, may be dried on trays or belts instead of in drums. Very fine material, such as fiber board furnish, might be dried in a tube dryer in which the air carries the fiber through the tube in seconds.

Moisture Content Measurement

Measuring moisture content is an important part of the drying process. Green lumber is sometimes sorted based on moisture content by simply weighing the pieces, measuring their size, and calculating a green density. In this case, accuracy is not critical and it is simply assumed that basic density does not vary among the pieces. At this point, no other good automated way exists to estimate the moisture content of green wood.

Hand-held meters (**Figure 9**) are used to measure the moisture content of dry wood. Conductance-type moisture meters have needles that are pressed or pounded into the wood and the electrical conductivity of a circuit including the pins and the wood is measured. The pins are about 3 cm apart and put into the wood to the depth at which the reading is desired. Pins up to 100 cm long are available for thick lumber while 0.5-cm needles might be used for veneer. Hand-held capacitance-type moisture meters are used by placing the meter on the surface of the wood. The meter generates an electric field into the wood to a depth of 2–3 cm. Based on the energy lost to the wood, moisture content is estimated. Several frequencies might be used simultaneously to reduce the effects of temperature and basic density. Pin-type moisture meter readings are corrected for species and temperature. Capacitance-type moisture meter readings are corrected for basic density and temperature. In modern meters these corrections are internal to the meter with user input for species, temperature, and/or density. Hand-held meters work well up to about 25–30% moisture content.

A capacitance-type moisture meter is often used in production to check the moisture content of each piece of dry lumber. If done before planing, the meter can be used to sort wet pieces for redrying. For veneer, the production line meter is often of conductance type with metal brushes instead of pins. It is located at the outfeed of the dryer. In particle

Figure 9 Pin-type (left) and capacitance-type (right) hand-held moisture meters.

operations, an infrared sensor is used to measure the moisture content of furnish as it moves along a belt.

Inside veneer and particle dryers, there is no moisture content measurement. The traditional method in lumber kilns is to weigh 0.5–1-m-long samples of the wood being dried (**Figure 10**). Approximately six to 12 samples are used to monitor a kiln charge. These samples are intended to represent the wettest (or slowest to dry) lumber and driest (or fastest to dry) lumber in the charge. The wettest pieces will control the schedule because these are most likely to surface check, collapse, and honeycomb. The driest pieces tell the operator when to start the equalization step. This technique is well developed and described in many texts. Variations on this technique include putting pins in the samples to measure conductance or having load cells inside the kiln to weigh the samples without the operator entering the kiln.

Some in-kiln systems utilize metal capacitance plates inserted into the lumber stack. Recently developed in-kiln meters can give a moisture content from about 60% to 80% to dryness and are accurate enough that operators typically do not enter the kiln with a hand-held meter. In-kiln will probably become standard for easy-to-dry species; however, for difficult-to-dry species operators want to know the variability and especially the moisture content of the wetter pieces. Therefore, acceptance into the hardwood industry is uncertain. Any of the in-kiln systems can be integrated with the kiln controller so that the schedule can be advanced based on the moisture content or the rate of moisture content change.

Energy and Environmental Considerations

Drying is a very energy-intensive process and uses up to 85% of the manufacturing energy. Energy use varies greatly, depending on dryer conditions. Difficult-to-dry products require more energy, 7–9 MJ per kilogram of water removed, because more make-up air is required due to the low temperature and humidity. Easy-to-dry products might require 3–6 MJ per kilogram of water removed with particles being on the low end of this range. Of this, approximately 2.3 MJ is used to evaporate each kilogram of water and the remainder consumed by heating make-up air, the kiln structure, the wood and water, by heat transfer through the structure, and electrical inefficiencies. Some dryers are equipped with heat exchangers to recover some of the energy in the vent gas. They have the greatest potential on low temperature dryers with large make-up air requirements. Fan speeds are reduced later in drying in lumber kilns to reduce consumption of electricity when high air velocities are not needed.

