Originally printed in Drying Technology-- An International Journal as a two-part article:
Part I: 2(2): 235-264; 1983-84
Part II: 2(3): 353-368; 1983-84
New York: Marcel Dekker, Inc.

DRYING WOOD: A REVIEW

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ABSTRACT

This paper reviews the technology of wood drying and recent developments in the field. The importance of drying is reviewed first. Then the fundamentals of wood properties as they relate to drying are discussed, including how water is held in wood, how it moves through wood, and how drying stresses that lead to drying defects develop. Traditional drying technology for lumber, veneer, and heavy timbers is then presented. With this background, the discussion moves to recent developments in drying technology that have been implemented commercially, such as high-temperature drying, low-temperature drying, continuously rising temperature drying, vacuum drying, and advances in process control. Finally, a discussion is presented on drying technology of the future. This topic describes processes that offer potential improvements in drying technology, but are still in the research and development stage.

INTRODUCTION

For many end uses,wood must be formally dried to perform satisfactorily. If formal drying is not carried out before the final product is made, “informal” drying will occur in service, often with disastrous results.

Wood is dried in a variety of shapes and sizes. The appropriate drying technique depends on size and species. Because there are 400-500 trees species or generic groups in the world with some commercial importance, we are faced with a formidable range of possible drying techniques. Fortunately, experience and certain commonalities make the choice easier.

Key Words and Phrases: Cell structure; diffusion; energy; form of water; heartwood; kiln; lumber; moisture movement; shrinkage; stresses, structure; thermodynamics; veneer.

Well-dried wood has many advantages for both producers and users:

- Because weight is reduced, so are shipping and handling costs.
- Subsequent shrinking and swelling is inconsequential.
- Cutting and machining is easier and more efficient.
- Wood parts join more readily and securely with nails, screws, bolts, and adhesives.
- Warping, splitting, cracking, and other harmful effects of uncontrolled drying (in service) are almost eliminated.
- Paint, varnish, and other finishes go on easier and last longer.
- Decay hazards are eliminated if dried wood is treated with preservatives or protected from excessive moisture regain. Drying is therefore a key processing step in the use of wood products.

Data are not available to make an accurate estimate of the amount of wood dried annually in the world, but an order-of-magnitude estimate is possible. Data gathered by the Food and Agriculture Organization of the United Nations (1982) place the 1980 world production of solid wood products at about 550 million cubic meters. The term solid wood products as used here includes items such as sawn lumber, timbers, sleepers, veneer, plywood, and particleboard, and excludes wood pulp products and fuelwood. If we assume that only one-half of this amount, 275 million cubic meters, is formally dried, then the amount of water removed is approximately 10^{11} kg. The energy required to evaporate this water is about 2×10^{17} joules, or 35 million barrels of oil.

In this paper I review some of the fundamentals of wood-moisture relations, moisture movement, wood properties related to drying, and quality considerations.- I also review current commercial drying practices, as well as some non-conventional or experimental processes that have good potential. The coverage is limited to solid wood products as previously defined.

FUNDAMENTALS

The structure of wood and the location and amount of water in wood influence its drying characteristics. A cross section of a tree (Figure 1) shows well-defined features from outside to inside. One sees the bark, a light-colored sapwood zone next to the bark, an inner and darker heartwood zone, and growth rings that show as concentric rings. Wood is a cellular structure. Each cell has a cell cavity, or lumen, and cell walls composed of several layers arranged in different ways (Figure 2). The cell wall constituents

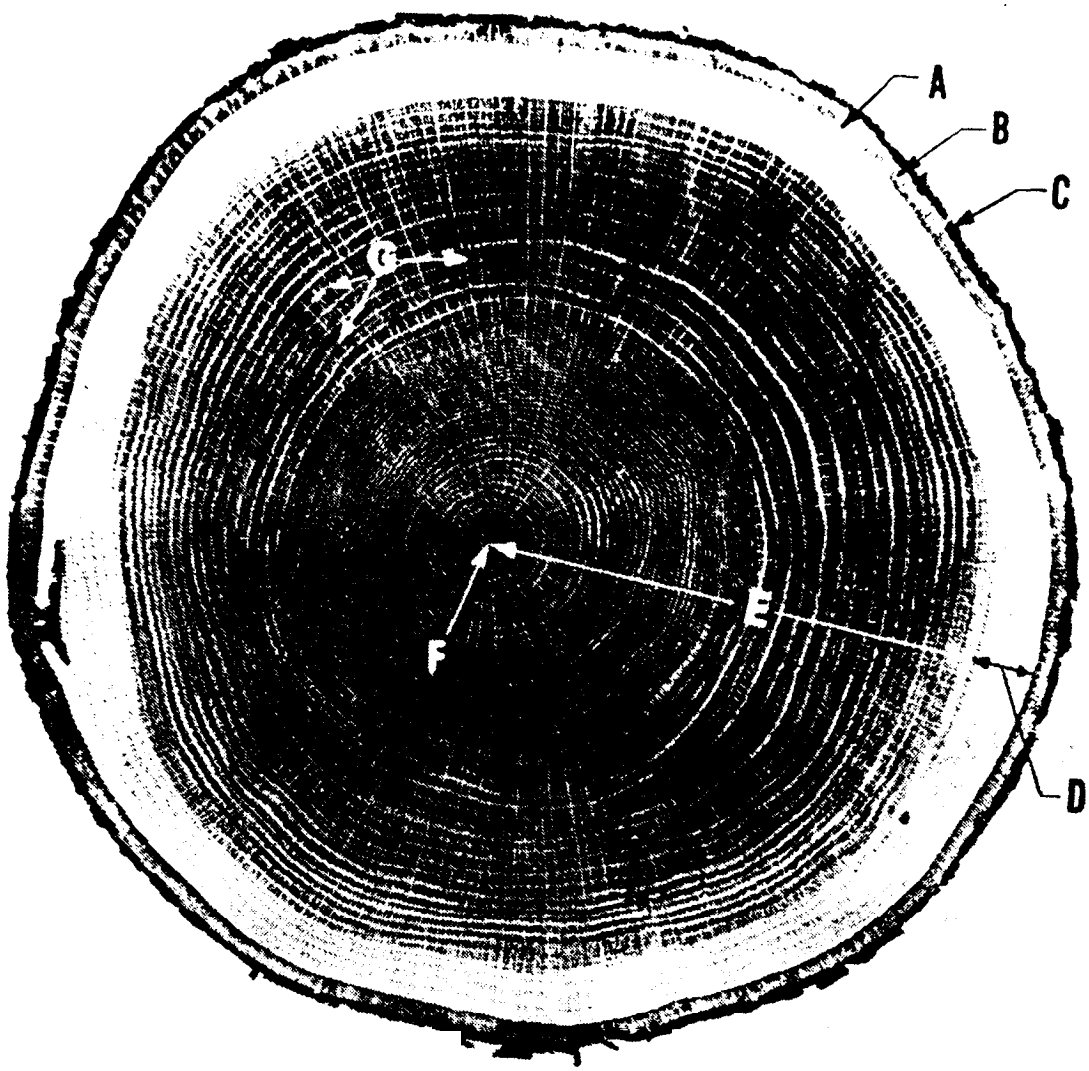

FIGURE 1. Cross section of a white oak tree trunk: A, Cambium layer (microscopic) is inside inner bark and forms wood and bark cells. B, Inner bark is moist, soft, and contains living tissue. Carries prepared food from leaves to all growing parts of tree. C, Outer bark containing corky layers is composed of dry dead tissue. Gives general protection against external injuries. Inner and outer bark are separated by a bark cambium. D, Sapwood, which contains both living and dead tissues, is the light-colored wood beneath the bark. Carries sap from roots to leaves. E, Heartwood (inactive) is formed by a gradual change in the sapwood. F, Pith is the soft tissue about which the first wood growth takes place in the newly formed twigs. G, Wood rays connect the various layers from pith to bark for storage and transfer of food. (M 88620 F)

