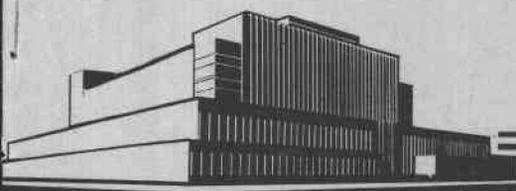


STRESSES IN WOOD DURING DRYING

Revised December 1958

(Report)
No. 1652



FOREST PRODUCTS LABORATORY
MADISON 5, WISCONSIN

UNITED STATES DEPARTMENT OF AGRICULTURE
FOREST SERVICE

In Cooperation with the University of Wisconsin

STRESSES IN WOOD DURING DRYING

By

J. M. McMILLEN, Technologist

Forest Products Laboratory,¹ Forest Service
U. S. Department of Agriculture

During drying, wood is subjected to highly complicated internal stresses. They come about because the outside of a piece of green wood dries below the fiber saturation point and tries to shrink before the interior is ready for shrinkage. They are greatly influenced by the temperature and relative humidity of the air in which the wood is dried. An understanding of these stresses is essential to kiln operators and others who set out to develop drying procedures, because the stresses can be used to advantage and unfavorable effects avoided. Initial drying conditions can be set up that will avoid surface and end checks, retain maximum dimension, and minimize warping. Intermediate and final kiln conditions can be modified to speed drying without fear of internal defects. Final conditioning treatments can be used when necessary to relieve residual stresses at the end of kiln drying, thus avoiding distortion when material is resawed or machined to a nonsymmetrical pattern.

The stress-set problem in wood has long been known as "casehardening." Early kiln operators found that wood dried in the "hot-box" kiln became extremely dry and hard on the surface. They therefore blamed "casehardening" for all their troubles. Early research workers found that the cause was stresses, not hardness. They retained the name, "casehardening," however. Later experiments by seasoning technologists at the Forest Products Laboratory and elsewhere have added considerably to the knowledge of stresses and set in wood.

A recent series of studies on red oak has emphasized anew that stress and set are not confined to the "case," or outer shell, of the wood; that the shell in properly seasoned wood is not "hardened"; and that the kiln operator

¹Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

who understands drying stresses and sets has a decided advantage. He can, for example, dry black walnut, one of our most valuable woods, very rapidly without surface checking or honeycombing, entirely free of stresses, for such exacting uses as the cabinetwork shown in figure 1. On the other hand, if he ignores drying stresses, he can risk the troubles shown in figure 2. The choice is his!

The purpose of this report is to state the basic facts on drying stresses and sets and to give simple procedures a kiln operator can follow to dry wood rapidly and produce stress-free stock. Some actual research results are used for illustrative purposes; for further details, the technologist may consult the references.

Cause and Nature of Drying Stresses

Basic Factors Underlying Stress Development

In order to understand the formation and effects of stresses in drying wood, several factors must be kept in mind:

1. When any portion of a piece of wood loses moisture below the fiber saturation point, it tends to shrink. Conversely, when any portion of the wood that is below the fiber saturation point absorbs water, it tends to swell.
2. If the normal shrinkage of wood, or any other material, is restrained, a tensile stress is produced within the material.
3. Tensile stresses in one part of a structure must be balanced by compressive stresses elsewhere in the structure.
4. When a material is stressed, it becomes distorted, or strained. Strain produced by short-time stress below a certain limit (called the proportional limit) substantially disappears when the load is released. This strain is called the elastic strain. Stress beyond the proportional limit, or stress below the proportional limit applied for long periods of time, produces some strain that does not disappear upon release of the load. This permanent strain is called set.

The basic ideas of stress, strain, and set for any kind of material and any kind of stress are illustrated in figure 3. A stress is a mutual force per unit area between contiguous surfaces, and is often expressed in terms of pounds per square inch. A strain is a change in dimension and may be expressed in terms of inches per inch of original dimension. Set, the permanent strain, also may be expressed in terms of inch per inch. In this report

it is shown as a difference between normal wood shrinkage in percent and actual shrinkage in percent. A 2 percent difference in shrinkage represents a set of 0.020 inch per inch.

General Stress-Set Pattern in Drying Wood

The kiln operator is generally familiar with the casehardening test section shown in parts A, B, and C of figure 4. Early in drying, the prongs will turn out as in A. Fully dried material shows typical casehardening as in B. In properly conditioned wood, the prongs are straight as in C. To fully understand drying stresses and sets, however, more exact tests are needed.

If the test section were cut into 10 instead of 3 prongs, a better idea of the stresses throughout the section would be obtained. The change in length of each prong as it was cut would show the elastic strain in each zone of the wood, provided the prongs were kept from curving. During the early stages of drying, results such as those shown in figure 4, D would be obtained. The unsliced piece would be slightly smaller than the same section in the green condition, as shown by the dotted line. Then, as each prong was cut, it would shorten if it had been held in tension or lengthen if it had been in compression. The shortening or lengthening would be measured from the dotted line.

In the special studies that tell most about drying stresses, green boards are marked off in sections and each section in slices as in figure 4, E. At any stage of drying, a section can be cut from the board, the freshly cut end of the board then being end coated and the board replaced in the kiln for further drying. The length of each slice in the section is measured by a micrometer, as in figure 4, F, before the slices are cut from the section. When the slices are cut completely free of the section they are remeasured as in G. The difference in these two measurements gives the elastic strain. From these strains one can calculate actual stresses in pounds per square inch by use of data now available on the stress-strain relationships across the grain at various moisture content values and temperatures.

Set, the nonrelieved or permanent strain, is shown in figure 4, H. The outside slices, which exhibit less than normal shrinkage, were set while under tension. The interior slices, which exhibit greater than normal shrinkage, were set under compression.

The general pattern of drying stress development in hardwoods is fairly well known. Individual hardwoods, of course, differ from the general pattern. Less is known about the exact pattern of stresses in softwoods. Most of the discussion in this report is based on knowledge of stresses in hardwoods.

Typical drying stresses and moisture gradients at different stages in the drying of red oak heartwood 2 inches thick are shown in figure 5. The relative contraction of a slice upon being released from tension is shown by a black bar extending below the zero line. The relative elongation of a slice upon being released from compression is shown by a bar above the line. While these contractions and elongations are technically strains they indicate the type of stress and give some idea of its magnitude, so they have been labeled as "stress" in figure 5. The main points shown by figure 5 and related set data are:

1. The surface tends to come to the equilibrium moisture content of the kiln atmosphere (EMC), as defined in terms of the moisture content wood will attain in such an atmosphere.
2. The outer zones of the wood thus dry below the fiber saturation point and tend to shrink but are restrained by the interior zones, which have not begun to shrink.
3. As a result, the outer zones are subjected to a tensile stress, and, as a reaction, the interior zones are subjected to a compressive stress.
4. Because of tensile stress beyond the proportional limit and the action of prolonged stress, tension set begins to take place in the outer zones almost immediately after they start to dry, and it gradually increases to a maximum.
5. The tensile stress in the outer zones rapidly proceeds to a maximum; in figure 5 this is shown occurring in 5 days.
6. As drying goes on, succeeding inner zones change from compression to tension and maximum tensile stresses develop that are not as big as the maximum in the outer slices.
7. In the center zones, maximum compressive stress develops more slowly.
8. As compressive stress in the interior zones increases beyond the proportional limit and stress is prolonged, compression set begins to take place.
9. Because tension set in the outer zones gives those zones a dimension larger than they would normally have at any moisture content, the stress in the outer zones changes from tension to compression as the interior zones dry and shrink in a more nearly normal manner.
10. Stress reversal is completed when the center zones go into tension.

11. After complete stress reversal, the outside zones rapidly proceed to a maximum compressive stress and the center zones to a maximum tensile stress. This tensile stress is influenced by the amount of compression set that previously occurred. At this time, the center zones of the wood are still near the fiber saturation point.

12. The strains continue about the same until drying is completed, although they generally are reduced somewhat as a result of prolonged duration of stress.

Examples of Drying Stress in Various Woods

The foregoing general points will be better understood by consideration of some of the actual results of drying stress research. In the figures that follow, the contractions and elongations of the slices are shown as tensile and compressive strains. The strains are shown in continuous curves as drying proceeds, in order to show the continuously changing pattern. The values shown are unit strains; the units are inch-per-inch. These actual strains are quite small; for instance, a strain of 0.003 inch per inch of board width is the equivalent of a 0.03-inch contraction of a 10-inch-wide strip.

Stress reversal in blackgum sapwood. -- Figure 6 shows the strains observed in the outside and center slices of a 2- by 10-inch blackgum sapwood board dried at a constant dry-bulb temperature of 180° F. For the first 2 days of drying, the relative humidity was 85 percent, corresponding to an EMC of 12.9 percent. The next day the EMC was 11.4 percent. Stress reversal occurred rapidly and completely during this step. For the fourth day the EMC was changed to 4.8 percent without any surface checks occurring! The outside layers were in compression. This same stress pattern has been observed in a number of the less refractory hardwoods. It is obvious that, after stress reversal occurs in hardwoods of this type, the relative humidity or EMC can be reduced drastically without fear of surface checking.

Stresses in red oak heartwood. -- Figure 7 shows the strains observed in all slices of a 2- by 7-inch board of northern red oak heartwood dried at 110° F. with small reductions in relative humidity as drying progressed. Slight adjustments in temperature were made at the end of the run to help in obtaining the low EMC condition desired. Development of stresses was slower and more readily observed at these lower temperatures and with a slower drying wood.

Maximum tensile strain in the outside slices was reached very early in the drying period. At that time, all of the interior slices except Nos. 2 and 9 were in compression and had the same amount of strain. Slices 2 and 9, which had gone into slight compression at the start of drying, were just going into tension. As drying progressed, the tensile strain in the outside slices decreased and the compressive strain in the center slices increased. Slices 2 and 9 increased in tensile strain, but did not reach the maximum strain of the outside slices. The center slices reached a maximum compressive strain at 18 days of drying, and their compressive strain stayed near this maximum until the outside slices were about ready to pass from tension into compression.

Slices 3 and 8 changed from compression into tension at the 19th day of drying. Slices 4 and 7 did not reach so high a compressive strain as the center slices. Soon after the outside slices went into compression, slices 4 and 7 went into tension and the center slices also went into tension a short while later.

Soon after the completion of stress reversal, the outside slices reached a maximum of compressive strain and the center slices reached a maximum of tensile strain. At the low temperatures in this test, the tensile strains in the interior were considerably smaller than the maximum tensile strains that developed in the outside slices. Although there are slight adjustments in the strains of the various slices, the general pattern after stress reversal remains the same until drying ends.

Stresses in sweetgum heartwood. --In another experiment, a 2- by 10-inch sweetgum heartwood board was dried at an initial dry-bulb temperature of 135°, a final temperature of 160° F., and more abrupt reductions in relative humidity. The results are shown in figure 8. As in the tests with blackgum and red oak, the maximum tensile strain of the outside slices was developed rapidly. After this maximum was passed, the EMC was lowered to 5.5 percent in 3 rapid steps in an attempt to maintain the tensile strain in the outside slices at or near the maximum. The changes in EMC had no apparent effect on the strain curves for the outside slices. Rapid development of tensile strain occurred in slices 2 and 9, while the compressive strain in the other inside slices increased. It is significant that the tensile strain in slices 2 and 9, even under these drastic drying conditions, did not reach so high a value as the maximum of the outside slices. Thus, tensile strain of slices 2 and 9 would not be expected to cause checking if no checking started at the surface.

Under the EMC conditions in this test, the outside slices apparently took on enough tension set to change the details of the strain pattern from those of the oak. These outside slices went into compression 12 days before the center slices went into tension. The maximum tensile strain in the inside slices,

however, did occur soon after completion of stress reversal, and the outside slices were about at maximum compressive strain at this time. These interior tensile strains were about twice as great as the matching strains in red oak after stress reversal.

Some decrease of compressive strain in the outside slices resulted from the use of the higher temperature during the last 10 days of drying.

Other stress data, including softwoods. -- Considerable additional information on drying stresses in red oak has been obtained in recent research at the Forest Products Laboratory (5, 6).² It shows that oak has similar stress patterns under a variety of temperature and humidity conditions. These patterns are somewhat different from the sweet-gum heartwood pattern. The woods which have stress-reversal patterns similar to that of blackgum sapwood in figure 6 are magnolia, sycamore, and yellow-poplar sapwood. Some limited stress data on black walnut show a pattern similar to that of the oak.

There is very little drying stress information on softwoods. The results are not easy to understand because the strains are considerably smaller than those in the hardwoods and techniques had not been perfected at the time of the tests. Espenas (3) reported that softwoods, notably Douglas-fir, do not develop the same stress patterns as most hardwoods. Tensile stresses that produce surface checking persist long into the drying cycle. During the middle and final stages of drying higher relative humidities are required than in drying hardwoods. Finally a reversal of stresses develops and humidity control is no longer needed. In one Forest Products Laboratory test many years ago, white pine underwent stress reversal while somewhere between 18 and 14 percent moisture content. A few recent exploratory tests on 8/4 ponderosa pine, white fir, and Engelmann spruce tend to confirm these early findings; stress reversal occurred at about 18 percent average moisture content.