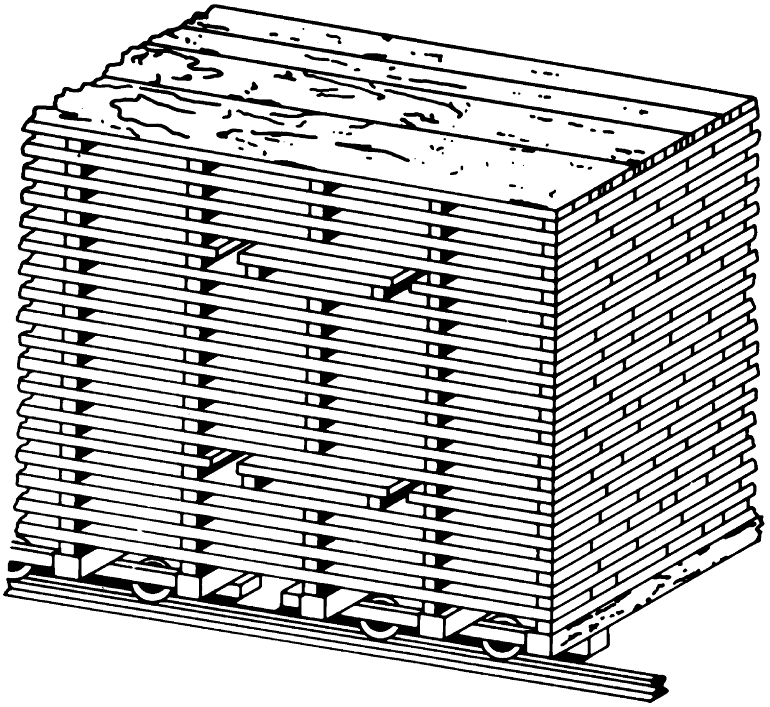

Figure 10 Lumber stack showing placement of kiln moisture samples. Six to 12 samples are weighed and selected to represent the moisture content range in the kiln and are used for determining the step in moisture content-based drying schedules. From Simpson WT (ed.) (1991) *Dry Kiln Operator's Manual*. US Department of Agriculture.

Perhaps the greatest environmental impact of drying is generating energy, either at the on-site boiler or off-site electrical power supplier. Additionally, the exhaust from wood dryers contains a small amount of organic material. Most of this is from volatile material in the wood, such as terpenes, and ranges from 0.1 to $3\,\mathrm{g\,kg^{-1}}$ (grams emitted per kilogram of oven-dry wood processed). Release of some organic compounds may be the result of breakdown of the wood, especially at high temperatures. The main breakdown product with toxicity is methanol which is emitted in quantities from less than 0.01 to $0.3\,\mathrm{g\,kg^{-1}}$. Methanol generation is very dependent on temperature and the moisture removed. A small amount of liquid effluent may come from some kilns, particularly if they are poorly insulated.

Other Technologies

Dehumidification kilns utilize heat pumps to remove water and recover energy. They are very energy efficient, consuming 1.4–2.3 MJ of electrical energy per kilogram of water removed. The operating cost is higher due to electrical energy costs; however, they offer an attractive alternative for low-volume producers because there is no boiler and the initial capital cost is low. An atmospheric pressure steam generator is sometimes added to these kilns to relieve stress. The effluent is water and must be treated prior to being released into the environment.

Solar kilns are used in tropical and even temperate regions. The slow drying and diurnal changes in temperature and humidity can produce lumber with minimal internal stress. Enough solar energy can be collected to evaporate about 5 kg of water per square meter of collector area per day.

Vacuum kilns operate at a pressure below atmospheric. This lowers the boiling point of water so that wood can be dried quickly at lower temperature. The wood remains stronger at lower temperature and fewer defects develop. Besides the cost of the vessel, a disadvantage of this method is that heat does not transfer in a vacuum and conductive metal blankets or electromagnetic energy is used to heat the wood. Rapid drying rates can be achieved when radiofrequency energy is combined with a vacuum. A variation on the vacuum kiln that has gained popularity is the superheated steam kiln. A partial vacuum is drawn and the remaining gas is circulated with fans. As water vapor is removed, the remaining gas becomes almost all water vapor and total pressure and temperature are used to control the drying rate. High air velocity, $10\text{–}20\,\mathrm{m\,s^{-1}}$, is needed for adequate heat transfer because of the low air density.

See also: **Solid Wood Processing**: Machining. **Solid Wood Products**: Lumber Production, Properties and Uses; Wood-based Composites and Panel Products. **Wood Formation and Properties**: Physical Properties of Wood. **Wood Use and Trade**: Environmental Benefits of Wood as a Building Material.

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Finishing

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Introduction

Like other biological materials, wood is susceptible to environmental degradation. When exposed outdoors above ground, a complex combination of chemical, mechanical, and light energy factors contribute to what is described as weathering. Weathering is detrimental to the surfaces and appearance of wood. Thus, weathering must be taken into account when considering the protection of outdoor wood but not indoor wood. Weathering of wood is not to be confused with wood decay (rot), which results from