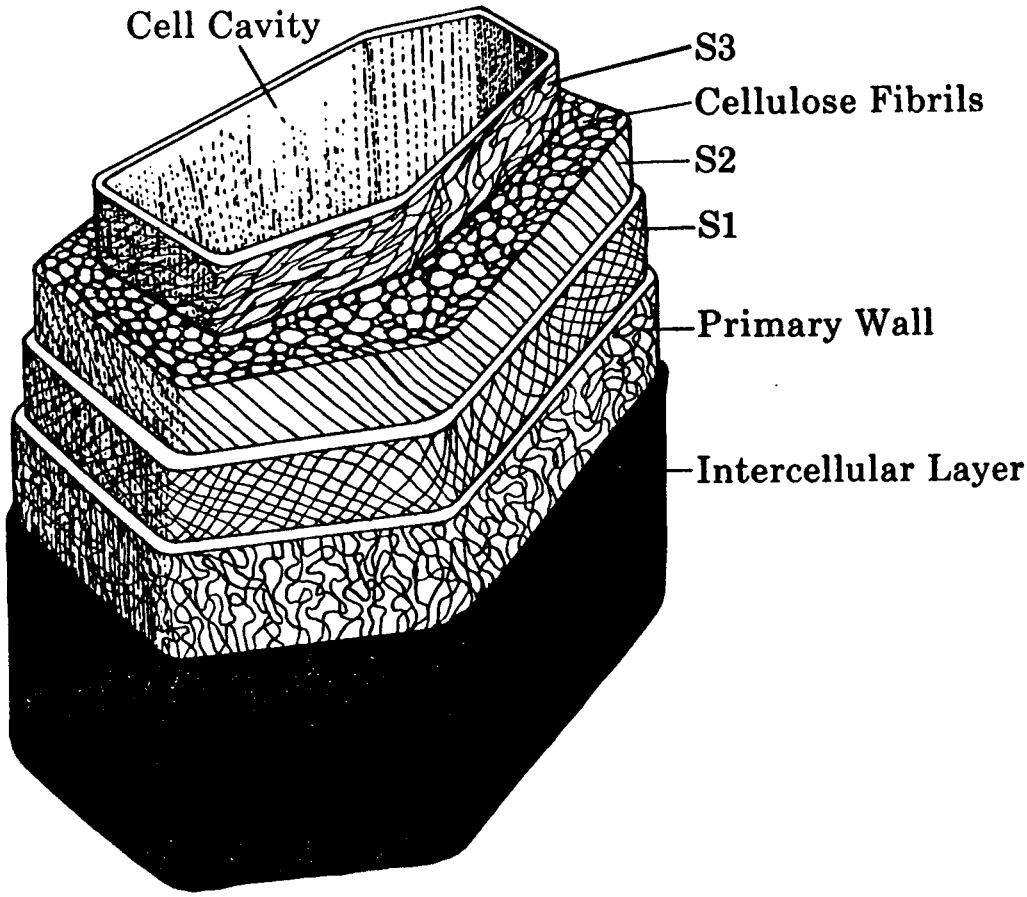

FIGURE 2. Cross section of a woody cell showing the several layers in the cell wall. (M 134,271)

are cellulose, hemicelluloses, and lignin. Most of the tube-like cells are oriented parallel to the long axis of the tree trunk and are termed fibers, tracheids, or vessels, depending on their particular anatomical characteristics and function. Another type of cell, wood rays, lie on radial lines from the center of the tree outward and perpendicular to the long axis. Figures 3 and 4 illustrate the arrangement of cells in conifers and broad-leaf trees, whose anatomies are similar but do have slight differences.

One particular type of anatomical element, called a pit, is important in water flow. A pit is a small, valve-like opening that connects adjacent wood cells and thus is an important pathway for the flow of water. Several types of pits are shown in Figure 5.

Another important characteristic of wood relevant in drying is the difference between sapwood and heartwood. In the living tree, the sapwood layer next to the bark contains living cells that are active in the transport of fluids. As the tree grows and increases in diameter by adding new layers of sapwood, the inner layers of sapwood die and become infiltrated with gums, resins, and other material. Because of these infiltrations, heartwood is more resistant to fluid flow than sapwood, and has quite different drying characteristics. Other details of wood anatomy and properties can be found in Panshin and deZeeuw (1980).

Water in Wood

Water occurs in wood in three forms--liquid (or free) water in the cell cavities; water vapor in the cell cavities; and bound (or hydroscopic) water in the cell walls. When a tree is felled, the moisture content may range from 30 to nearly 200 percent (dry basis), depending on species and sapwood or heartwood. Sapwood is usually higher in moisture content than heartwood. If drying is required for an end use, the final moisture content requirement will vary from about 5 to 20 percent, depending upon end product and use environment. As wood dries, water leaves cell cavities first. When cell cavities are empty, cell walls begin to dry. The term fiber saturation point (fsp) has been defined as the moisture content at which cell cavities are empty and cell walls have not begun to dry, and is in the range of 25 to 30 percent. Although the fsp is difficult to determine experimentally because of capillary condensation and moisture gradients that form during drying, the property is important. Most physical properties do not vary much with moisture content above the fsp, but they do begin to change as water leaves cell walls. Shrinkage begins at fsp. As we will see later, this change in properties and shrinkage below fsp has great significance in wood drying.

Another property of the wood-water system important in drying is equilibrium moisture content (EMC). Wood will come to a moisture content, somewhere between zero percent and the fsp, that is at equilibrium with ambient relative humidity and temperature. The

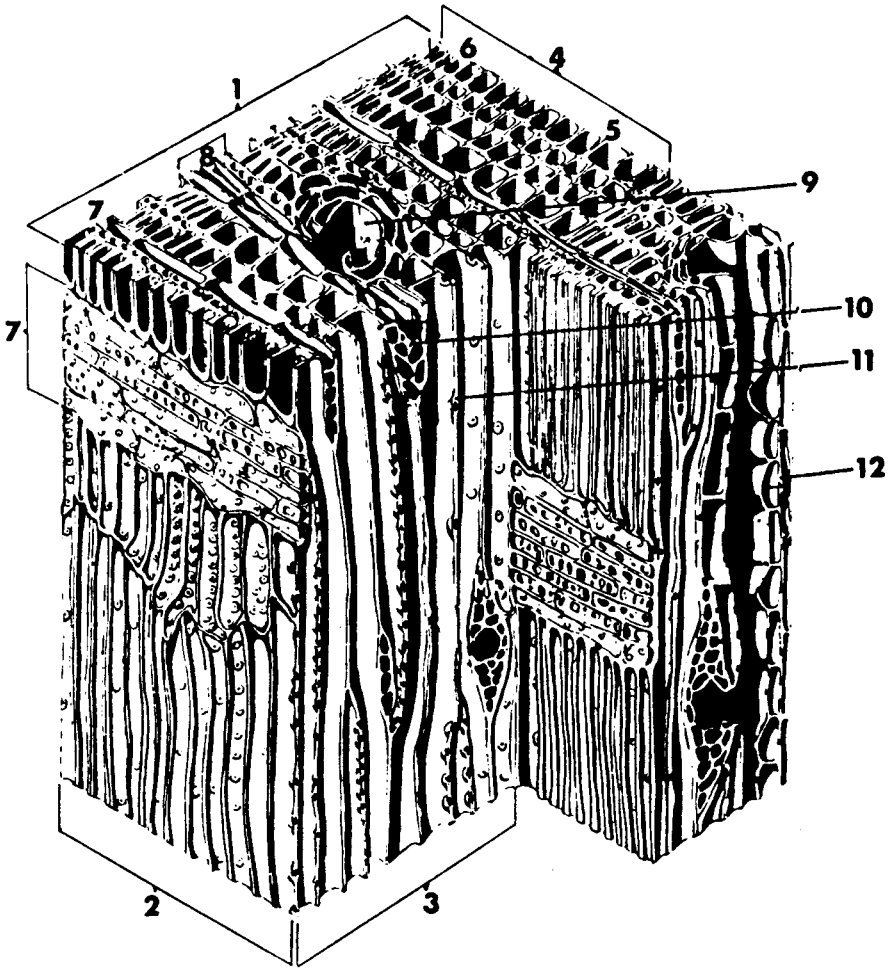

FIGURE 3. Wood structure of a softwood

KEY--

1. cross-sectional face
2. Radial face
3. Tangential face
4. Annual ring
5. Earlywood
6. Latewood
7. Wood ray
8. Fusiform ray
9. Vertical resin duct
10. Horizontal resin duct
11. Bordered pit
12. Simple pit

(M 134,267)