Probably the rapid movement of water from the interior to the surface during the drying of softwoods results in a moisture gradient that is not so steep as those of the heartwood of hardwoods. Thus, there is less tendency for strong tensile stresses to develop in the outer layers during drying. The comparative tensile and compressive properties of the wood perpendicular to the grain and the tendency to become set also must be taken into consideration. Softwoods do, however, become surface and end checked, honeycombed, and casehardened; so they ultimately undergo the same general pattern of stress development as the hardwoods. The exact details of the softwood stress patterns, rather than the general pattern, are what are lacking.

²Underlined numbers in parentheses refer to literature cited at the end of this report.

An attempt was made to develop stress data for maple bowling-pin blanks, which are essentially all sapwood. Although the data are somewhat obscure, they indicate stress reversal does not occur until comparatively late in drying. Presumably, the maple sapwood has a flat moisture gradient like the soft-woods and therefore does not follow the hardwood heartwood pattern.

Effects of Drying Stresses

It has long been known that drying stresses that have not been kept under control have many ill effects. Surface and end checking, splitting, collapse, honeycombing, and severe casehardening are all directly connected with excessive drying stresses. Therefore, early kiln schedule research was generally directed toward keeping stresses at a minimum. Drying stresses, however, produce sets, and these sets act to modify stresses considerably during the drying process. On the basis of some detailed knowledge of stress and set, therefore, kiln schedules for hardwoods have in recent years been modified to shorten drying time greatly. Also, some use has been made of low-temperature drying and its resultant sets to minimize shrinkage and warping. These positive aspects of stress and set control, however, have not been fully realized.

Set, a Tool in Drying-Schedule Development

Stresses always occur in wood as it dries. Usually the drying gradient is steep enough to cause the stresses to exceed the proportional limit of wood in tension or compression and cause set. The time factor also contributes to set. If the drying conditions can be manipulated to cause set in proper amounts, yet not cause drying defects, stresses will be reduced sooner and drying can be accelerated without danger of surface checks, end checks, and splits. There are two types of set, tension set and compression set. Both must be taken into consideration. There is no quick and easy way for a kiln operator to determine the stress and set condition in the wood he is drying and thus operate each kiln run on an optimum schedule based on drying stresses. He can, of course, rapidly determine when the stresses have completely reversed, but with modern kiln schedules usually all relative humidity changes are made by the time stress reversal has been completed. Lacking more precise methods, therefore, the kiln operator should use the kiln sample method to follow schedules based on the moisture content of the stock to which the stress and set pattern are directly related. A good knowledge of stress will help him to understand the fundamentals of kiln schedules.

Set, a Tool for Decreasing Shrinkage and Warping

It has been generally held that a maximum of tension set, developed by use of low temperatures and low humidities during the initial stages of drying, would reduce the overall shrinkage of lumber being dried and produce the greatest amount of dry board footage from a given volume of green material. What has not been realized, however, is the effect of compression set on this result. Information developed during research on the stresses in red oak heartwood has shed considerable light on how set can be manipulated to control shrinkage.

Figure 9 shows the effect of two different relative humidity schedules on the set in red oak at 110° F. The data shown were obtained by carefully drying the slices from the stressed wood to the ovendry condition without developing new set in the process. Under these conditions, slices 2 and 9 had approximately normal shrinkage during the first half of the drying process. Slices 1 and 10, which underwent tension set, shrank less than normally. Such tension set started to occur as soon as drying started and continued to increase during the first third of the drying. Tension set in the outside slices was increased by having a more severe relative humidity schedule at this one temperature, 110° F. Compression set, as evidenced by greater-than-normal shrinkage, did not occur until just before maximum tension set developed. A comparison with the strain curves for these kiln runs would have shown that compression set in the interior started shortly before the center slices reached their maximum in compressive strain. The amount of compression set is apparently smaller with the more severe relative humidity schedules.

Only two slices had tension set at this temperature, while six underwent compression set, so that the resultant shrinkage was probably affected more by the compression set than by the tension set.

In any given humidity schedule pattern, the temperature appears to have little effect on the amount of, or number of zones with, tension set. The exception to this seems to be at temperatures below 90° F., where slices 2 and 9 as well as 1 and 10 appear to have considerable tension set.

If a kiln schedule is developed entirely on the basis of speed of drying and avoidance of visible seasoning defects, it may possibly work out to give a maximum of shrinkage rather than a minimum. Such shrinkage can result in a considerable reduction of footage in kiln-dried stock. Details of some temperature effects on shrinkage will be discussed in the section of this report on kiln schedules.

The type of warp known as cupping is affected by the differential in percentage shrinkage between the radial and tangential directions. The less the shrinkage, the less the cupping. Also, the tension set that occurs during the first stage in drying, while the lumber is held flat, will work to keep the lumber flat in spite of the ring curvature and the differential in shrinkage between radial and tangential. It must also be argued, however, that the compression set in the interior slices will tend to increase cupping in spite of tension set in outside layers. Anyone attempting to use stress control and set to control warping should keep this fact in mind.

Surface Checking, End Checking, and Splitting

Checking and splitting stem from the same source, reduction of the surface moisture content to a value so low as to cause stresses that exceed the maximum tensile strength of the wood perpendicular to the grain. These are tensile stresses, tending to pull the wood apart. They are very great, and so the kiln operator should be alert to keep kiln conditions under perfect control during the early stages of drying, when these defects are most likely to occur. They need not be feared after stress reversal has taken place.

Splits and checks reduce the strength of wood, particularly in shear. Checks that have closed may escape detection, but the weakness is still present because the bond between the fibers has been broken. The reversal of stresses in the final stages of drying tends to close ordinary surface checks tightly. Overconditioning, however, or steaming of stock that has been checked during air drying, may reopen the checks, which stay open when drying ends. Even though the checks are closed, they may be hazardous if they are present in a highly stressed part of small cross section. Splits and checks are responsible for much waste during wood fabrication. They also cause greater amounts of waste if pieces containing them are allowed to go through the manufacturing process and they do not show up until many high-cost operations have been performed on say, an article of furniture. Surface checks may even remain hidden until opened by changes of atmospheric humidity after an article is put in use.

Collapse

Collapse, which may be defined as abnormal shrinkage accompanied by distortion of the cell wall structure, is caused in two ways. When the volume of wood that is in tension exerts on the interior wood a stress that exceeds the proportional limit of the compressive strength, the wood takes on a smaller dimension, which is commonly known as compression set. If the stress becomes so great that it exceeds the ultimate strength of the wood,

however, the cell walls will be distorted or crushed badly, and this constitutes one form of collapse. This is a common hazard when high temperatures are used.

The second cause of collapse, which occurs in the early stages of drying, is due to a liquid tension in the cell cavities that are completely filled with water and devoid of air. As water is evaporated from pit membrane openings, the very small meniscuses in the openings exert a strong pull on the water in the cell cavity. Since this water is held very tenaciously by the surface of the cell wall and the water itself has a very high cohesive force, the pull or force can sometimes exceed the strength of the wood in the cell walls. As a consequence, opposite sides of the cell wall are drawn together as the volume of water in the cell decreases. Such collapse can occur only when the fiber cavity is completely full of water and is inaccessible to air, since any air bubble in the cell cavity will expand and there will be no pull on the cell wall. The tensile forces are very much greater than the effect of a vacuum, which amounts to only about 15 pounds per square inch. High temperature has a vital effect on this form of collapse because it greatly lowers the strength of the cell wall.

Collapsed lumber often shows grooves on its surface, and in extreme cases collapse may severely distort the piece. Since the cell walls have been fractured, the wood has been weakened seriously.

The control of both forms of collapse is achieved during the first one-third of the drying, and the means of control is to keep the temperature down below critical values while the interior wood is at a high moisture content. The danger of liquid tension collapse is gone when there is some air or vapor in the cell cavity of every cell. The resistance to stress-caused collapse is least when the cell wall is above the fiber saturation point. Some of the wood still is considerably above this moisture content just before stresses reverse. This type of collapse can no longer occur after stresses reverse.

Honeycombing

Honeycombing is internal checking. The most common form develops along the wood rays of flat-sawed stock, but in quarter-sawed Douglas-fir and some other woods it may occur in the form of ring separation. The basic cause is always an internal tensile stress perpendicular to grain that exceeds the maximum strength of the wood. As seen above, internal tensile stress develops after the surface has taken on tension set and started to cause stress reversal.

There are several ways in which internal checks can form. These are: (1) deepening of surface checks to form what are sometimes called bottleneck checks; (2) extension of end checks; (3) spontaneous formation of new interior

checks during the normal course of drying; (4) failure of cells that have previously been collapsed; (5) separation between a layer of wood that is normal in drying characteristics and an adjacent layer of wood subject to a tensile force connected with the liquid-tension type of collapse; (6) separation of quarter-sawed stock along planes of weakness, such as the bond between the summerwood of one ring and the springwood of the next ring. A seventh way, formation of new interior checks by increasing internal tension of dried stock during steaming at 100 percent relative humidity, is a possibility, but at present there is no direct evidence to support it.

The first and second ways of forming internal checks are probably the most common. The fact that surface checks form in some of the wood when initial conditions are too severe does not prevent the rest of the surface layer from being set with a larger than normal dimension. As shown in figures 7 and 8, the first interior zones to go into tension are the second and ninth slices. Thus, if a surface check has extended into the zones beneath the surface, the points of the check will represent a plane of weakness which allows the check to extend deeper into the wood at stresses considerably lower than those necessary to start checking at the surface in the first place. As figures 7 and 8 show, all of the internal layers ultimately go into tension, and a honeycomb check thus started may go all the way across the interior layers of a piece before drying is completed. Such checks starting from surface checks not only may go deeper into the wood but can extend for considerable distances along the grain, depending upon the drying conditions used. Careful examination of the piece of lumber containing honeycomb checks will generally indicate that the checks started at either the surface or the end, but because of the compressive stress in the surface when drying stops, the initial check may be very tightly closed and invisible to casual inspection. Where the check is closed only at the extreme surface and open slightly below the surface, the cross section of the check may take on the form of a bottle and is called a bottleneck check.

A frequent form of honeycombing is the extension of end checks. No detailed studies like those for the transverse stresses have been made of end stresses and end set, but the same principles hold. Unless the drying conditions are very mild indeed, some end checks will form during the drying of any wood. If the conditions are mild, the end checks probably will be small and numerous and will not extend very far back into the interior. Under more severe conditions, one or more large end checks will form, and as the stresses reverse because of end set, the surface will close tightly and the end check will move back into a zone of internal tensile stress. This form of honeycombing can extend from one end of the piece to the other, depending upon the drying conditions. Losses can be severe from this type of honeycombing. Black walnut, which is not generally subject to surface checking, is very subject to end checking and subsequent honeycombing. Because of this, walnut gunstock blanks must be well endcoated.

It is, of course, possible for honeycomb checks to form spontaneously in the interior wood when the tensile stresses exceed the maximum strength of the wood. Although the strain information of the type shown in figures 6, 7, and 8 generally indicates that the amount of internal tensile strain is not as great after stress reversal as that developed at the surface during the first stage of drying, the wood in the interior has been subjected to the weakening effect of long-time exposure in the green condition to high temperatures and thus is weaker than the surface wood was at the start of drying. Therefore, the higher the temperature has been during this long stage of initial drying, the more likely is it that honeycomb checks will form. The stress experiments with oak indicate that greater internal compression set occurs at higher temperatures too, and that this internal compression set has an effect of increasing the tensile stress after stress reversal.

Honeycombing is rather unusual under normal air-drying conditions, but when it does occur the cause is believed to be an extension of surface or end checks.

Cells that have been greatly weakened by collapse or cell-wall distortion will be more likely to pull apart under tensile stresses after stress reversal. The tensile stresses brought about by liquid tension can also pull zones of such wood apart from normal zones not under such tension. Such pulling apart occurs usually in one of the wood rays, which represent planes of weakness, and cells on both sides of the ray can be distorted or collapsed upon abrupt release of the tensile stress.

It is not fully known just what causes a plane of weakness parallel to the rings of the wood that may open up to form a so-called ring separation. It is conceivable that different amounts of shrinkage in the springwood and summerwood, when they are at greatly different densities, result in shear stresses that contribute to honeycombing. The very dense summerwood of some species tends to shrink in the tangential direction up to 3 times as much as the adjacent springwood.

Honeycombed lumber is unsuitable for any use where high strength is required. It also is unfit for fabricating articles, since resawing, planing, and working will expose the interior checks. Severe honeycombing usually can be detected in rough lumber by visual inspection because of characteristic depressions running lengthwise on the lumber surface. In many instances, however, ordinary honeycombing is not visible until the lumber is crosscut, resawed, or ripped.

Casehardening, or Final Stress-Set Condition

Casehardening is a condition of stress and set in wood in which the outer fibers are under compressive stress and the inner fibers under tensile stress when

the wood is uniformly dry. It is the normal behavior of wood to undergo stress and set changes, or "casehardening" as it dries. In the present concept of the phenomenon, the wood is not "casehardened" until the stresses have reversed and both maximum tension set in the outer zones and maximum compression set in the inner zones have been achieved. By manipulation of drying conditions, it is possible to vary the amounts and location of both tension and compression set to advantage. Thus, early in drying wood cannot be "casehardened" severely, but a large amount of tension set can be achieved in a fairly deep surface zone.

Residual drying set and stresses will cause trouble when lumber is resawed. Such resawed lumber will cup (be concave) toward the sawline. When cupped lumber is run through a planer for surfacing, it may split. In fact, stressed lumber, even though flat, may split when put through the planer. In gluing, additional pressure is needed to bring the entire surface of one cupped lamination into contact with that of an adjacent lamination, and, even if good contact is secured, the glue bond is stressed by the tendency of such laminations to return to the cupped form. When casehardened lumber is scarfed for assembly into large laminations, cupping may occur during the scarfing operation and create an irregular scarf that will not glue properly. Also, a stressed piece of lumber will cup if, when being surfaced on two opposite sides, more material is removed from one side than from the other. Squares or other items may become seriously distorted if they are worked to patterns or irregular shapes. Thus, tongue-and-groove joints may not fit together.

Fortunately stresses can be relieved in a kiln in a reasonably short time by a proper conditioning treatment, either at the end of the kiln run or at a subsequent time. Methods of stress relief are described in a later section of this report.

Residual stress and set are not determinable by visual inspection. Special testing methods, such as the prong or slice methods described later, are necessary to detect it and estimate its degree.

Reverse Casehardening

If, in the conditioning treatment to relieve stresses or because of subsequent wetting, the surface layers of the lumber absorb too much water, they may swell so much that they relieve all tension set and take on a compression set. In this event, when the lumber assumes a uniform moisture content, the outside layers will be under a tensile stress while the interior ones will be under a compressive stress. Such a condition is known as reverse casehardening. This condition may be serious when lumber is resawed. The boards will cup (be concave) away from the sawline instead of toward it.

Severe reverse casehardening is rather rare with modern high-final-temperature drying and conditioning treatments. In fact, there is no danger that it will happen when controlled-humidity treatments described in this report are used. Mild reverse casehardening is of no consequence in most uses of wood. Whereas it was previously thought that there was no practical means of relieving severe reverse casehardening, some recent research at the University of Michigan indicates that it may be possible. This will be discussed later under the heading, "Recent Stress Relief Research."

Stresses and Kiln-Drying Schedules

Temperature Factors

Temperature during initial drying. -- It has generally been considered that, for each species of wood, there is a critical temperature that must not be exceeded during the initial stages of drying if the whole drying job is to be completed successfully. At present, there is no clear-cut connection between drying stresses and critical temperature. Experience has shown that surface checking is more likely to occur at a relatively high temperature during the early stage of drying. It is definitely known that prolonged use of a high temperature at that stage of drying will weaken the wood enough that it will honeycomb when subjected to internal tensile stress after stress reversal.

It appears probable, however, that a multitude of factors enter into the determination of critical temperature, rather than stress alone. Severe surface stress, leading to surface checking, would be expected when the moisture gradient is steep. The higher the temperature, however, the more rapid the moisture diffusion through wood. Thus it might be expected that, if relative humidity could be held high, the moisture gradient would be flatter at the higher temperatures.

Various strength factors also affect the critical temperature. Wood is weaker at high temperatures, therefore more prone to failure and development of surface checks at a given stress value. On the other hand, wood is more plastic at high temperatures and can yield or become set at lower stress levels than at the low temperatures. Until the information now available (2, 12) on the strength properties of woods perpendicular to the grain is properly correlated with the data on the influence of temperature on drying stresses, the critical temperature must necessarily be determined empirically.

High temperatures are known to have a tendency to cause collapse in woods that are prone to this defect. It is obvious that, if the wood cells are completely filled with water and relative humidity conditions are such as to pull

this water out by capillary action, the cell walls will be less able to resist this pulling force if the temperature is high. Thus thin-walled cells, such as those in redwood and western redcedar, will collapse when drying temperatures are too high.

Collapse caused by extreme compressive stresses during the first part of drying will also be accelerated by temperature. In the first place, the temperature will probably have some effect on the amount of compressive stress, but it probably will have its greatest effect on the ability of the cell walls to withstand the compressive force. When the stress becomes too great, and the effect on the wood goes from the point of compaction of material to that of distortion of the cell walls into the cell cavity, collapse occurs. Thus it is necessary to keep temperature comparatively low while the wood is subject to capillary withdrawal of water or to mounting compressive stresses. These generally continue to build up until just before stress reversal.

From the practical standpoint, it may be better to use a subcritical temperature during the initial stages of drying, followed by appropriately high intermediate and final temperatures so as to get lower cost and better quality wood with only a slightly longer drying time. In many instances, the water above the fiber saturation point comes out very easily. It should be possible to control the drying conditions to get free water out economically while controlling the effects of drying stresses.

As will be seen in the next section, surface checking is more likely to be related to relative humidity than to temperature, but at low kiln temperatures (100° to 110° F.) it is sometimes difficult to get relative humidity as high as desired because humidification is achieved by introducing a steam spray with the vents closed. The small amount of superheat in the steam as discharged to the atmosphere raises the temperature above the dry-bulb setting. Thus, control of very high relative humidities is more easily obtained at 120° and 130° F. than at lower temperatures. On the other hand, checks may occur more quickly when high initial temperatures are used if the kiln operator fails to keep relative humidity high enough.

Intermediate and final temperatures. -- During the intermediate stages of drying danger from surface checking is past, but interior compressive stresses and compression set are continuing to build up, so it is usually desirable not to exceed a critical temperature here.

After the reversal of stresses, high temperatures need only be concerned with their effect on internal tensile stresses. It has been stated that danger of honeycombing from such tensile stresses is past when the wettest zone in the wood goes below the fiber saturation point. As is well known, the drier the wood below the fiber saturation point, the stronger it is, and the less likely to fail as a result of the tensile stresses. Wood above 20 percent moisture content is still relatively weak, however, so that it is still subject to

failure with high tensile stresses, but the reduction of the time effect due to the rapid moisture diffusion at the high temperatures may avoid failure. Thus, wood between 20 and 30 percent moisture content should be considered to be in a marginal zone and, under some circumstances, use of too high temperatures here might cause it to honeycomb. In one experiment, use of a 220° F. temperature while one of the boards was at 22 percent average moisture content resulted in honeycombing. At such an average moisture content, the midthickness should be just at the fiber saturation point.

After the danger of honeycombing is past, it is desirable to use as high a temperature as possible to help relieve some of the previous exterior tension and internal compression sets. Thus the practical kiln schedule for green material will probably consist of a subcritical initial temperature, a critical intermediate temperature, and a high final temperature for each wood. The kiln drying of previously air-dried material will be subject to the same temperature factors, with perhaps some minor modification that must be made under any circumstances of application of ideal principles.

Temperature effects on shrinkage. --As has previously been brought out, temperature has a profound effect on the amount of internal compression set in the drying of a hardwood. Naturally this would have an effect on ultimate shrinkage of the wood. Figure 10 shows the amount of board shrinkage in red oak at various moisture levels as a function of constant drying temperature. Thus, at 30 percent moisture content or below, 2-inch red oak dried at 140° F. will have about 1.3 percent more shrinkage than similar red oak dried at 95° F. The relationship seems to be direct and uniform between those two temperature values. Below 95° F. another influence appears to contribute to the decrease in shrinkage--presumably more of the wood is set in tension. Also, there is very little compression set at 80° F. Thus, preliminary air drying or predrying at a comparatively low temperature would result in the least footage loss due to shrinkage, if the final drying could be accomplished under conditions that would not change the original sets.

The compression set is more important in shrinkage consideration because it generally exists in six-tenths of the cross section while tension set generally exists in only two-tenths of the cross section. The amount of relief of the original tension set and the formation of compression set by high intermediate temperatures have not been fully investigated, nor has the effect of high final temperatures. If compression set can be kept at a minimum and there is less tendency for shrinkage as a whole, there will be less warping. If, on the other hand, high initial temperatures are used and there is a minimum of tension set and much compression set, the interior of the wood will tend to shrink and distort in accordance with the ring curvature in the piece, and large amounts of warping will occur. Much lumber is cut from small trees with growth rings of sharp curvature, and this is a considerable factor in drying. While 1-inch lumber from such trees can be held reasonably flat

by careful stickering and weighting of a load, thicker lumber is more likely to undergo cupping.

Relative Humidity Variation

Initial relative humidity. -- In the heartwood of hardwoods, as the surface of the wood comes to equilibrium with the relative humidity of the atmosphere, a steep moisture gradient develops between the surface and the interior wood. Much the same thing occurs in the sapwood of hardwoods and in softwoods after the capillary movement period of drying. The severity of the drying stresses is associated with the steepness of the gradient. When the surface stresses become too great for the strength of the wood, checks are formed. Thus, it is clear that the relative humidity must be controlled to maintain a high initial equilibrium moisture content (EMC) during the initial stages of the drying of heartwood. The wet-bulb depressions given for the start of recommended kiln schedules generally maintain high enough EMC conditions in the kiln to prevent surface checking. Lower relative humidities probably can be used during air drying and predrying at temperatures below 100° F., but exact information on how much lower these can be is not available.

Minimum relative humidity after stress reversal. -- After the stresses in the surface have reversed from tension to compression, there is no need for maintaining a high relative humidity. This principle has been made use of in modern kiln-drying schedules and is universally recognized. There are some indications, however, that drying stresses do not develop as rapidly in wood that dries initially by capillary action--softwoods and the sapwood of hardwoods--and in such wood the point of stress reversal is somewhat obscure. It may be possible in such cases that surface tensile stresses can be renewed by abrupt humidity changes after stress reversal has taken place. In the light of present limited knowledge on this point, however, it is most practical to consider that, after stress reversal, very low relative humidity values can be used without danger of surface checking or without a bad effect on honeycombing. Faster shrinkage of the surface at this stage of drying should tend to lessen the chance of honeycombing.

Intermediate reductions in relative humidity. -- There remains the period in between the initial control of relative humidity and the lack of control after stress reversal. Present recommended kiln schedules for hardwoods, which are in wide commercial use and which have been pilot tested for a large number of woods, indicate that it is entirely safe to reduce relative humidity with a sequence of increases in wet-bulb depression that is roughly geometrical. That is, a very small first change in relative humidity is followed by larger and larger changes. Such changes result in larger and larger changes in equilibrium moisture content (EMC).

Whether or not more abrupt and drastic reduction in relative humidity can be made for all woods after the major amount of tension set has occurred in the outer zones is still problematical. The early stress results with blackgum sapwood and sweetgum heartwood shown in figures 6 and 8 raised the hope that this would be the case. On the other hand, surface checking can occur with 2-inch red oak when the wet-bulb depression is changed from 4° F. to 6° F. after 3 weeks of drying. Stress analysis results on oak have shown that an abrupt reduction from a 15 percent to a 5 percent equilibrium moisture content, after the initial tensile strain in the outer zones has fallen to 80 percent of its original value, resulted in an immediate resumption of almost the maximum tensile strain. Except for species where research or experience has shown that large, abrupt reductions in relative humidity can be used early in the intermediate stage of drying, the geometrical pattern described above and incorporated in the Forest Products Laboratory recommended kiln schedules should be followed in commercial operations with hardwoods.

For softwoods, changes in wet-bulb depression between 15° and 35° F. should be made gradually, 5° F. at a time. Wet-bulb depressions of 40° F. or more should not be made until the controlling average moisture content reaches 15 percent.

Time Effects

Although not so obvious as temperature and relative humidity, time is a factor of almost equal importance in kiln-schedule design. At present there are not enough data available to outline clearly the influences of time. Two can be discussed briefly, however, and the kiln operator should keep his eyes open for ways he can use time to his advantage.

Time-temperature strength reduction. -- It is well known that wood deteriorates rapidly above 300° F. and at a moderate rate between 200° F. and 300° F. Similar degradation also takes place, but at a much slower rate, between 100° F. and 200° F., the temperatures ordinarily used in kiln drying. The wetter the wood and the higher the relative humidity of the circulating air, the greater the rate of degradation. This degradation of the basic components of wood results in a lowering of strength. The longer the time and the higher the temperature, the greater the loss of strength. Use of higher temperature, however, results in shorter drying time and more rapid lowering of moisture content. Strength losses are not so great as would occur if the higher temperature were used for the original time.

In kiln drying, while the temperatures are relatively low compared with 300° F., there are present the factors of wet wood, high relative humidity, high air circulation for rapid heat transfer, and comparatively long times. Strength

reductions are very slight under recommended kiln schedules in which final temperatures up to 200° F. are not used until after the average moisture content has reached 15 percent. Under circumstances where strength is not a primary consideration, use of a very high final temperature (200° F. or higher) with an accompanying 5 to 10 percent strength loss may be permissible, with considerable shortening of drying times.

Time-load (creep) effects. -- Creep is defined as strain or deformation that occurs in proportion to the elapsed time the wood is under a load or stress. As time increases, the amount of creep increases. Accompanying the creep is another phenomenon, known as relaxation. When stress is created by restraint of normal shrinkage, any creep that occurs tends to relax or lower the stress.

In standard strength tests, loads are increased at a uniform rate so that the test will go to completion in 10 to 15 minutes. Under much slower rates of loading, the test specimen will deform more for a given load and ultimately fail at a load smaller than found in the standard test. This same situation would prevail in the drying of wood. Surface checking, under conditions just above the critical ones, doesn't occur until a considerable period of time has elapsed at the abnormal conditions. The same would apply to honeycombing. Relaxation would complicate the situation, however. It is conceivable that there is a critical time before which prolonged stress may cause failure but after which it will not. Also, tensile stress on the outside is influenced by time effects on the dimensions of the inside.