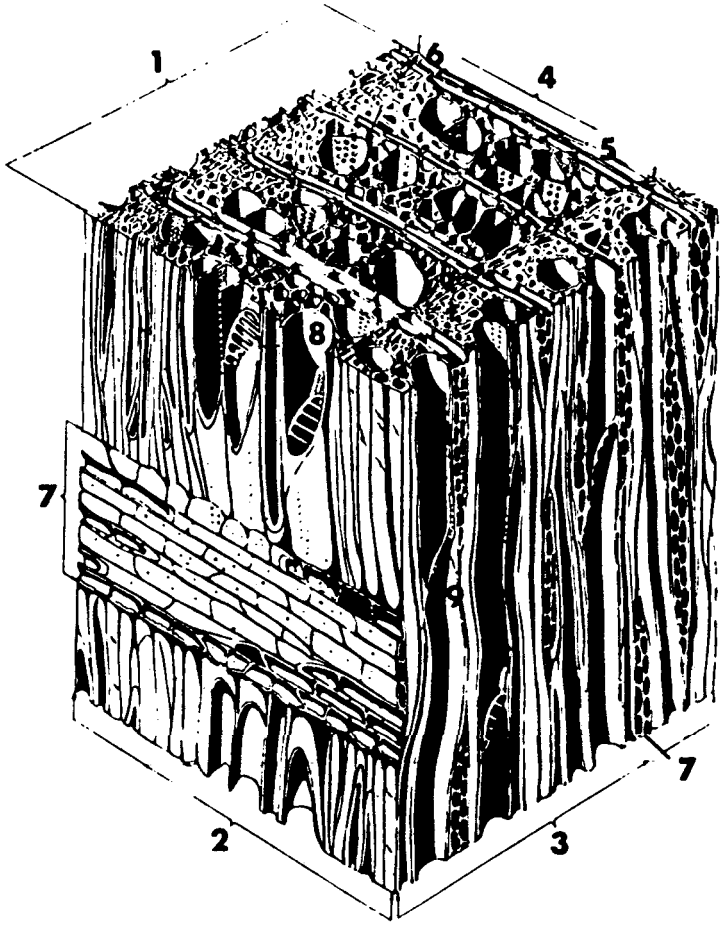

FIGURE 4. Wood structure of a hardwood.

KEY--

1. Cross-sectional face
2. Radial face
3. Tangential face
4. Annual ring
5. EarlyWood
6. Latewood
7. Wood ray
8. Vessel
9. Sieve plate

(M 134,265)

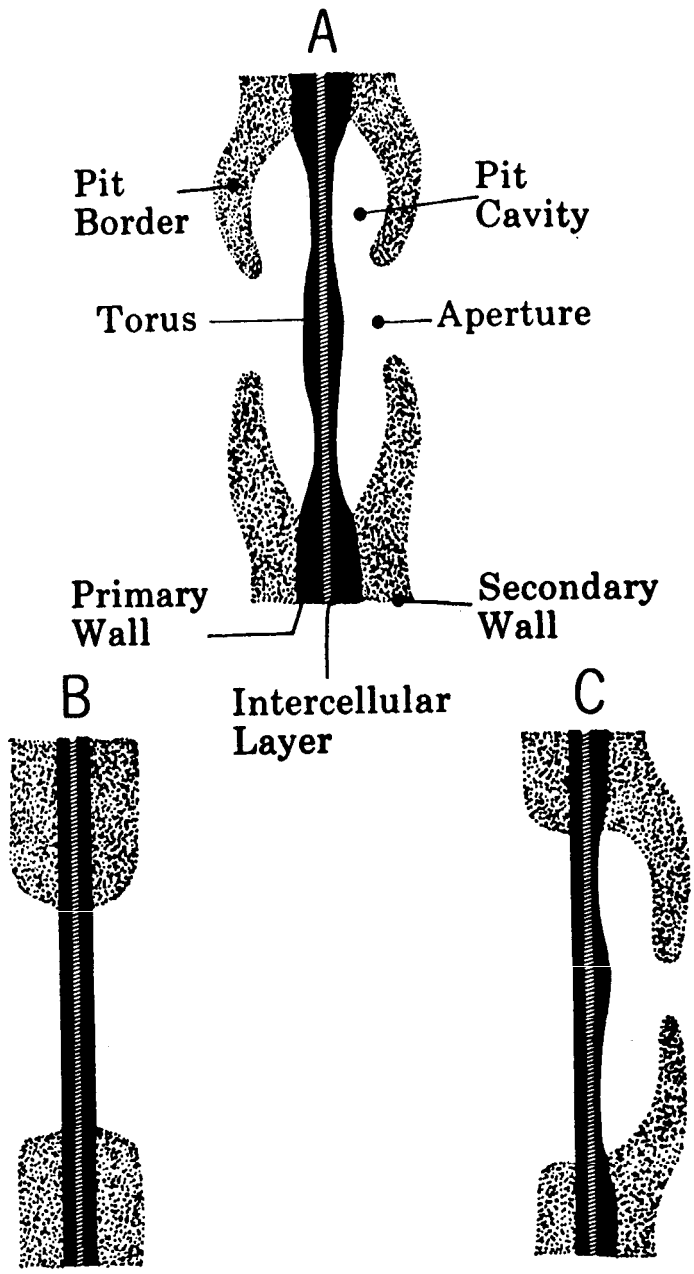

FIGURE 5. Cross sections of: A, a bordered pit; B, simple pit; and C, a half-bordered pit. (M 134,593)

importance of EMC in drying technology, which will be discussed later, is its use in controlling drying rate. Typical sorption isotherms for wood are shown in Figure 6.

The thermodynamics of adsorption of water on wood are discussed by Stamm (1964) and Skaar (1972). The energies of adsorption are of particular interest in drying because they determine energy requirements in drying. The energies can be divided as follows (Figure 7): The energy released when water is absorbed by the cell wall of wood (or the energy required to evaporate water from the cell wall of wood) is termed Q_v; the energy released when water vapor condenses to water (or the energy required to evaporate water from the liquid state) is the heat of vaporization of water, Q_o. The difference between these two quantities

$$Q_L = Q_v - Q_o \qquad (1)$$

is the differential heat of adsorption. Q_L is the additional energy, above the heat of vaporization of water, released when water is adsorbed by wood. It is also the additional energy, above the heat of vaporization of water, required to evaporate water from wood.

Shrinkage of Wood

Shrinkage of wood is the root of most of the problems that occur during drying and many that occur in service. When water begins to leave the cell walls at 25-30 percent moisture content, the walls begin to shrink. Even after drying, wood will shrink and swell in service as relative humidity varies. The direction in which wood shrinks is the cause of many drying problems. Wood shrinks most in the direction tangent to the concentric growth rings. This tangential shrinkage ranges from about 4 to 13 percent, depending on species. Radial shrinkage, i.e., perpendicular to the growth rings, ranges from about 2 to 8 percent.

This differential shrinkage is caused by the basic anisotropy of wood shrinkage, and leads to undesirable drying stresses. The orientation of most of the long-chain cellulosic structure in the cell-wall is nearly parallel with the long axis of the cell which, in turn, for most wood elements, is parallel to the long axis of the tree (or boards). As water molecules leave the cell walls, most of the resulting shrinkage is perpendicular to the cell walls, with little change in length. This longitudinal shrinkage is usually only about 0.1-0.2 percent from wet to total dryness, although it may reach as much as 2 percent in certain abnormal types of wood.

Moisture Movement

Wood drying includes three mechanisms of moisture movement that occur in various combinations and proportions, depending on species, thickness, and stage of drying. 1) Mass flow of liquid

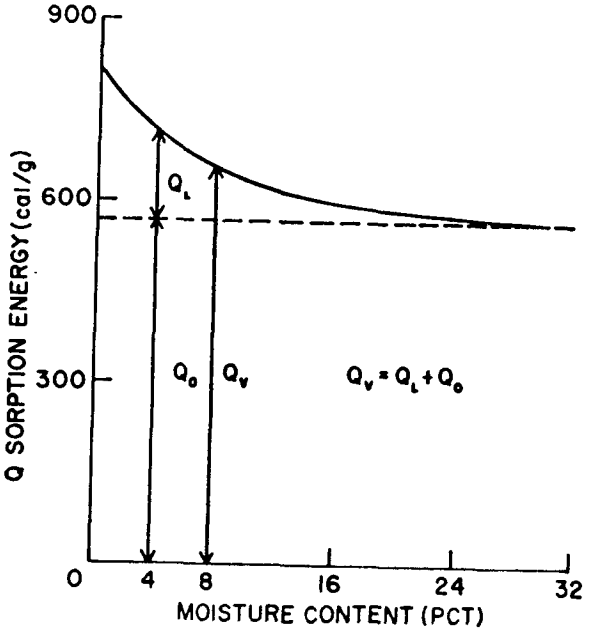

FIGURE 7. Energies of adsorption of water by wood.
Q_v = Energy of evaporate water from cell wall.
Q_o = Heat of vaporization of water.
Q_L = Differential heat of adsorption. (M148154)

water through the capillary structure of cell cavities and interconnecting pits occurs at moisture contents above fsp. 2) Below fsp, diffusion of water occurs through the network of cell walls and cell cavities. These two mechanisms bring water to the surface, and the third mechanism of moisture movement is 3) removal from the surface.