Present knowledge of the correlation of slice-analysis and strength-test data does not fully explain what actually happens. It is sufficient to point out the importance of time effects, so that the researcher or experimenting kiln operator will look out for them and recognize them when they occur. Kiln operators are cautioned not to attempt to go too far beyond recommended kiln schedules with large commercial kiln loads of valuable material.

Relief of Stresses

Stress relief, or conditioning, is needed when the product is going to be re-sawed or unequally machined so that the stresses become unbalanced. Such unbalance leads to distortion. Distortion leads to imperfect fitting of closely designed parts of assemblies as well as unsightly deformation in final products. It also results in poor glue joints in edge-glued panels, because the edges of the boards will not be parallel or in the same plane. When cupped boards are flattened as by nailing, or by the rollers during planing, they tend to split. Unbalanced stress is one of the causes of seasoning degrade.

Residual tensile stress in the cores can cause end checking and splitting when freshly cross-cut surfaces are exposed to low relative humidities.

Softwood dimension and sheathing usually do not need stress relief, nor do hardwoods used for some manufactured items. Material for finer construction items, laminating, cabinet work, and furniture does need stress relief, however.

Prerequisites for Good Stress Relief

Because conditioning is a precise treatment that must be properly carried out to get full and uniform stress relief without getting reverse casehardening, two things are necessary before conditioning can start:

1. The average moisture content of the whole charge of lumber must be accurately known.
2. The charge must have a high degree of uniformity of moisture content.

In any commercial kiln charge, even if it consists entirely of one species at one original moisture condition, there may be considerable difference between the moisture content of the driest and the wettest boards. Whenever, wood of two or more species or at more than one moisture condition is included in a charge, the differences will be greater. If these differences are great enough, the temperature and relative humidity used during conditioning cannot properly relieve stress in all boards. Generally, where there is a spread of more than 3 percent moisture content in the kiln samples, equalizing is advisable. Equalizing is a process that stops the drying of the driest boards while continuing the drying of the wettest boards.

Principles of Stress Relief

For good stress relief, four major principles must be adhered to:

1. Increasing the existing stresses to cause yielding, or major deformation, of the various portions of the wood in a direction opposite, and equal in magnitude, to the original sets.
2. Plasticization of the wood to produce yielding by increasing moisture content while maintaining a high temperature.
3. Sufficient time to permit the time-temperature effects to bring about relief.

4. A balanced opposition of original sets, so that relief forces will be balanced.

In addition to relieving stresses, conditioning establishes a uniform moisture content throughout the thickness of each board or item. Figure 11 shows moisture and stress relationships during four stages of equalizing and conditioning. Stage 1 is the casehardened or stressed condition at the end of drying. There is a high degree of compressive stress in the outer layers and lesser degrees of tensile stress throughout the rest of the piece. These stresses are the result of a considerable degree of tension set in the outer zones and compression set present to varying degrees in the interior. The moisture content gradient is still rather steep when a final EMC of about 3 percent is used. The midthickness still has a comparatively high moisture content.

After equalizing, the moisture gradient is flatter, with the surface not so dry and the midthickness lower in moisture content than at the end of drying. Stresses are generally the same, but they may be lower in magnitude if the equalizing period has been carried out at a high temperature.

During conditioning, enough moisture must be added to the surface and the zone just beneath it to increase the compressive stress. This causes an increase in the tensile stress in the interior zones. When conditioning is carried out at a high enough temperature for a long enough period of time, the stresses, are relieved all the way across the cross section (fig. 11).

In order to accomplish stress relief, the present recommended method calls for increasing the moisture content of the surface to a value higher than the midthickness moisture content. In calculating the required kiln EMC the phenomenon called hysteresis also must be taken into account. This is the tendency of wood exposed to any specified temperature and relative humidity conditions to reach equilibrium at a lower moisture content when absorbing moisture from a drier condition than when losing moisture from a wetter condition.

The conditioning treatment temporarily results in a reverse moisture gradient as shown by the top boundary of the moisture line in the lower left-hand diagram of figure 11. This gradient flattens out in a very short time, and the lumber can be used immediately after cooling. The abrupt lowering of surface moisture content to the equilibrium moisture content of the atmosphere when hot conditioned lumber is tested for casehardening usually results in an immediate indication of reverse casehardening, but equalization of the moisture content across the test prongs causes them to straighten.

In commercial drying operations, kiln operators often "steam" at saturation or employ higher-than-recommended EMC values for very short times. In some cases the stress relief is satisfactory, in others it is superficial only.

There is a danger in such treatments, however. A wood such as oak or beech, if surface checked during air drying or the early stages of kiln drying, may have its checks permanently opened by such "steaming." Because of surface compressive stresses at the end of drying and before conditioning, the checks normally would be closed. They would stay closed during the recommended conditioning treatment. Steaming may compress the surface so much that, when the moisture gradient levels off, the checks will open up and stay open. There is no method of permanently closing the checks thereafter.

Recommended Equalizing and Conditioning Treatments

Treatments have been devised (9, 10) to produce stock free of stress or case-hardening and with a degree of moisture uniformity that can be classified as precision drying. The equalizing treatment brings about moisture uniformity among boards. The conditioning treatment relieves drying stresses and brings about moisture uniformity between the shell and core of each board. Where the highest degree of uniformity is not required, the procedures can be slightly modified, sometimes omitting equalizing, and still provide reasonably satisfactory stress relief. If the moisture content variation is large, however, satisfactory stress relief cannot be obtained for all the material in a charge

Toward these ends, an adequate number of properly selected and prepared kiln samples must be used to represent the moisture content of the stock. One or more samples must represent the driest and fastest drying material, while several are needed to represent the wettest and slowest drying material. When kiln drying has been started from moisture content values above 30 percent, intermediate moisture content determinations for all samples are usually necessary before the start of equalizing.

Another important factor is the performance of the kiln, particularly the control instrument. This must be in near-perfect calibration. If the wet-bulb depression is greater or smaller than that recommended, the EMC condition in the kiln will not be correct, and satisfactory stress relief may not be obtained on all the stock. Since the wet-bulb depressions required are so critical, it is absolutely necessary that the wick be clean, free of all deposits, and adequately supplied with water during equalizing and conditioning.

While best results are obtained by combining the equalizing and conditioning procedures, the description below has been separated into two major parts for clarity and possible use of one without the other.

Equalizing treatment. --The procedure for the equalizing treatment is as follows: 1. Start equalizing when the driest kiln sample in the kiln charge has reached an average moisture content 2 percent below the desired final average moisture content.

Example. --If the desired final average is 8 percent, start equalizing when the driest sample reaches 6 percent.

2. As soon as the driest sample reaches the moisture value stated in (1), establish an equalizing EMC condition in the kiln equal to that value. During equalizing, use as high a dry-bulb temperature as the drying schedule permits.

For the example given in step (1), the equalizing EMC would be 6 percent.

3. Continue equalizing until the wettest sample reaches the desired final average moisture content.

In the example given in step (1), the wettest sample should be dried to 8 percent.

If the equalizing treatment is to be followed by a conditioning treatment, it may at times be necessary to drop the temperature to obtain the desired EMC for conditioning. When this is necessary, the dropping of the temperature should be started 12 to 24 hours prior to the start of conditioning. The wet-bulb temperature also should be lowered to maintain the desired EMC.

Conditioning treatment. -- Whether or not preceded by an equalizing treatment, conditioning should not be started until the average moisture content of the wettest sample reaches the desired final average moisture content.

1. As soon as the wettest sample has reached the moisture content value stated in step (3) of the equalizing procedure, conditioning should be started. The conditioning EMC should be 3 percent above the desired final average moisture content for conditioning softwoods, and 4 percent above the desired final average moisture content for conditioning hardwoods. If at any desired conditioning temperature, no whole wet-bulb depression value gives the exact EMC value desired, use the wet-bulb depression giving a slightly higher EMC. The conditioning temperature should be the same as the final step of the drying schedule, or the highest temperature at which the conditioning EMC can be controlled.

Example. --Assuming that this case involves a hardwood and the final desired moisture content is 8 percent, the conditioning EMC is 12 percent. At 170° F. use an 8° F. wet-bulb depression giving an EMC of 12.4 percent. For a softwood, the conditioning EMC would be 11.0 percent and the wet-bulb depression is 10° F.

2. Continue conditioning until satisfactory stress relief is attained.

The time required will vary considerably, depending upon species and thickness of the lumber, the type of kiln used, and kiln performance. Hardwoods generally require 16 to 24 hours for 4/4 and up to 48 hours for 8/4 stock. The 4/4 thickness of some species of softwoods can be conditioned in as short a time as 4 hours. It is advisable to hold conditioning time close to the minimum, to decrease steam consumption and kiln deterioration and avoid excessive moisture pickup in low-density species.

The recommended method for determining the minimum time necessary to get stress relief in a particular thickness of a particular species is the prong test described elsewhere in this report. Stress-test sections for 4/4 cherry conditioned 24 hours are shown in figure 12.

Table 1 gives the basic information on the moisture content of the kiln samples and the kiln EMC conditions for equalizing and conditioning lumber and other items to be dried to final average moisture content values from 5 to 11 percent. Table 2 gives wet-bulb depression values to use at various dry-bulb temperatures to obtain specific EMC conditions in the kiln.

The higher the dry-bulb temperature, the faster will be the equalizing and conditioning. In tight commercial kilns supplied with low-pressure steam for humidification, the high EMC conditions required for the conditioning treatment can be obtained at dry-bulb temperatures of about 180° F. When high-pressure steam is used for the spray, the superheat will tend to raise the dry-bulb temperature above the instrument setting. If the required EMC cannot be obtained, the dry-bulb temperature should be dropped 12 to 24 hours before conditioning is started.

Limitations and Modifications of Recommended Procedures

The general EMC rules stated in the equalizing and conditioning procedures do not apply for moisture content values above 11 percent. Conditioning is hard to accomplish at these higher values, but if the kiln will hold a very high equilibrium moisture content at temperatures of 140° F. or above, the formulas given in a later section may be used to calculate the proper value of EMC.

In cases where the kiln operator wishes to shorten or possibly omit equalizing but still wants to condition the stock, he can continue on the final step of the drying schedule until the driest sample reaches a value 1 percent lower than that shown for the start of equalizing in table 1. If the wettest sample has then reached the desired final average moisture content, equalizing can be omitted. If, however, the wettest sample has not reached this value, an

equalizing treatment should be used. In this case, an EMC value 3 percent below the desired final average moisture content may be used. A greater range in final moisture content will be obtained, compared with that obtained by the recommended procedures in table 1. This modification may be useful for easily conditioned woods that have a wide range of initial moisture content values. It also will be effective in handling items to be dried to a comparatively high final moisture content.

If stock is to be equalized without being conditioned, the moisture content and EMC values given for equalizing in table 1 should still be used, because there generally will be some surface moisture regain when the equalized stock is exposed to the atmosphere, particularly at the lower moisture content values.

If average moisture content determinations are made immediately after the conditioning treatment, the moisture content obtained will be about 1 to 1-1/2 percent above the desired value because of surface moisture regain. After cooling, the average moisture content of the lumber should be close to that desired.

Method for Calculating Equalizing and Conditioning Values

The importance of having the wettest points in all boards of a kiln charge dried down to a value equivalent to the desired final average moisture content in order to do a perfect job of conditioning has been described by Loughborough (10). He also described a mathematical formula for calculating the moisture content at the midthickness, which in most cases would be the wettest point. Actual conditioning of kiln charges by Kimball and Rasmussen (10) during the kiln examination and control work, demonstrated that highly satisfactory results could be obtained by a modified calculation that allowed for a 2 percent range in moisture content of the kiln samples. The recommended equalizing and conditioning procedures described in this report and first published in 1951 (9) were developed from the modified calculations. A review of the calculating method will help the kiln operator understand the equalizing and conditioning treatments. The method also may be used to determine the key moisture values and EMC conditions when the desired final average moisture content is over 11 percent.

The method of calculation is as follows:

$$\text{Basic formula: } A = \frac{2Y + EMC}{3}$$

Let: A_1 = Average moisture content of driest sample at start of equalizing.

A_2 = Average moisture content of wettest sample at end of equalizing and start of conditioning.

Y_1 = Midthickness moisture content of driest sample at start of equalizing.

Y_2 = Midthickness moisture content of wettest sample at end of equalizing and start of conditioning.

EMC = Equilibrium moisture content in kiln during the 6 hours just prior to the time for each calculation.

Assumptions: For precision drying, allowing a range of 2 percent in moisture content of the kiln samples, it is necessary to bring the Y_1 value down to the minimum average value desired after the completion of conditioning. The Y_2 value must be brought down to the maximum average value desired after conditioning. The conditioning EMC should bring the surface moisture content up to or slightly above the Y_2 value in the wettest board.

Calculations:

1. Determine the average moisture content of driest sample (A_1) at start of equalizing. To do this use a Y_1 value equal to the final desired average moisture content minus 1. Then

$$A_1 = \frac{2Y_1 + EMC}{3}$$

If the desired final average moisture content is 13 percent and the EMC during the final stages of drying is 5 percent, then

$$A_1 = \frac{[2 \times (13-1)] + 5}{3}$$

$$A_1 = \frac{[2 \times 12] + 5}{3} = \frac{24 + 5}{3} = \frac{29}{3} \text{ or } 9.67 \text{ percent}$$

A_1 may be rounded to 9.5 percent.