The reader can expand upon the following brief discussion of moisture movement in Stamm (1964), Hart (1965), and Siau (1971). The flow of free water above the fps requires both a continuous passageway for flow and a driving pressure. The continuous passageway is provided mainly by cell cavities and interconnecting pits. Pit openings range from 0.1 to 1 micrometers in diameter. The driving pressure is the difference between the pressure in the gas phase and the liquid phase, and is given by the equation:

$$P_o - P_1 = \frac{2\sigma}{r} \tag{2}$$

where

P_o = pressure in gaseous phase
P_1 = pressure in liquid phase
σ = surface tension of liquid
r = radius of capillary

Below the fsp, water moves through wood by diffusion of water molecules through cell walls and cell cavities. The path may be continuous through cell walls or through a combination of cell walls and cell cavities. Stamm (1964) has analyzed diffusion with an electrical analogy using parallel and series networks of diffusion paths.

Diffusion in wood drying is usually characterized by Fick's second law and the mathematics of diffusion, which follow from the basic differential equation (Crank, 1975]:

$$\frac{\partial c}{\partial t} = \frac{\partial}{\partial x} D \frac{\partial c}{\partial x} \tag{3}$$

where

c = moisture concentration
t = time
x = distance in flow direction
D = diffusion coefficient

From a process or equipment design engineer's standpoint, it would be desirable to have handbook tables or coefficients available for estimating the drying time for *any* species, thickness, *dryer* relative humidities and temperatures, initial and final moisture

contents, and air velocity, This information is not available for wood products. Not only is there only limited basic drying rate data, the framework necessary to use such data has not been fully developed. (For the purpose of this discussion, we will assume that the statistical problem of variability of wood properties influencing drying behavior can be overcome.) The mathematics of diffusion are of little help in predicting drying time from the variables that effect it because they have not been integrated with mass liquid flow. They could be used to estimate drying times from fsp to final moisture content, but a workable system complete with engineering data on diffusion coefficients is not available.

Several researchers have attempted to develop equations or series of equations to estimate drying time. Some attempts have been built on a relatively simplified physical model and have resulted in simple but effective equations. Others have attempted a detailed description of the physics involved and have developed complex models that are also effective. No one, however, has carried through a systematic development that would result in engineering handbook data.

Comstock (1971), Tschernitz and Simpson (1979), and Rosen (1980) have developed semi-empirical models that are based on a combination of simplified physics of drying and empirical observations of the shape of the drying rate vs. moisture curve. In several cases the authors have related the parameters of their models to relevant physical quantities, such as temperature, so that the models do have some generalized applicability. Bramhall (1979), Ashworth (1980), Spolek and Plumb (1980), and Hart (1981) have developed models that attempt to describe the physics of drying. The models are derived from the basic heat, mass, and momentum transport equations. The resulting models are quite complex. They also require the use of physical constants that are not always available. However, the models represent admirable attempts to address the complex mechanisms of drying and reduce them to a manageable phenomenon that can be described quantitatively.

Drying Stresses and Defects

Drying stresses are the main cause of defects that occur in wood during drying. There are two causes of drying stresses, hydrostatic tension and differential shrinkage. Hydrostatic tension develops on the cell walls of water-filled lumens according to equation 2. Differential shrinkage is either due to the anisotropy of shrinkage or as the result of moisture content gradients in wood as it dries.

Hydrostatic tension leads to a defect known as collapse. With pits as small as 0.1 micrometer, the hydrostatic tension of equation 2 can reach 1400 kPa, which exceeds the proportional limit at high drying temperatures for some woods. The result is

an inward collapse of cell walls that shows externally as excessive shrinkage or a washboard effect (Figure 8).

Differential shrinkage between the shell and core of lumber is also a cause of drying defects. This occurs because the outer fibers in the shell dry first and begin to shrink. However, the core has not yet begun to dry and shrink, and consequently the shell is restrained from shrinking by the core. Thus the shell goes into tension and the core into compression. If the shell dries too rapidly, it is stressed beyond the elastic limit and dries in a permanently stretched condition without attaining full shrinkage. Sometimes surface fractures occur during this early stage of drying, and they can be a serious drying defect for many uses, As drying progresses, the core begins to dry and attempts to shrink. However, the shell is set in a permanently expanded condition and prevents normal shrinkage of the core. This causes the stresses to reverse--the core goes into tension and the shell into compression. These internal tension stresses may be severe enough to cause or contribute to internal fractures called honeycomb (Figure 8).

Differential shrinkage caused by differences in radial, tangential, and longitudinal shrinkage are a major cause of distortion of lumber during drying. Five common types of warp are shown in Figure 9.

TRADITIONAL DRYING TECHNOLOGY

Before turning to some of the newer developments in drying technology, we should spend a short time on the traditional ways of drying wood. Then we will turn to some recent technology now in commercial use and conclude with some of the promising technology still in the research and development stage.

Lumber

The oldest method of drying lumber is simple air drying. With proper stacking for air circulation and with support for warp prevention, lumber can be dried with no need to add energy above the drying capacity of the ambient air. However, this advantage of free energy is offset by several serious disadvantages. One is the long drying time, which can range from several months to several years depending on species, climate, and lumber thickness. Another disadvantage for some end uses is the impossibility of reaching a moisture content low enough for certain environments such as air-conditioned spaces in the tropics or heated homes in northern latitudes. In air drying we are at the mercy of the weather. Temperature is limited to below-optimum drying temperatures, and air drying almost ceases in northern winters. The most serious vagary of the weather is the alternating wet and dry periods that subject surface fibers to cyclic periods of drying, which might be violent at times, and wetting. The subsequent

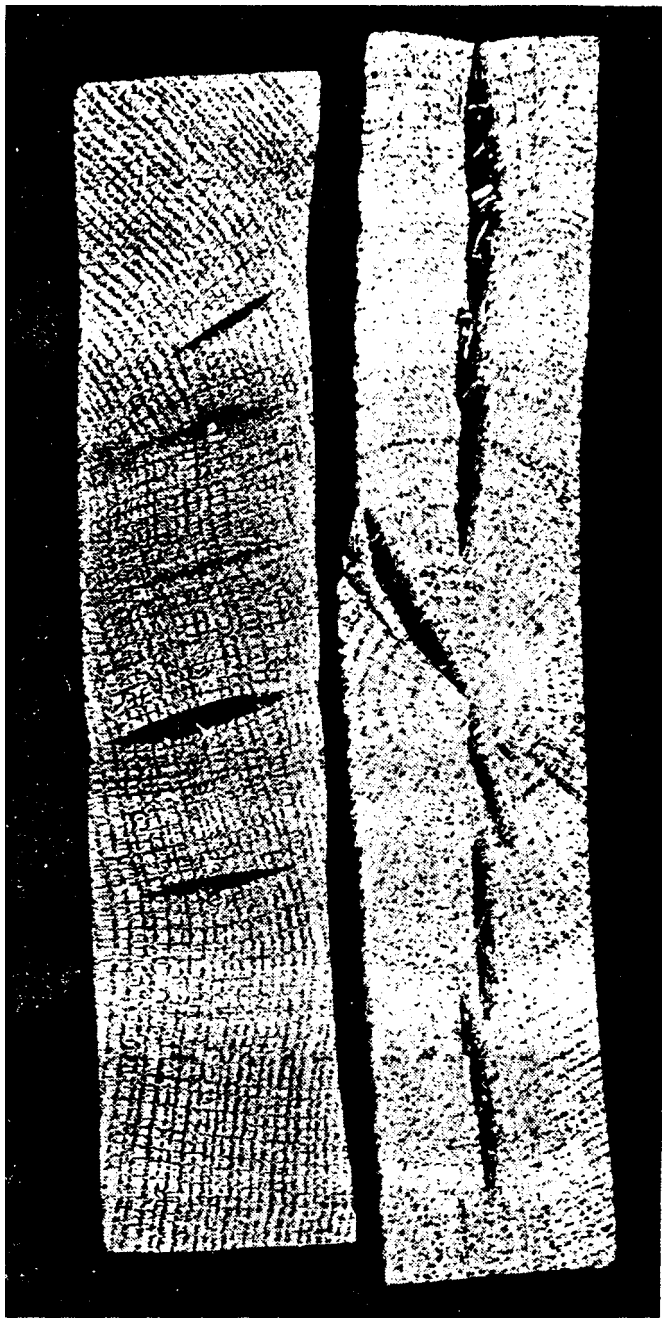

FIGURE 8. Cross section of boards showing collapse and honeycomb.

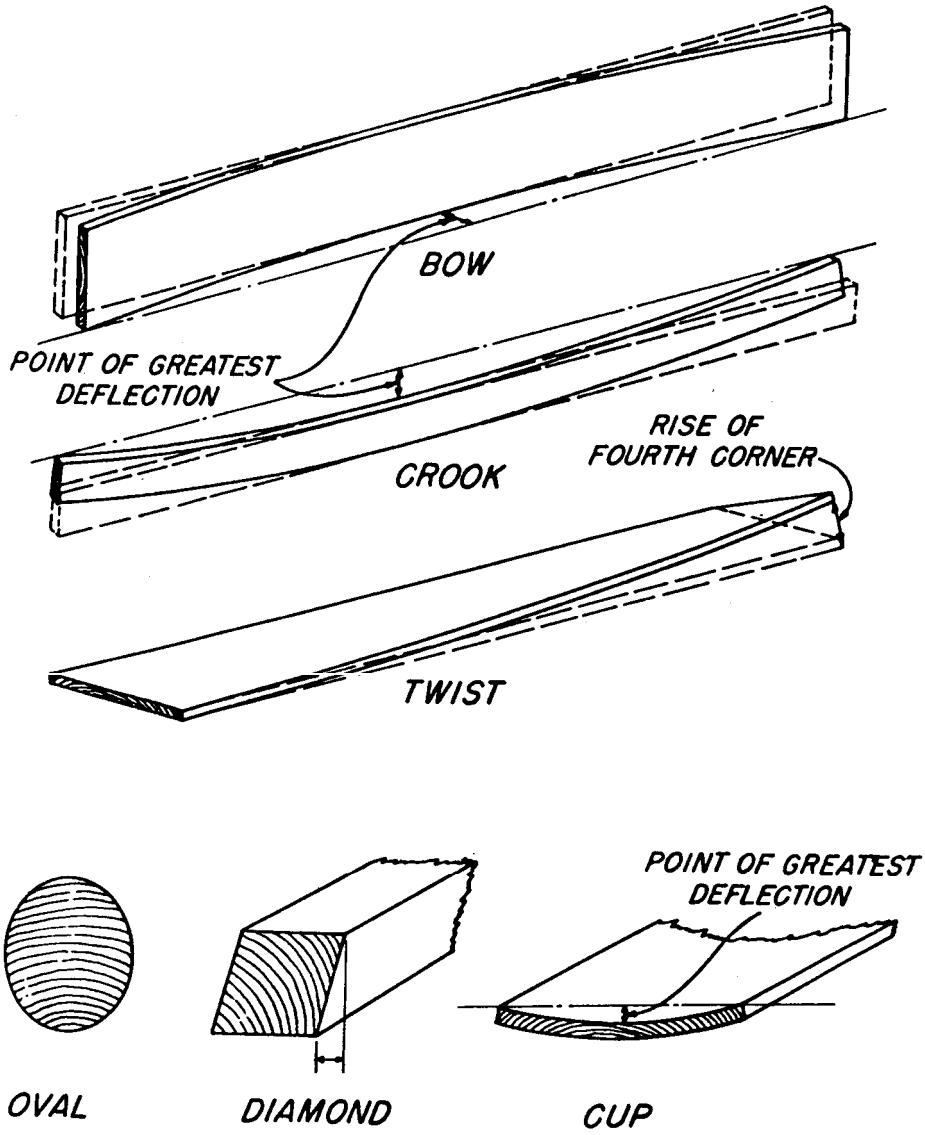

FIGURE 9. Various types of warp. (M 89552 F)

shrinking and swelling of the surface often leads to surface cracks and consequently value loss. Despite all of its drawbacks, air drying is still used extensively, either alone or as a prelude to kiln drying.

In the early 1900's, producers of wood products recognized the limitations of air drying and developed dry kilns for providing a drying environment at elevated temperatures. Experience soon showed that there were definite limits to temperature elevation before drying defects (collapse, surface and internal cracks) developed. A controlled environment was necessary. A kiln thus provides means for temperature and humidity control, air circulation, and removal of moist air.

Drying schedules were empirically developed. A drying schedule is a compromise between the desire to dry wood as rapidly as possible yet slowly enough to avoid drying defects. Early in drying, wood dries the fastest, and because of high moisture content, it is in its weakest condition. Thus wood is very susceptible to drying defects early in drying, and relatively low temperatures and high humidities are required for many species. As drying progresses, drying rate decreases. We would like to raise temperature and reduce humidity to maintain drying rate. Fortunately, as wood dries below fsp it becomes stronger, and we can make these changes. A kiln schedule is thus an empirically determined (trial and error) recipe for gradually increasing temperature and decreasing relative humidity at certain moisture contents in such a way as to minimize both drying time and drying defects. Species and thickness are the main factors influencing selection of kiln schedule. Here are examples of a mild schedule for a species very susceptible to drying defects and a severe schedule for a species not as susceptible to drying defects:

A) Mild Schedule--25-mm-thick southern (U.S.) lowland oak (*Quercus*)

Moisture Content (%)	Temperature (°C)	Relative Humidity (%)
Above 40	38	89
40-35	38	86
35-30	38	80
30-25	43	70
25-20	49	40
20-15	54	10
15-7	66	8

B) Severe Schedule--25-mm-thick lauan (Shorea)

Above 50	66	82
50-40	69	76
40-35	66	66
35-30	66	48
30-25	71	31
25-20	71	21
20-15	77	24
15-7	82	26

These schedules are based on making temperature and relative humidity changes at certain moisture content levels. This requires a process control scheme that includes monitoring of moisture content. The most certain way to do this is by periodic weighing of pre-selected sample boards. This is a cumbersome and sometimes impractical procedure but is often necessary for high-value lumber susceptible to drying defects.

Electrical methods are sometimes used to monitor moisture content. The electrical properties of wood change with moisture content. Unfortunately, most of the change occurs between fsp and total dryness, so electrical methods are of little use at high moisture contents where critical changes in conditions are sometimes necessary.

Time-based schedules are not as precise as moisture. content schedules, but they are often used for certain species and for end uses where minor drying defects can be tolerated. They simplify process control because changes can be made automatically or manually without the need to sense any wood properties. Time-based schedules are derived by trial and error and long experience with a standard species-thickness combination that is dried repetitively.

Process control in lumber drying is quite primitive. The combination of susceptibility to drying defects and the variability of wood properties within one given species (or even one tree) prohibits establishing standard drying cycles of time, temperature, and relative humidity that can be applied universally with certainty. Wood that enters a dryer will not all have the same initial moisture content, drying rate, or mechanical strength. Furthermore, the traditional parameters that vary with moisture content and that might be used as a basis for process control will not be uniform. The end result is a statistical problem that is difficult to manage and has hindered advances in process control.

Veneer

Commercial veneer, either peeled or sliced, is usuallY 4 mm or less in thickness compared to lumber that is usually at least

25 mm thick, Because of this thinness, veneer is dried differently than lumber. Much shorter drying cycles are possible because drying time varies exponentially with thickness, and drying temperatures can be relatively high because internal drying stresses are not as damaging as in lumber. The end result is drying cycles that are usually less than 1 hour and often less than 10 minutes. With such short drying times, veneer operations are often continuous production systems. Surface evaporation and heat transfer to the veneer, rather than internal moisture flow, are usually the controlling factors that determine veneer drying rates. Therefore, high air velocity across or perpendicular to the veneer surfaces is important.