2. Determine the equalizing EMC. This is the same as the average moisture content of the driest sample (A_1) at start of equalizing -- in the above example, 9.5 percent.

3. Determine the average moisture content of the wettest sample at the end of the equalizing and the start of the conditioning treatment. This is calculated in the same manner as A_1 , but using Y_2 with a value equal to the desired average moisture content plus 1, thus:

$$A_2 = \frac{2Y_2 + EMC}{3}$$

Or using the EMC values of step (2) above:

$$\begin{aligned} A_2 &= \frac{[2x(13+1)] + 9.5}{3} \\ &= \frac{[2x14] + 9.5}{3} = \frac{28 + 9.5}{3} = \frac{37.5}{3} \\ &= 12.5 \text{ percent} \end{aligned}$$

4. To determine the conditioning EMC, the Y_2 value is multiplied by a numerical factor that more than takes care of hysteresis, which is the tendency for wood to come to a lower EMC when approaching equilibrium from a drier condition. Experience has shown that the factor should be 1.33 for hardwoods and 1.18 for softwoods.

Assuming that the wood is a softwood, then

$$\begin{aligned} \text{Conditioning EMC} &= 1.18 \times Y_2 \\ &= 1.18 \times (13 + 1) = 1.18 \times 14 \\ &= 16.5 \text{ percent.} \end{aligned}$$

The calculation of the moisture content and EMC values for a desired final moisture content above 11 percent serves to point out the greater difficulty of doing a satisfactory stress relief job at the higher moisture content values. There is a greater danger of reverse casehardening in the driest stock, and it becomes increasingly difficult to achieve the required conditioning EMC in commercial kiln equipment. For practical purposes, it may be necessary to use a lower conditioning EMC than the calculations call for and be satisfied with incomplete relief of stresses in the wettest stock. A prolonged conditioning time may be of help in such circumstances.

Effect of Steaming or Excessively High Relative Humidity During Conditioning

As has been indicated, "steaming" the stock with an atmosphere that is saturated or near 100 percent relative humidity may result in permanent opening of previously closed checks. It also can cause reverse casehardening. The action is that of completely relieving tension set and producing compression set in the surface layers. Figure 13 shows a series of stress slices cut from cross sections of a sap gum board taken after various periods of steaming at 170° F. Note that at 3/4 and 1-1/2 hours the outer slices curved out, but the interior stresses were not relieved. If casehardening test prongs had been cut to include the first and second slices in each of these cases, they might have stayed straight. After 3 hours of steaming, the reverse casehardening condition has just started in the interior. Six hours of steaming caused severe reverse casehardening.

At the higher temperatures, it is very difficult to bring the atmosphere close to saturation in a commercial dry kiln. This probably saves the dry-kiln operator from reverse casehardening in many cases when he thinks he is steaming at saturation. At 150° F. or below, however, reverse casehardening is a danger.

Dipping or Water Spray Casehardening Relief

When controlled high-temperature, high-humidity conditioning equipment is not available, some degree of casehardening relief can be obtained by wetting the surfaces of the boards. Methods that have been used commercially consist of dipping bulk-piled packages in water or spraying a water mist onto the lumber in the kiln to cool the lumber at the end of drying. In either case, prolonging the treatment too long would result in too much moisture pickup by the stock. Dipping times varied from a few seconds to 5 minutes. No actual stress test data are available, but the methods were helpful in avoiding planer splitting. In a test of a portable crop drier for drying lumber, each course of the load was sprayed with water at the completion of drying. Then drying was continued for a short time at a low temperature. Two of eight kiln samples still showed signs of stress, but after a week of bulk storage, 12 spot-check casehardening tests showed no stress. The material was satisfactorily used for interior trim and cabinet stock.

Tests have indicated that prolonged storage may be helpful in relieving some of the stresses in softwoods, but not in hardwoods.

Recent Stress Relief Research

The relief of stresses during the last stages of drying and a subsequent 48-hour high-temperature conditioning treatment in one Forest Products Laboratory experiment with 2-inch northern red oak is shown in figure 14. The material had been dried at 110° F. until the 60th day of drying. Raising the temperature to 180° F. at the start of the 70th day reduced the tensile strain in the interior slices but did not affect the compressive strain in the exterior slices. The conditioning treatment completely relieved the existing stresses and caused a small reversal. Most of this was caused by relief of tension set in the outside and adjacent slices.

A very interesting study of stress relief and reversal was made by Churchill (1). In his study, casehardened 4/4 yellow birch was equalized at a low temperature to 5 percent moisture content, then different lots were subjected to 150°, 170°, or 190° F. at 5, 7, or 9 percent EMC. Figure 15 shows the results at 9 percent EMC. At 150° F., stresses were not quite relieved in 30 hours. At 170° F., stresses were relieved in 12 hours and some stress reversal was developed by continuing to 21 hours. At 190° F., relief was achieved in 3 hours. Severe reversal developed at 12 hours. At 5 percent EMC, 190° F. gave considerable relief at 12 hours and almost complete relief at 30 hours. This research shows that the effect of temperature in stress relief should be studied further.

Based on Churchill's indication that high temperatures might relieve reverse casehardening, Huber (4), deliberately reverse casehardened some red oak boards, then subjected different lots to 170°, 190°, and 206° F. at an 8 percent EMC. He found that the 170° F. temperature relieved reverse casehardening in 10 hours and the two higher temperatures did it in 5 hours or less.

Winkel (11) has published stress-relief data on ponderosa pine. A part of his paper was devoted to practical means of getting the high-temperature, high-humidity conditions needed for relief. Eighty percent relief of stresses was obtained in 10 to 23 hours' time with 80 pounds of steam per hour, and in 2 hours with 340 pounds of steam per hour. The injection of water into the steam spray or cooling of the lumber before conditioning reduced conditioning time by as much as 5 hours.

Stress Tests

Conditions of Tests

Research results discussed earlier in this paper have shown that tension and compression sets and the resulting stresses involve the entire cross section

of seasoned lumber. A thorough testing procedure, therefore, should take into account means of determining the condition of stress throughout the cross section. For some specific uses, however, complete relief of stress is not necessary, and a test that approximates the resawing or machining operation that will be performed on the lumber will suffice.

Figure 16 shows prong-type stress test sections that can be used for various sizes and shapes of lumber and dimension stock. Since practical cutting of stress prongs on a bandsaw requires that the prongs be not too thin, one saw cut (fig. 16, A) is about all that can be made in 5/8-inch or thinner lumber. This same method can be used for thicker boards that will be resawed only once.

The standard test for 3/4- to 5/4-inch stock is to make 2 saw cuts and remove the center prong (fig. 16, B). For more precise tests in stock of this thickness, a line should be marked across the cross section near one end before making 4 saw cuts (fig. 16, C). The difference in length between the outer and center prongs should be measured before removing the second and fourth prongs. For wide boards of these thicknesses, the judgment as to degree of stress should be made at a point about 7 or 8 inches from the uncut edge of the board. When the tips of the prongs of a wide board press together moderately, the board is less casehardened than an 8-inch or narrower board with the same tip reaction.

The standard test for 6/4 and thicker lumber is to make 5 saw cuts and remove the second and fifth prongs (fig. 16, E). For precise tests, 6, 8, 10, or more cuts should be made after marking a straight line across the section near one end (fig. 16, F). Measurement of differences of length of the center, the outer, and the other prongs should be made before the prongs are removed. The total length from the uncut edge to the measuring line should be measured in all precise tests, so that the difference can be converted to an inch-per-inch or percentage basis.

When cutting stress tests from squares or nearly square rectangles, 2 outer prongs 1/4 inch in thickness should be sufficient (fig. 16, G). For round or irregularly shaped cross sections, a single saw cut all the way across the middle of the cross section will give a good idea of stresses. A precise method possible with a round cross section is to cut a quarter-round segment from it and trace saw cuts parallel to the round surface to give 3 prongs about 1/8 to 3/16 inch thick. Such cuts can be made with a jig saw. Spacers equal to the thickness of the saw kerf must be inserted to keep the prongs in their originally parallel disposition.

Evaluation of Stress Test Sections

When a stress test is made soon after a charge of lumber is dried or conditioned, there are likely to be some differences in moisture content across the cross section, and the test prongs may curve one way or the other because of these moisture differences. A completely accurate evaluation of the stress condition cannot be made until all moisture gradients have been removed. Preliminary indications of the stress condition can be obtained, however, without waiting for flattening out of the moisture gradients.

When the kiln operator believes the stresses have been relieved at the end of a drying run, the kiln should be shut off and the kiln samples or other boards should be removed and tested. If, at the time of sawing, the outer prongs of the test section turn away from the saw a distance about equal to the thickness of the prong or slightly more, the stock is usually free of set and the charge can be pulled and used as soon as it is cool. If, however, the outer prongs remain straight or pinch the saw, the stock still contains stress and set and the conditioning should be continued 2 to 4 or more hours until subsequent preliminary tests show satisfactory relief.

The test sections should be room dried 12 to 24 hours before the final determination of stress is made. Then the following results may be obtained:

- (1) The outer prongs have turned in considerably. The stock is still stressed.
- (2) The outer prongs are straight. The lumber is stress-free.
- (3) The outer prongs have turned out considerably. The stock is reverse case-hardened. The major reactions of stress test sections and their evaluation after room drying are shown in figure 17.

When result (1) is obtained, subsequent charges should be conditioned a longer time. Result (3) indicates subsequent charges should be conditioned at a lower relative humidity or for a shorter time. Reverse casehardening should not occur when the recommended conditioning treatment is used properly.

When a kiln charge has been allowed to cool enough to eliminate all moisture gradients before testing or when material is tested after a period of transit or storage, the immediate reaction may be the same as that after room drying.

Less frequently observed stress results can occur when the wood has regained surface moisture after conditioning or for some other reason has acquired an unusual moisture gradient. By combining careful stress tests and moisture distribution results, the past history of the lumber and its present stress condition can be worked out (8).

Literature Cited

- (1) Churchill, J. W.
1954. The Effect of Time, Temperature, and Relative Humidity on the Relief of Casehardening Stresses. Jour. Forest Products Research Society 4 (5): 264-270.
- (2) Ellwood, E. L.
1954. Properties of American Beech in Tension and Compression Perpendicular to the Grain and Their Relation to Drying. Yale School of Forestry Bull. 61, 82pp. illus.
- (3) Espenas, L. D.
1952. Minutes of Annual Meeting of Western Dry Kiln Clubs, Redding, Calif., May 2, 3, 1952.
- (4) Huber, H. A.
1956. The Effect of Time and Temperature on Reverse Casehardening Stresses. University of Michigan Wood Technology No. 9 (Jan.)
- (5) McMillen, J. M.
1955. Drying Stresses in Red Oak. Forest Products Jour. 5 (1): 71-76.
- (6) _____
1955. Drying Stresses in Red Oak: Effect of Temperature. Forest Products Jour. 5 (4): 230-241.
- (7) Rietz, R. C.
1950. Accelerating the Kiln Drying of Hardwoods. Southern Lumberman 181 (2262): 43-44, 46, 48, 52, 54 (July 1).
- (8) _____
1951. How is Casehardening in Kiln-Dried Lumber Determined? U. S. Forest Products Laboratory Report No. 1769-10.
- (9) Torgeson, O. W.
1951. Schedules for the Kiln Drying of Wood. U. S. Forest Products Laboratory Report No. 1791.
- (10) U. S. Forest Products Laboratory.
1946. Kiln Certification. ANC Bull 21, 157 pp., illus.
- (11) Winkel, L. D.
1956. Casehardening Stress Relief of Ponderosa Pine. Forest Products Jour. 6(3): 124-128.
- (12) Youngs, R. L.
1957. The Perpendicular-To-Grain Mechanical Properties of Red Oak as Related to Temperature, Moisture Content, and Time. U. S. Forest Products Laboratory Report No. 2079.