Poles and Heavy Timbers

The large size of poles and heavy timbers make their drying as different from that of lumber as veneer drying. The large size means that drying rate is low, which causes steep moisture gradients and drying stresses of long duration. The result is long drying times and the almost certain occurrence of surface cracks. The long drying times often make kiln drying prohibitively expensive, so that air drying is the most common practice. Poles, which are often treated with preservatives to prevent decay, are usually partially dried before treatment. Surface moisture is removed to allow successful penetration of preservative. Drying cycles for this purpose are short enough to be done economically in a kiln or in some processes in a treating cylinder just before treatment begins.

RECENT IMPLEMENTATION OF NEW DRYING TECHNOLOGY

Most of the recent advances in drying technology, as well as newer technology still in the research stage, have been motivated by the following factors:

1. Growing recognition of the economic value of lumber and veneer and the need to maintain quality of the dried product.

2. Growing recognition of the high cost of long drying times. High interest rates raise the cost of holding large inventories during prolonged drying.

3. Increased concern over energy consumption in drying and the need to identify ways to minimize energy use.

4. More interest in sophisticated drying processes and methods of process control.

High-Temperature Kiln Drying

One of the first improvements in traditional kiln drying technology was an increase in drying temperatures to reduce drying time.

Whether by tradition *or* good reason, kiln schedules seldom called for drying temperatures above 80-90° C, and then only at the last step in a schedule, when the wood was nearly dry. Over the past 10-15 years, higher drying temperatures, up to 120° C or more, have been found safe for more and more species. The major limitation has been drying defects. Each species reacts differently to high-temperature drying, so progress has been made on a species-by-species basis. Some species can be dried at high temperature from initial to final moisture content with little or no honeycomb, collapse, *or* surface cracks. Other species will not tolerate such drying at all, and others will survive high drying temperatures if first partially dried at low temperatures. In general, high-temprature drying has worked best on softwood structural lumber and not well on hardwood lumber.

Some of the early success in implementing high-temperature kiln drying occurred in Germany. Kollmann (1961) reported that hardwoods first partially dried at low temperature and some softwoods could be successfully dried at high temperatures. Another successful application of high-temperature kiln drying was for the pines grown in the southern United States. These pines are an important source of structural lumber. They are very permeable and can be dried in 24 hours or less at 120° C without serious drying defects (Koch, 1971). Traditional schedules often required up to 80-90 hours. This was a major advance in kiln drying technology and helped motivate the search for additional applications. Reductions in drying time similar to those found for the United States southern pines have also been found for radiata pine, which grows in Australia, New Zealand, and South Africa (Kininmouth, 1973). Cech and Huffman (1971) reduced drying of spruce structural lumber from 60 to 15 hours, and Huffman (1972) showed that drying time of aspen structural lumber could be reduced from 175 to 59 hours using high-temperature drying.

A problem more subtle than obvious drying defects like honeycomb and collapse sometimes occurs in high-temperature drying. The time of exposure to high temperature at high moisture content sometimes results in a thermal degradation that reduces some mechanical properties such as modulus of rupture and modulus of elasticity. Property reductions range from a low of about 5 percent for the southern pines to 20 percent for Douglas-fir (Gerhards and McMillen, 1976).

Continuously Rising Temperature (CRT)

The continuously rising temperature (CRT) process is a patented process (Dedrick, 1968, 1973) that has been implemented in softwood structural lumber drying. CRT is credited with reductions in kiln drying time, energy, and drying defects. Early in conventional kiln drying when lumber is wet, the wood surface assumes the wet bulb temperature. As drying progresses, the surface temperature rises and approaches the dry bulb temperature. As a result, the

temperature difference between air and wood, which is the driving force for heat transfer from air to wood, becomes progressively smaller. The CRT process is claimed to control heat transfer from air to wood by maintaining a constant air-to-wood temperature difference by continuously increasing dry bulb temperature during drying. The result is a nearly constant drying rate throughout drying instead of the usual falling rate (Figure 10). One advantage of CRT is that initial drying temperatures can be kept relatively low (60°C typical) and still realize a respectable drying rate, which minimizes drying defects and mechanical property 1oss due to thermal degradation. Then later in drying when high temperature (100° C typical) becomes necessary to maintain drying rate, the wood is not as susceptible to drying defects and degradation.

Low-Temperature Drying

At the opposite end of the drying temperature spectrum, low-temperature drying has certain applications quite different from high-temperature drying. High-temperature drying has been implemented mostly for softwood structural lumber. Most of these species dry relatively easily, and the end use permits minor drying defects. The production of softwood structural lumber is a high volume system with emphasis on throughput. The product is relatively low value, so rapid, low-cost drying is necessary. Conversely, hardwood lumber is usually more difficult to dry without defects than softwood lumber, drying times are longer, and for many common uses (e.g. furniture) no drying defects can be tolerated. Because of long drying times and the high cost of kiln drying, hardwood lumber has commonly been air dried before final kiln drying. However, air drying is a slow process and drying defects often develop because of lack of control over drying conditions. Until recently, air drying was still often economical despite these disadvantages. But with the increasing cost of lumber and interest costs on inventory during long air drying periods, air drying defects and long air drying times are less and less tolerable. The result has been an upsurge in the use of previously little-used low-temperature dryers as a replacement for air drying. Low-temperature dryers are lypically low-cost dryers that provide a minimum of air circulation and temperature and relative humidity control, but just enough to reduce drying time and drying defects significantly. Temperatures typically are 27-40° C. Wengert (1979) estimates a 23 percent reduction in total drying costs of oak lumber (including reduced drying defects) by the combination of pre-drying plus kiln drying vs. air drying plus kiln drying, and a 40 percent reduction compared to kiln drying alone from initial to final moisture content.

In addition to use in pre-drying to be followed by kiln drying, low-temperature dryers are also sometimes used for the entire drying process. A particularly popular and widely implemented type of low-temperature dryer for this purpose is the dehumidifier dryer, which typically operates below 50° C. Instead of the usual venting systems to remove moisture from kilns, dehumidifier kilns

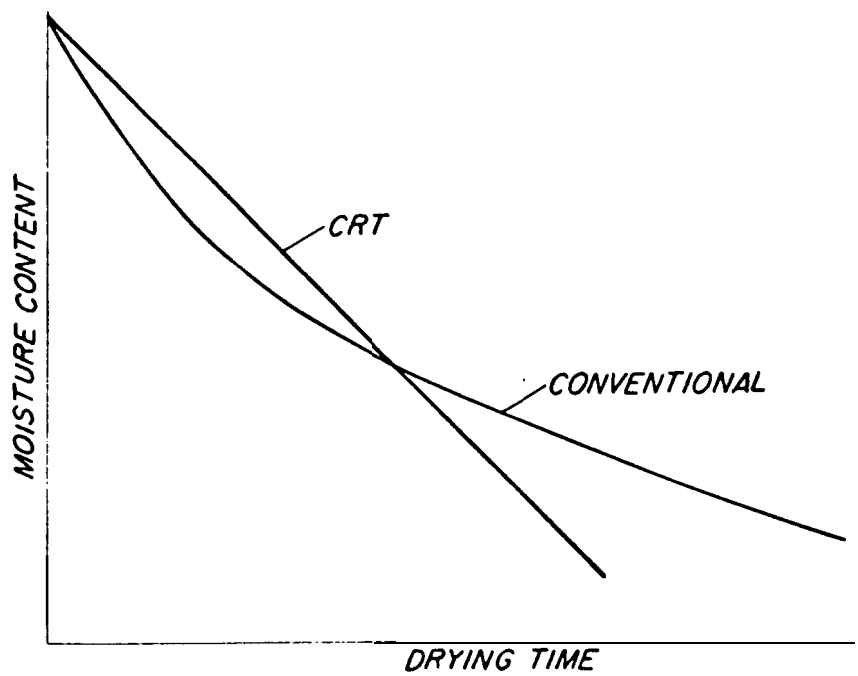

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FIGURE 10. Schematic drying curve of CRT constant rate vs. conventional falling rate drying.

operate by passing air over cooling coils of a dehumidifier and condensing water. The dried air is then reheated and sent back to the drying chamber. The latent heat of vaporization is recovered and used in drying. Lack of venting losses and recovery of the heat of vaporization combine to make dehumidification drying more energy efficient than conventional kiln drying. Pratt (1968) found that energy consumption in dehumidification drying ranged from 15 to over 50 percent less than in conventional kiln drying, depending on species. Cech and Pfaff (1977) also found energy reductions of over 50 percent.