Table 1.--Kiln sample moisture content and equilibrium
moisture content values for equalizing and
conditioning a charge of lumber

| Desired final average moisture content | | Equalizing | | Conditioning | |
|--|--------------------|---|--------------------|---------------|---------------|
| Moisture content of driest sample at start | EMC for equalizing | Moisture content of wettest sample at end | EMC for equalizing | For softwoods | For hardwoods |
| Percent | Percent | Percent | Percent | Percent | Percent |
| 5 | 3 | 3 | 5 | 8 | 9 |
| 6 | 4 | 4 | 6 | 9 | 10 |
| 7 | 5 | 5 | 7 | 10 | 11 |
| 8 | 6 | 6 | 8 | 11 | 12 |
| 9 | 7 | 7 | 9 | 12 | 13 |
| 10 | 8 | 8 | 10 | 13 | 14 |
| 11 | 9 | 9 | 11 | 14 | 15 |

Table 2.--Wet-bulb depressions to be used with various dry-bulb temperatures in equalizing and conditioning treatments

| Desired EMC | Wet-bulb depression for equalizing or conditioning at dry-bulb temperatures of: | | | | | | |
|----------------|---|--------|--------|--------|--------|--------|--------|
| | 140°F. | 150°F. | 160°F. | 170°F. | 180°F. | 190°F. | 200°F. |
| Percent | °F. | °F. | °F. | °F. | °F. | °F. | °F. |
| 3 | 47 | 50 | 51 | 52 | 53 | 54 | 54 |
| 4 | 40 | 42 | 42 | 43 | 43 | 44 | 44 |
| 5 | 34 | 35 | 35 | 35 | 35 | 35 | 34 |
| 6 | 29 | 29 | 29 | 28 | 28 | 27 | 26 |
| 7 | 24 | 24 | 24 | 24 | 23 | 22 | 21 |
| 8 | 20 | 20 | 19 | 19 | 18 | 17 | 17 |
| 9 | 17 | 16 | 16 | 16 | 15 | 14 | 14 |
| 10 | 14 | 13 | 13 | 12 | 12 | 12 | 11 |
| 11 | 11 | 11 | 11 | 10 | 10 | 9 | 9 |
| 12 | 9 | 9 | 9 | 8 | 8 | 8 | 8 |
| 13 | 8 | 8 | 7 | 7 | 6 | | |
| 14 | 7 | 6 | 6 | 6 | 5 | | |
| 15 | 6 | 5 | 5 | 5 | 4 | | |
| 16 | 5 | 4 | 4 | 4 | | | |
| 17 | 4 | 4 | 3 | | | | |
| 18 | 3 | 3 | 3 | | | | |
| 19 | 3 | | | | | | |

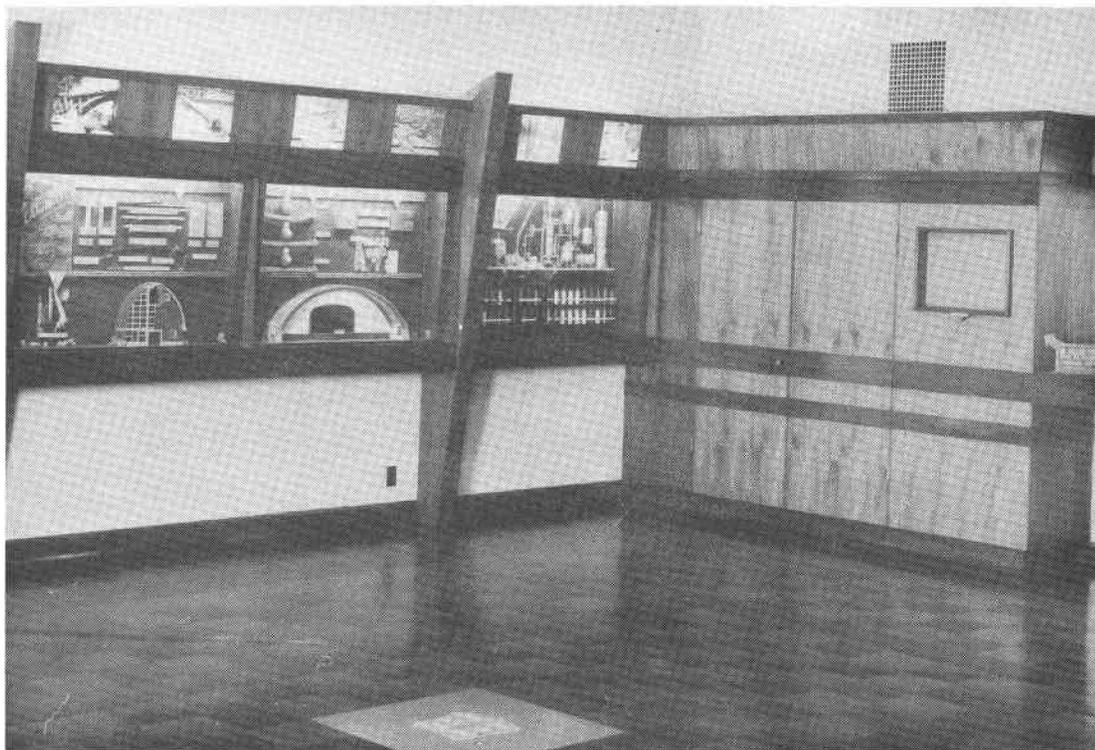


Figure 1. --Rapidly dried, properly conditioned black walnut in display cabinets of Forest Products Laboratory lobby.

ZM 112 000

Report No. 1652

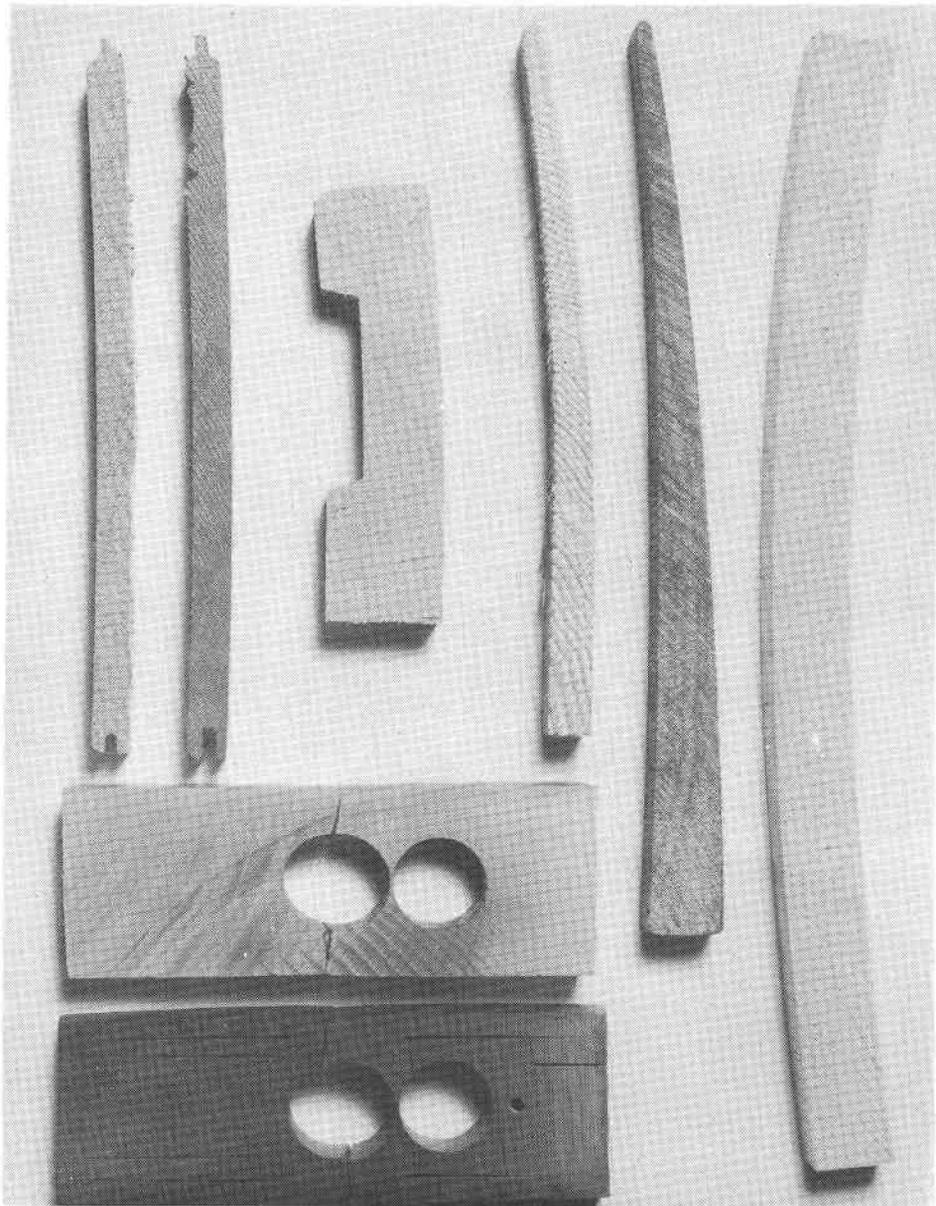


Figure 2. --Distortion resulting from resawing or unequal machining of stressed lumber.

ZM 111 996

Report No. 1652

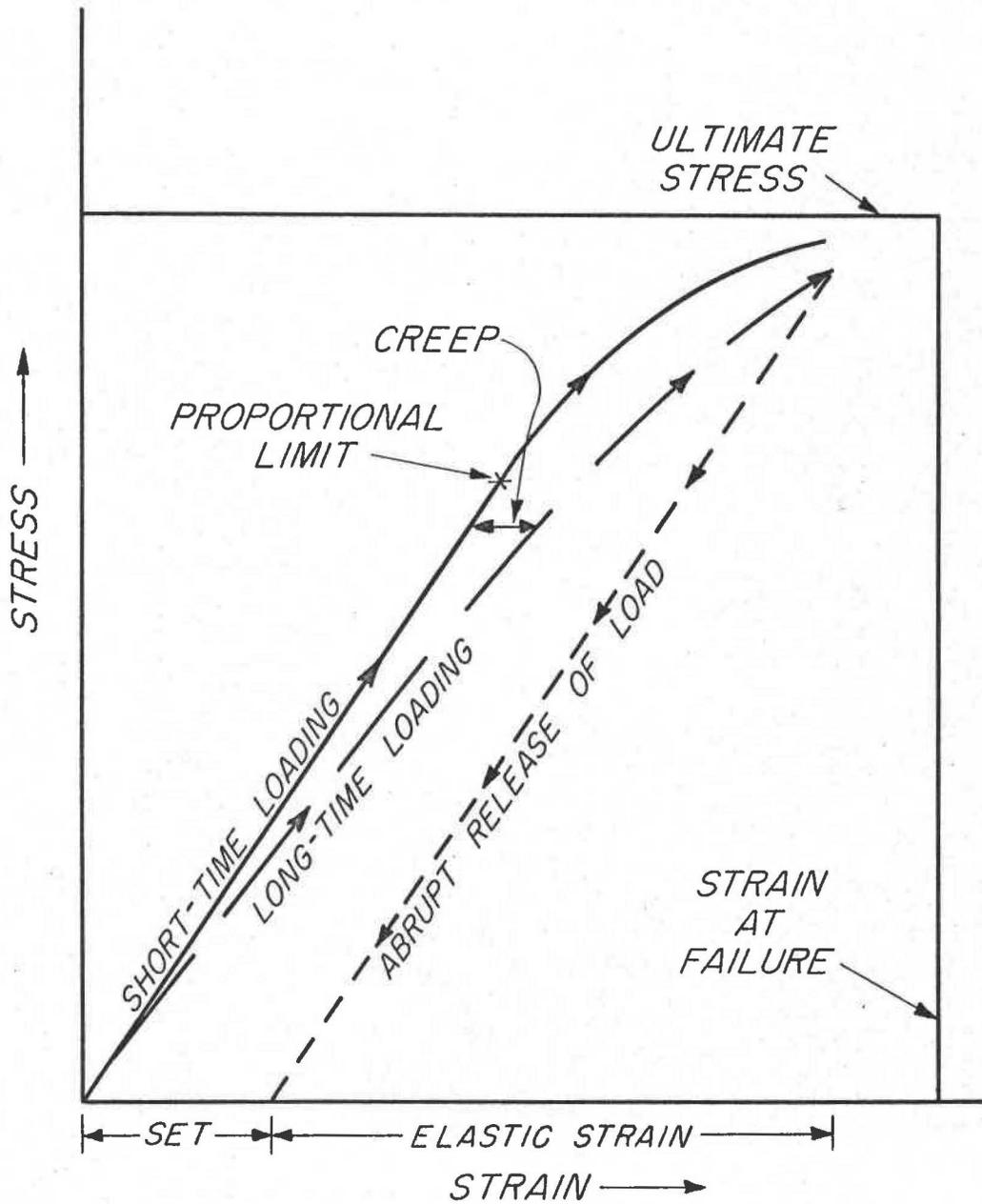
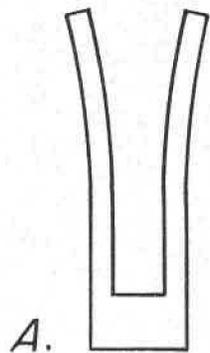
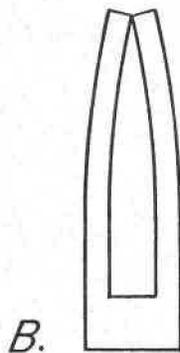


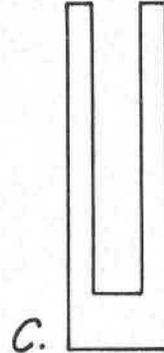
Figure 3. --General stress-strain diagram.



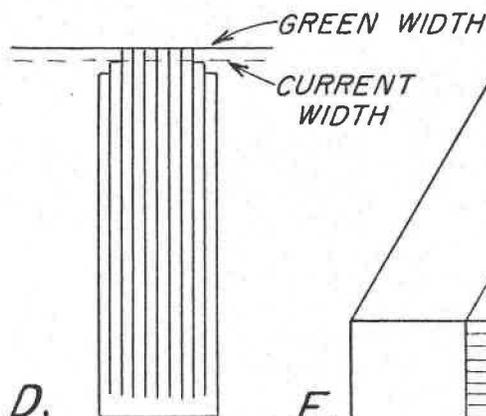
A. EARLY IN DRYING



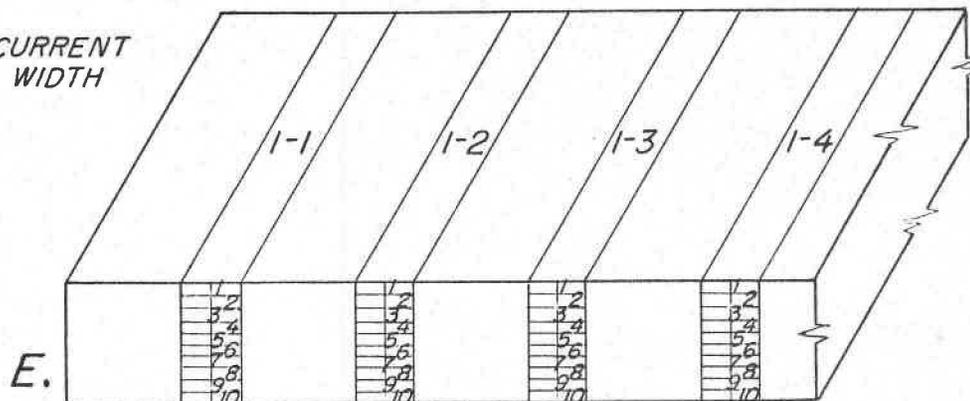
B. END OF DRYING



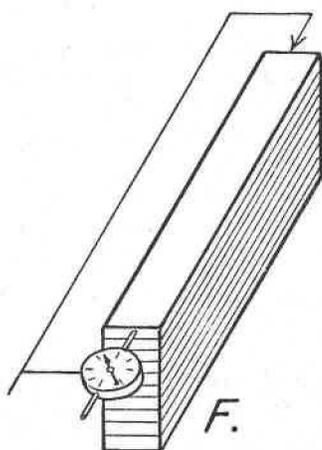
C. STRESSES RELIEVED



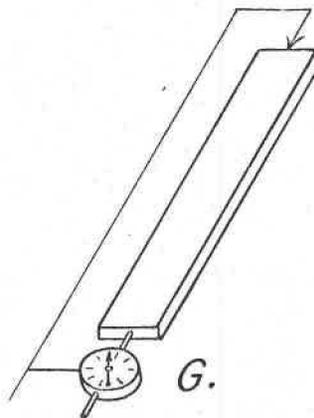
D. 10 PRONGS SHOW STRESS



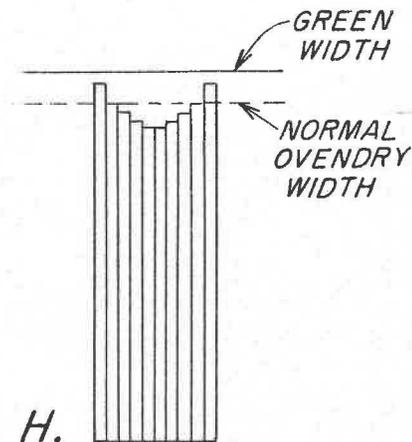
E. LAYOUT OF SECTIONS & SLICES



BEFORE SLICING MEASUREMENT

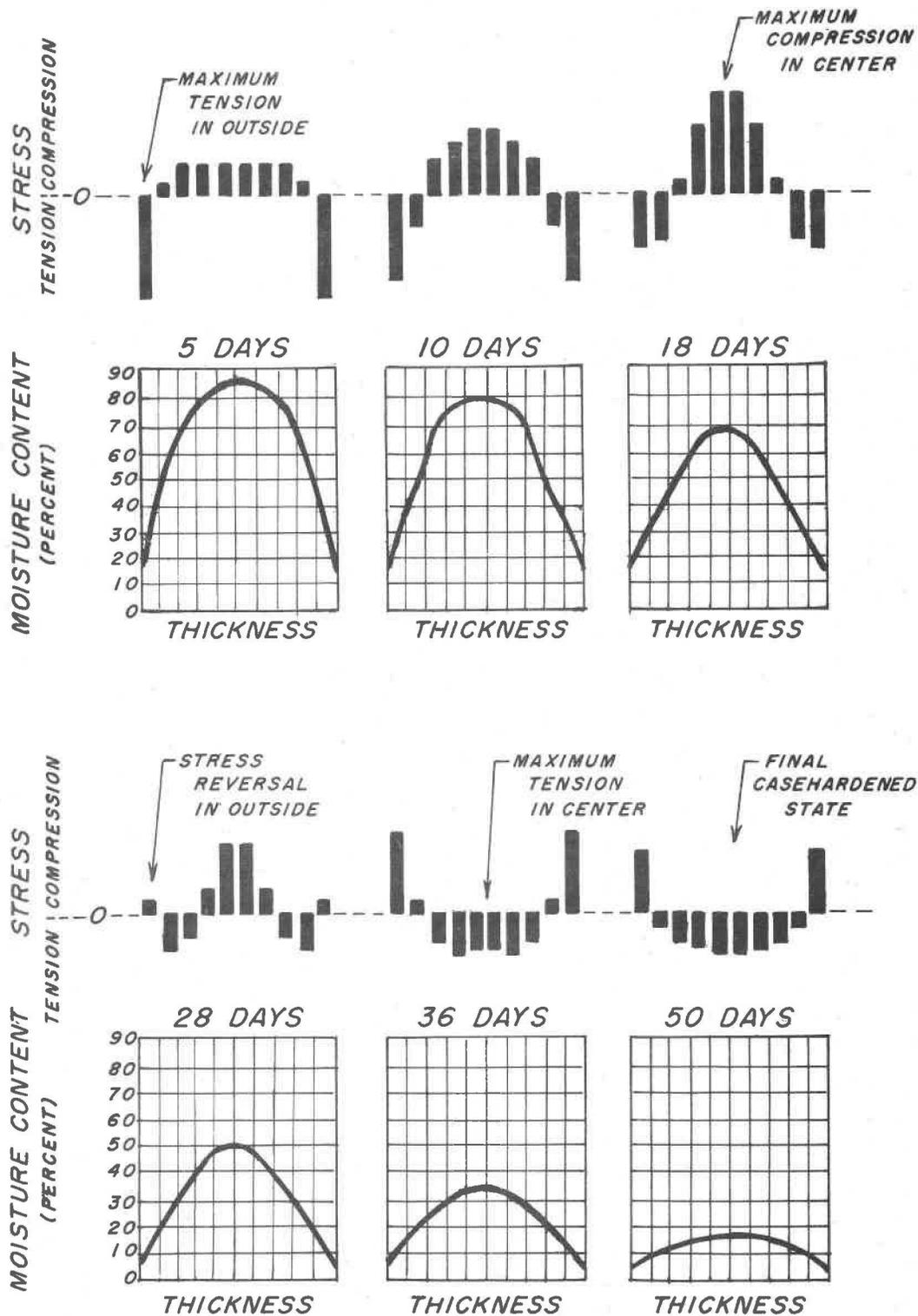


AFTER SLICING



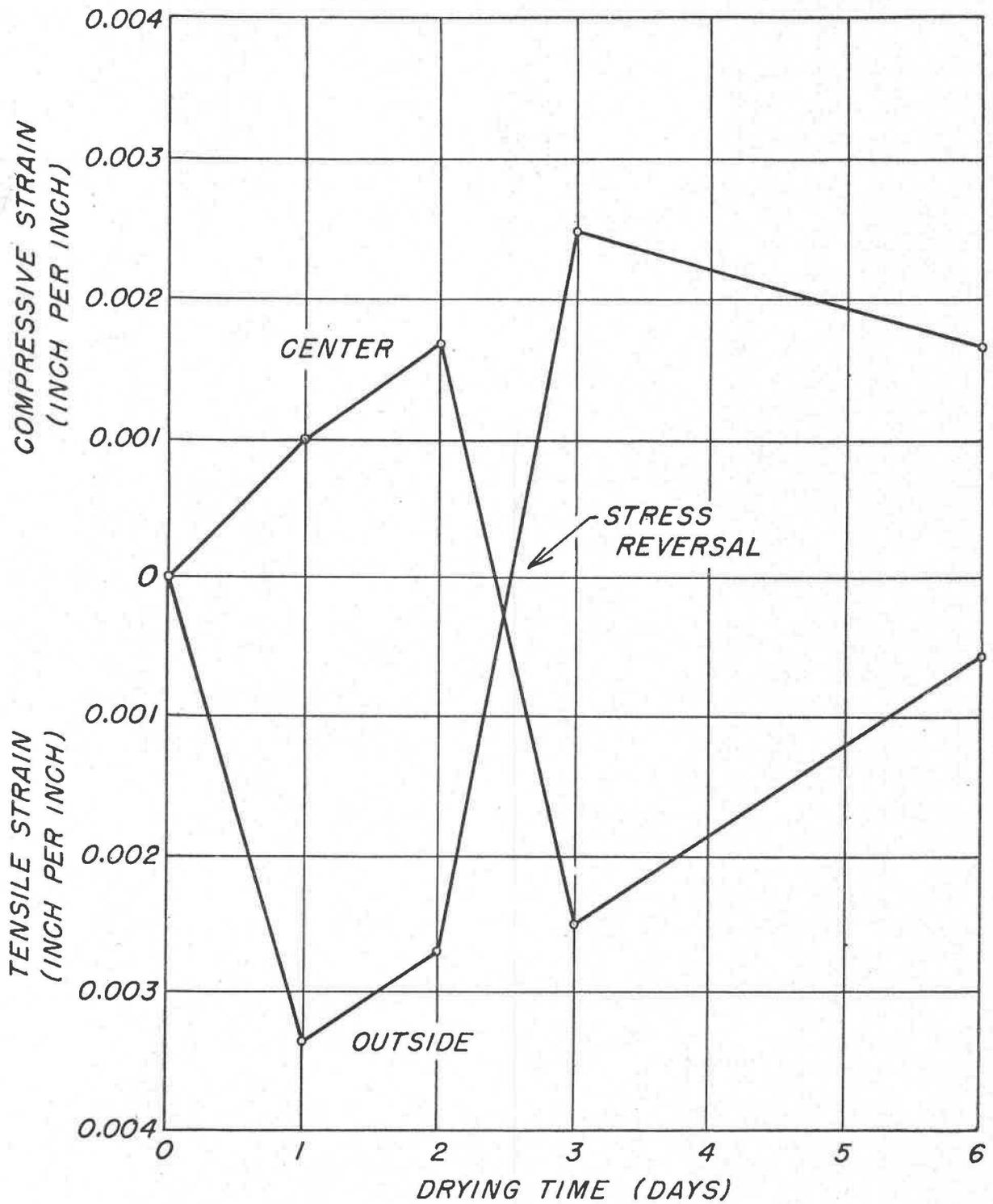
H. OVENDRY SLICES SHOW SET

Figure 4. --Slice method of studying drying stresses.



ZM 108 162

Figure 5. --Moisture-stress relationship during six stages of kiln drying 2-inch red oak.



M 108 160

Figure 6. --Stress reversal curves for a 2- by 10-inch black gum sapwood board.

Report No. 1652

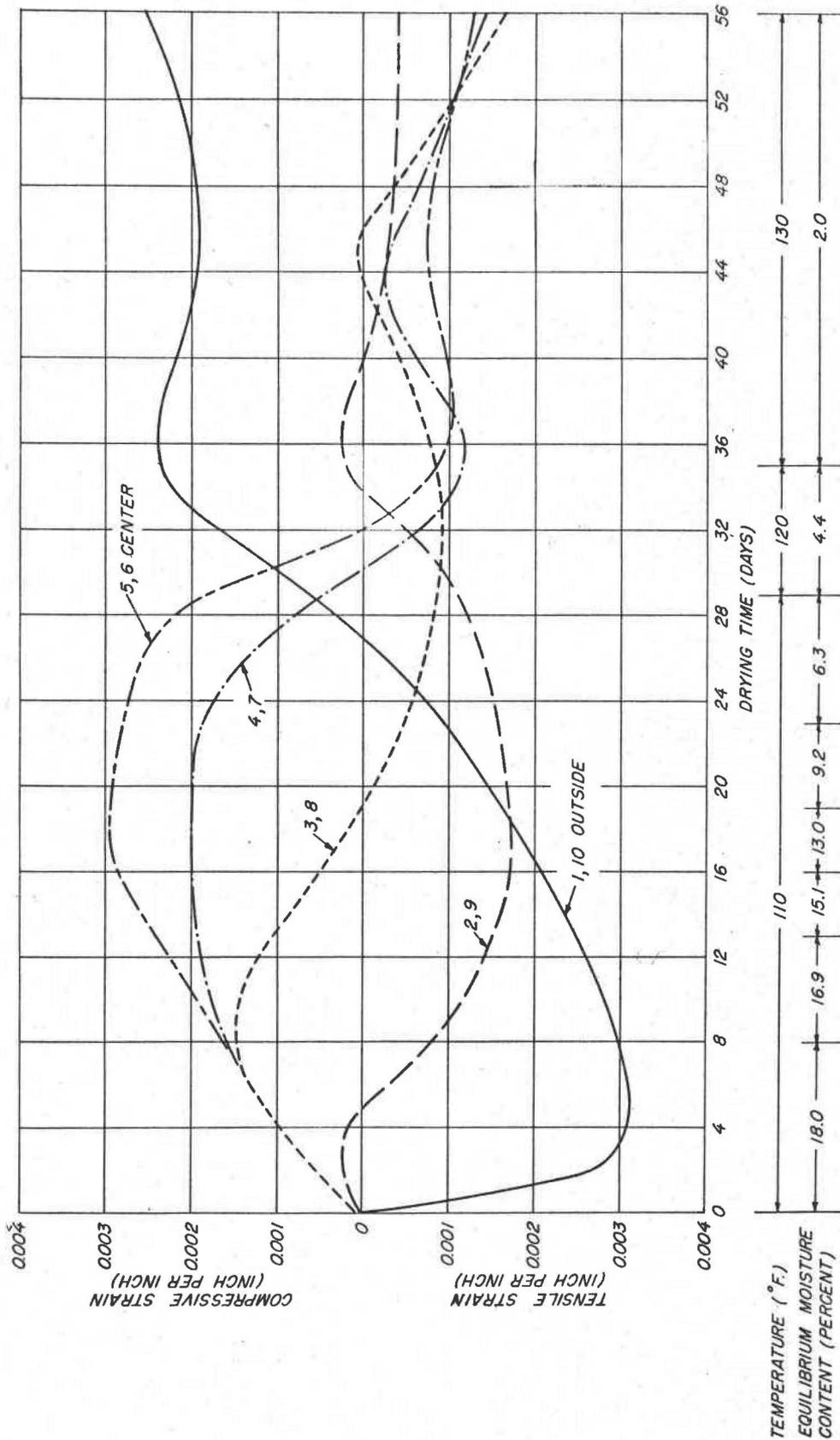


Figure 7.--Stress development curves for a 2- by 7-inch red oak board at 110°, 120°, and 130° F. The numbers on the curves refer to the slices of wood taken from the board.