Dehumidification is not, however, without its penalties, Drying times to final moisture content are often two or more times longer than in a conventional kiln operated at higher temperatures. Even though total energy consumption is reduced, electrical energy is required, which is often more expensive than alternate sources of energy. Recent advances in equipment technology have raised the operating temperature of dehumidifier dryers to 70-80° C, so newer dryers are not necessarily limited to low-temperature drying.

Solar Drying

Interest in solar drying of lumber dates back many years, but the energy crisis of the early 1970's brought on a flurry of activity. Most of the activity has been confined to design and testing of small experimental dryers, with only a few in commercial use. The proposed designs, both greenhouse and external collector types, have usually been intended as low-cost dryers, often for use by small producers or in tropical developing countries. With only a few exceptions, the designs incorporate flat-plate collectors with air as the heat transfer medium. Typical temperatures realized in solar kilns usually range from 15-20° C above ambient, with maximum temperatures of from 50-60° C. Controls have usually been crude or non-existent, but there has been a recent trend to provide some control through low-cost humidistats, thermostats, humidifiers, etc.

Plumtre (1967, 1973) designed a solar kiln in Uganda. He built several versions, observed their performance, and then made improvements. The design has operated successfully in commercial use for several years. Gough (1977) designed and built a production capacity solar kiln for use in Fiji. The dryer was built as an experimental unit, but practical economic and technical details were carefully considered so that the final design is offered for commercial use. Tschernitz and Simpson (1979) have designed a low-cost solar kiln that has been operating successfully at a furniture factory in Sri Lanka for several years. The kiln is equipped with low-cost controls that allow unattended kiln operation. Chen et al. (1982) have coupled dehumidification and solar drying. The resulting dryer takes advantage of the two energy efficient technologies in a low-cost dryer that can operate 24 hours a day with a minimum of purchased energy.

One notable exception to the low-cost solar kilns that have been designed is a kiln built in the southern United States with U.S. Department of Energy funds (Robertson and McCormick, 1977). The system is built with state-of-the-art solar technology using factory manufactured collectors and other system components and is far more costly than the relatively unsophisticated solar kilns built previously. The system has a lumber capacity of 100 m^3 and was designed to test technical and economic feasibility of solar heating in commercial size kilns. The design goal was for solar to provide about 40 percent of the total energy and natural gas the rest. A water system was used to provide both heat transfer and energy storage.

Process Control

Process control in lumber drying is still often limited to cumbersome manual sampling procedures or inexact time-based procedures. Recently, however, two new methods have been implemented to a limited extent, and both are based on the fact that electrical properties of wood change with moisture content. James and Boone (1982) describe an evaluation of two slightly modified commercial in-kiln moisture monitors that measure the change in dielectric properties of wood as it dries. Electrodes are placed within the stacked lumber before drying begins and thereafter give a continuous monitor reading throughout drying. Even though it is not possible to accurately calibrate the monitor readings with moisture content, experience with monitors in specific kilns with repetitive lumber configurations leads to a characteristic monitor reading vs. time relationship that allows operators to determine when final moisture content is reached. These monitors are used primarily in drying softwood structural lumber, where the most important need is a reliable and easily determined estimate of when target moisture content is reached.

The second process control method, based on a continuous monitoring of moisture content, uses the increase of electrical resistance of wood with decreasing moisture content. Electrodes are imbedded into the wood at a numer of locations. Another type of probe senses the EMC conditions in the kiln. Once the wood has fallen below fsp, the imbedded sensors can begin providing useful estimates of internal moisture content. These estimates are compared to the EMC conditions of the kiln, which estimates surface moisture content. With surface and core estimates, the operator has an estimate of the moisture gradient. Experience then reveals approximations of maximum safe moisture gradients that allow drying to proceed as rapidly as possible without drying defects. One of the problems with this type of monitor is changes in contact resistance as drying proceeds. These changes may be due to surface polarization or other electro-chemical surface effects. In any case, the reliability of the readings is suspect.

Vacuum Drying

Researchers in wood drying have long recognized the potential benefits of vacuum drying. By drying wood under vacuum, the boiling temperature is lowered, and the free water in wood can be vaporized and removed rapidly below 100° C. Drying rate is therefore increased without the dangers of defects that would surely develop during drying at 100° C. The problems with vacuum drying systems have been development of techniques for energy transfer to the wood and the high cost of the equipment. In a recent development (Koppelman, 1976; Woodworking and Furniture Digest, 1982) dielectric heating has been combined with vacuum drying in a process just now gaining some commercial acceptance. The system reportedly can dry lumber faster than possible in a conventional dry kiln, and with no drying defects. The best application of the process seems to be for high value, thick lumber that might take weeks or months to dry conventionally. For example, 100-mm-thick oak is reported to dry in 72 hours. Normal drying time in a kiln would be several months. Despite the high cost of the equipment, economic analyses by the manufacturer estimate that the dryer has a cost advantage over kilns in drying high value, thick hardwood lumber. In another variation of vacuum drying, Pagnozzi (1982) has developed a method of introducing steam into a cylinder. An energy recovery system is also incorporated.

Veneer Drying

Current veneer dryers depend on air-to-wood heat transfer either by parallel flow or high speed perpendicular impingement. In a new type of veneer dryer recently implemented, the sheets are pressed between hot platens (Allen and Pierson, 1980). The primary advantage is better heat transfer to the veneer and therefore a reduced drying time. Platen temperatures range from 120 to 200° C and platen pressures from 35 to 500 kPa. Drying times range from 2 to 12 minutes compared to an hour or more in some convection dryers. An additional benefit of platen drying is the reduction in warp that drying under pressure restraint provides.

Warp Control

Warp has always been a problem in drying, but in some countries it has become more of a problem as the nature of the timber resource has changed. Large diameter, old growth trees are no longer always available. Small diameter, young growth, sometimes plantation grown, is becoming the norm in many countries. Young growth timber often has a high proportion of juvenile wood present, which shrinks more longitudinally than normal wood and leads to warp. Because of this characteristic, crook, bow, and twist in softwood structural lumber is a major concern. Various methods are being used commercially to reduce warp. One of the simplest methods is restraint imposed by weighting the top of lumber stacks with 500-2000 kPa (Mackay and Rumball, 1971). This reduces the vertical

distortion of bow and twist but not the lateral distortion of crook. Koch (1971) developed a stacking system that clamps boards so that they cannot warp laterally and develop crook. A further precaution against twist is to apply a reverse twist during stacking (Australian Forest Industries Journal, 1973) by raising one corner of the stack base. All of these restraint methods require high-temperature drying for maximum effectiveness. High temperatures increase stress relaxation, so that when restraint is released, boards are less likely to distort.

DRYING TECHNOLOGY OF THE FUTURE

The age-old fight in advancing drying technology is product quality vs. drying time. Sometimes we cannot have both high product quality and short drying time, but some of the advances in the past 5-15 years have shown that opportunities exist to reduce drying time and still avoid serious drying defects. I would expect future drying research and development to continue this struggle to identify opportunities to reduce drying time. What follows is a description of several avenues of research pursued in recent years. The ideas have either not been implemented or implemented to only a limited extent, but they do represent Potential for improvements in drying technology.

Pretreatments

While we cannot engineer wood structure to be favorable for drying, we can consider ways to modify it or its interaction with water to improve drying. Research in pretreatments has aimed at techniques to increase drying rate or reduce susceptibility to drying defects. Presurfacing is one pretreatment that reduces both drying time and drying defects in oak lumber. When boards are sawn from logs, their surfaces have many small fractures and tears left from the saw blade. During drying these fractures act as points of stress concentration and open up into surface cracks. If the lumber receives a shallow presurfacing before drying, the surface tears are removed and the incidence of surface crackling is reduced. This in turn allows faster drying as well as increased kiln capacity by reducing thickness (McMillen and Baltes, 1972).

Cech (1971) has developed a precompression process whereby lumber is momentarily compressed from 2.5 to 20 percent of its thickness before drying. The result is creation of many microscopic splits in the impermeable pit membranes of hardwoods and an increased drying rate. The increased permeability greatly reduces susceptibility to drying defects and allows acceleration of drying. Precompressed yellow birch was dried at high temperature in 200 hours compared to the usual 430 hours at lower temperatures. Presteaming has also been shown effective in increasing the drying rate of some species (Simpson, 1975).

Wetwood

A problem that has plagued wood drying technology for many years is beginning to be understood, and the potential to reduce the problem looks promising. Trees of several commercially important species groups (pines, firs, hemlocks, oaks, and poplars) are susceptible to infection by bacteria in the living tree. An association has been found between this infection and subsequent drying problems with lumber and veneer cut from infected trees (Ward and Pong, 1980). The term wetwood has developed *over* the years because one of the symptoms of bacterial infection is pockets within the wood that are higher than normal in moisture content and quite impermeable compared to normal wood. Wetwood dries more slowly than normal wood, and since wetwood and normal wood are often mixed in the same dryer and even the same board, the final moisture content varies unacceptably. In addition, wetwood is more susceptible to honeycomb and collapse than normal wood. Present techniques for separating wetwood from normal wood are either unreliable or time consuming laboratory tests. The goal of research in this area is to develop separation techniques that are fast and reliable enough to be used in production. Ward (1983) has reported results that show differences in electrical properties may be a base for separation.

Continuous Lumber Dryer

Veneer drying cycles are short enough that continuous dryers are possible. Even though a continuous lumber drying process has long been a dream of many researchers, the long drying times of lumber make it impractical. However, recent advances in high-temperature drying of non-collapsing, permeable species like radiata pine and the United States southern pines have changed that thinking. With permissible drying temperatures of 140-150° C, the drying time can be shortened enough that a continuous dryer becomes a practical possibility. Christensen and Barker (1973) developed a prototype continuous feed dryer where 25-mm-thick radiata pine can be dried in 4 hours at 140° C and an air velocity of about 10 m/sec. Boards are loaded into racks that are bolted onto a conveyor chain to help reduce warp. The racks then slowly move the individual boards through the dryer. Koch and Wellford (1977) have developed a concept for a continuous tunnel dryer in which stacked lumber is moved continuously through a zone-controlled tunnel. In simulation studies in a conventional kiln they showed that Southern Pine structural lumber 44 mm thick can be dried at 132° C and an air velocity of 8 m/sec. in about 12-14 hours. The dryer they envision would have several zones for drying, conditioning, and cooling, and would be 30 meters long.

Press Drying

Press drying of veneer has been implemented. Press drying of lumber, however, presents problems that do not affect veneer

drying. Therefore it has had very limited implementation. But because press drying means greatly reduced drying time, it has been the object of considerable research. The main problem is the development of honeycomb, but the payoff is drying cycles for 25-mm-thick lumber of only 1-2 hours compared to a week *or* more in a dry kiln. Schmidt (1967) reported on a commercial process in Denmark on press drying of 25-mm-thick European beech for flooring. Drying from 80 to 7 percent moisture content took 1-2 hours at platen temperatures of 150-170° C. Hittmeier et al. (1968) press dried nine hardwood species at 170° C platen temperature to 6 percent moisture content in from 20 to 200 minutes, depending on thickness (12 or 25 mm) and species. All species showed drying defects ranging from minor for some of the lower density hardwoods at 12-mm thickness, to major for the higher density hardwoods at 25-mm thickness. Haygreen and Turkia (1968) press dried aspen and paper birch at 170° C in from 80 to 130 minutes and noted major defects in aspen heartwood. Quality of the paper birch was apparently acceptable. Chen (1978) press dried 25-mm-thick walnut and noted the presence of honeycomb. Alternating ambient air drying with press drying significantly reduced, though did not eliminate, the occurrence of honeycomb but extended the drying time. Chen (1979) showed that prefreezing reduced but did not eliminate honeycomb in press dried walnut.

Recent research has shown two potential ways to reduce honeycomb and still retain the advantage of greatly reduced drying time. One way is to precede press drying by a lower temperature pre-drying to approximately the fsp (Schmidt, 1967; Simpson, 1982a). This apparently alters internal stress levels and strength properties enough to avoid honeycomb. The process still requires an unshortened pre-drying time, but the press drying from fsp to final moisture content is less than 1 hour in a press compared to as much as 1 week in a dry kiln. The second way to reduce honeycomb in press drying can be applied without the necessity of low-temperature predrying. By altering the pattern by which boards are usually sawn from logs it is possible to avoid honeycomb (Simpson, 1982b). Boards can be produced and oriented in the press so the critical internal tension forces that cause honeycomb are oriented in such a way that the compressive force of the press counteracts them and prevents honeycomb.

Other Rapid Drying Processes

In addition to press drying, several other rapid drying methods have been developed recently. Rosen and Bodkin (1978) developed an experimental jet impingement dryer for lumber. In this dryer, air heated to between 100-200° C is impinged perpendicular to the surface at velocities ranging from 5 to 45 m/sec. Drying times for maple ranged from 1.2 to 37 hours depending on board thickness (25 and 50 mm), air velocity, and temperature. Air velocity above 10 m/sec. did not reduce drying time. Honeycomb was present and

severe in all 50-MM boards and still present in 25-40 percent of the 25-mm boards.

Rosen (1981) has also developed a prototype pressure steam dryer where the circulated steam in the drying cylinder is generated from the wet wood. Drying is done at temperatures from 115° to 150° C and at pressures up to 2 atmospheres. One advantage of this system is the ability to control the relative humidity in the dryer at levels higher than are possible at high temperatures at atmospheric pressure. Therefore, the high drying rates possible at high temperatures are realized, but the severity of drying conditions can be tempered somewhat by the ability to maintain high relative humidities in the dryer.

Process Control

Process control in lumber drying is usually based on some estimate of moisture content. In many cases the limiting factor in drying is the internal stresses that lead to drying defects. If we could somehow monitor internal stresses we might be able to use them as warning signals that drying defects are about to occur. In this way, drying rate could be pushed to the maximum without drying defects.

Hill (1981) has developed a differential strain gauge that is capable of monitoring internal strains during drying. Surface fibers dry before interior fibers and thus shrink first. The result is a differential strain between shell and core that can be measured at the edge of a board by this gauge. The differential strain increases as drying progresses, then reaches a maximum and begins to decrease as the core begins to dry and shrink. If this strain record can be correlated with development of drying defects, it will provide a powerful tool in process control.

Another use of internal drying stresses for process control is that of acoustic emissions as an early warning signal of the approach of dangerously high internal stress levels. Several researchers (Skaar, et a1., 1980; Noguchi, 1980; Becker, 1982) have shown that during drying, low-level acoustic emissions are produced that are inaudible unless isolated from extraneous noise and amplified. Furthermore, they have shown that the rate of drying and incidence of surface cracks is related to the amplitude and number of acoustic emissions. If a reliable correlation between defects and acoustic emissions can be developed to identify the approach of dangerously high emissions, then drying rate can be maximized and defects minimized.

High-Frequency Drying

High-frequency electrical energy for wood drying has been studied for many years in research and prototype development studies. High equipment and energy costs have prevented more than token

implementation. However, the method is attractive enough that research and development continues, and perhaps as the relative costs of energy sources shift in the future, electrical energy may become competitive. High-frequency heating has ihe advantage of rapid and direct energy transfer to all parts of a piece of wood rather than by conduction from external heat sources. The result is the possibility of rapid drying--in fact, so rapid that considerable research is devoted to maintenance of quality. Another advantage of high-frequency heating is that energy is preferentially absorbed by high moisture content regions, and a moisture leveling effect occurs. McAlister and Resch (1971) successfully dried 25-mm-thick pine in less than 3 hours using a microwave dryer. This compared to normal kiln drying times of 3 days. They manipulated microwave power input and dryer air temperature to eliminate drying defects. Barnes et al. (1976) developed a prototype continuous microwave dryer for softwood structural lumber. Hemlock and Douglas-fir 50 mm thick were dried in 5-10 hours with little degrade. This compares with several days in conventional kiln drying. Despite the dramatic decrease in drying time, the authors did not believe the process would be economically feasible except for high value products.

SUMMARY

In this paper I have attempted to review the fundamentals of wood drying, traditional wood drying practices, new drying technology that has been implemented recently, and new technology that seems promising but is still in the research and development stage.

Most of the recent advances in drying technology have been motivated by the following factors.

1. Growing recognition of the economic value of lumber and veneer and the need to maintain quality of the dried product.

2. Growing recognition of the high cost of long drying times.

3. Increased concern over energy consumption.

4. More interest in sophisticated drying processes and methods of process control.

I expect drying research and development in the future to also be motivated by these factors. The timber resources of any country are a valuable, and sometimes scarce, asset. Wise and efficient use of these natural resources will help extend the timber supply and bring economic benefit to both producers and consumers. Improved drying technology is one way to improve efficient use.

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