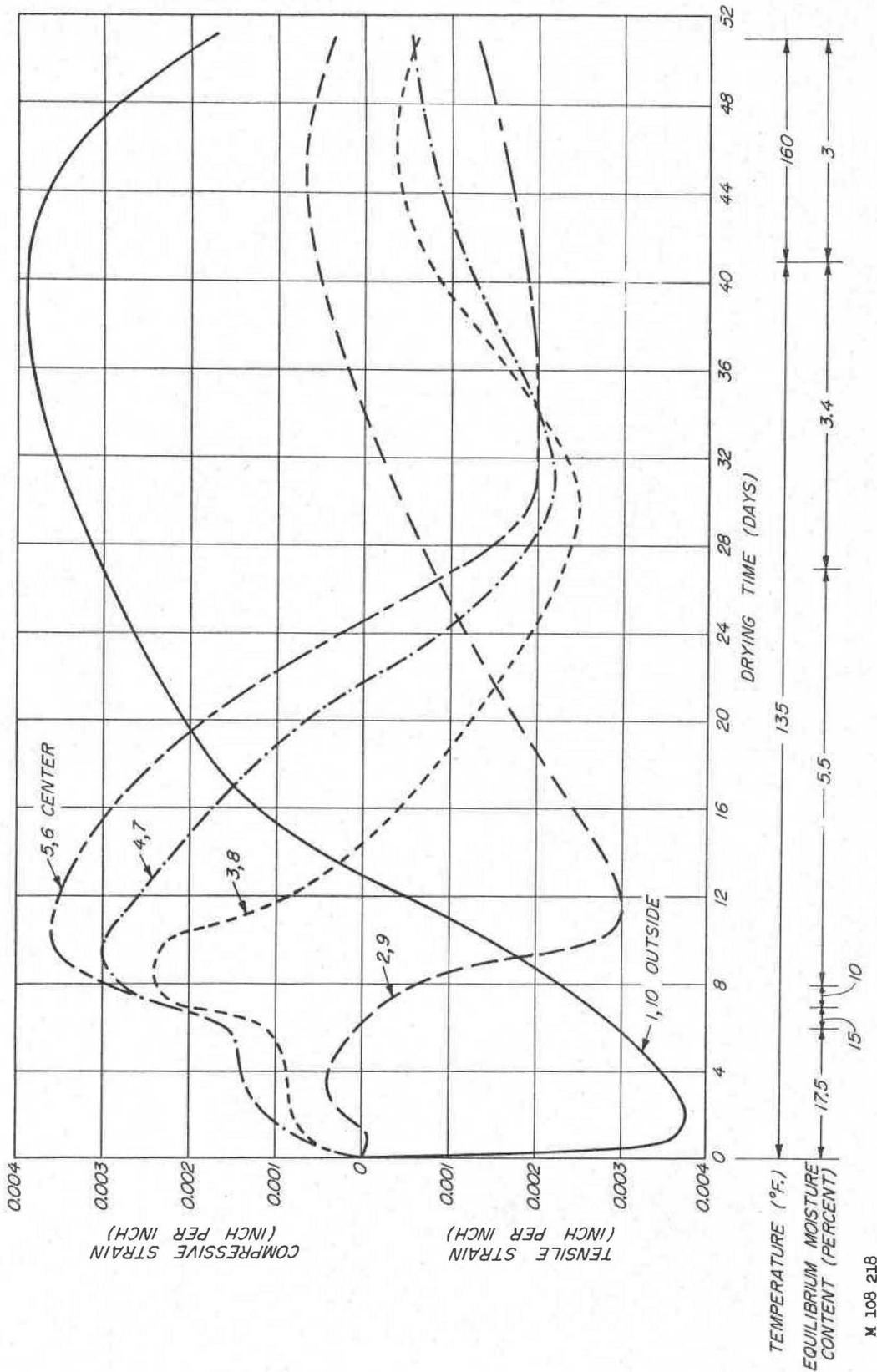
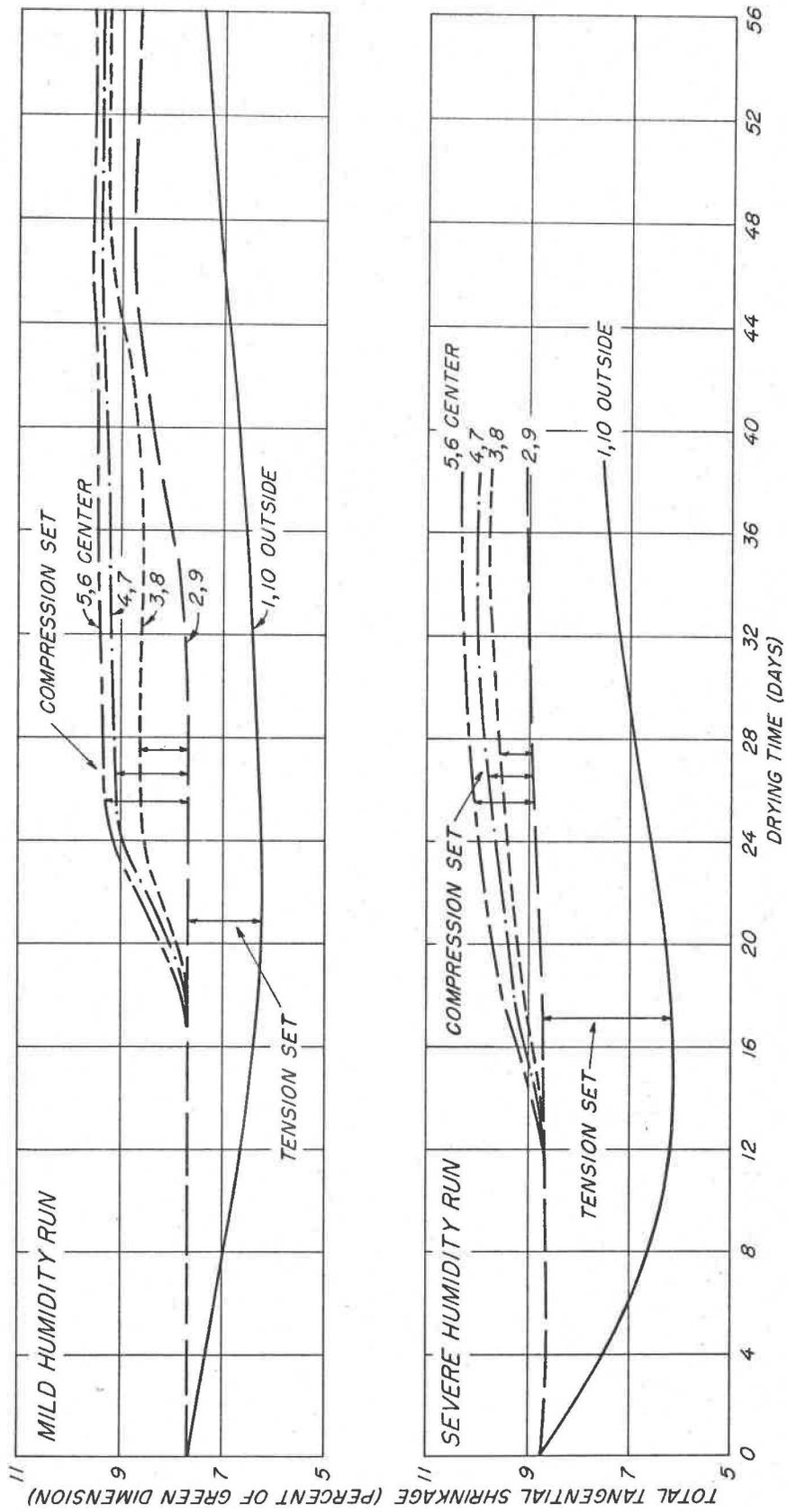
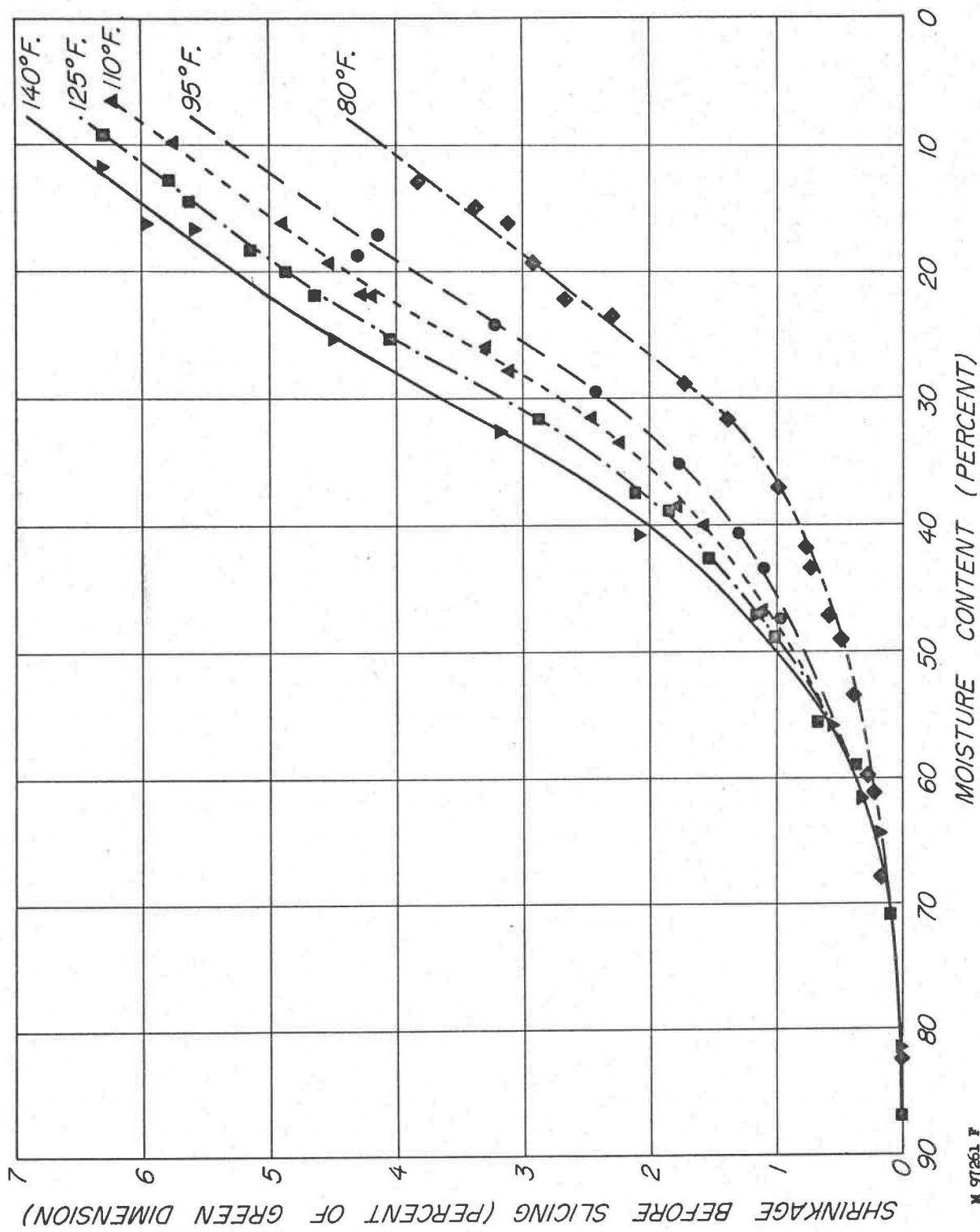


Figure 8. --Stress development curves for a 2- by 10-inch sweetgum heartwood board at 135° and 160° F.



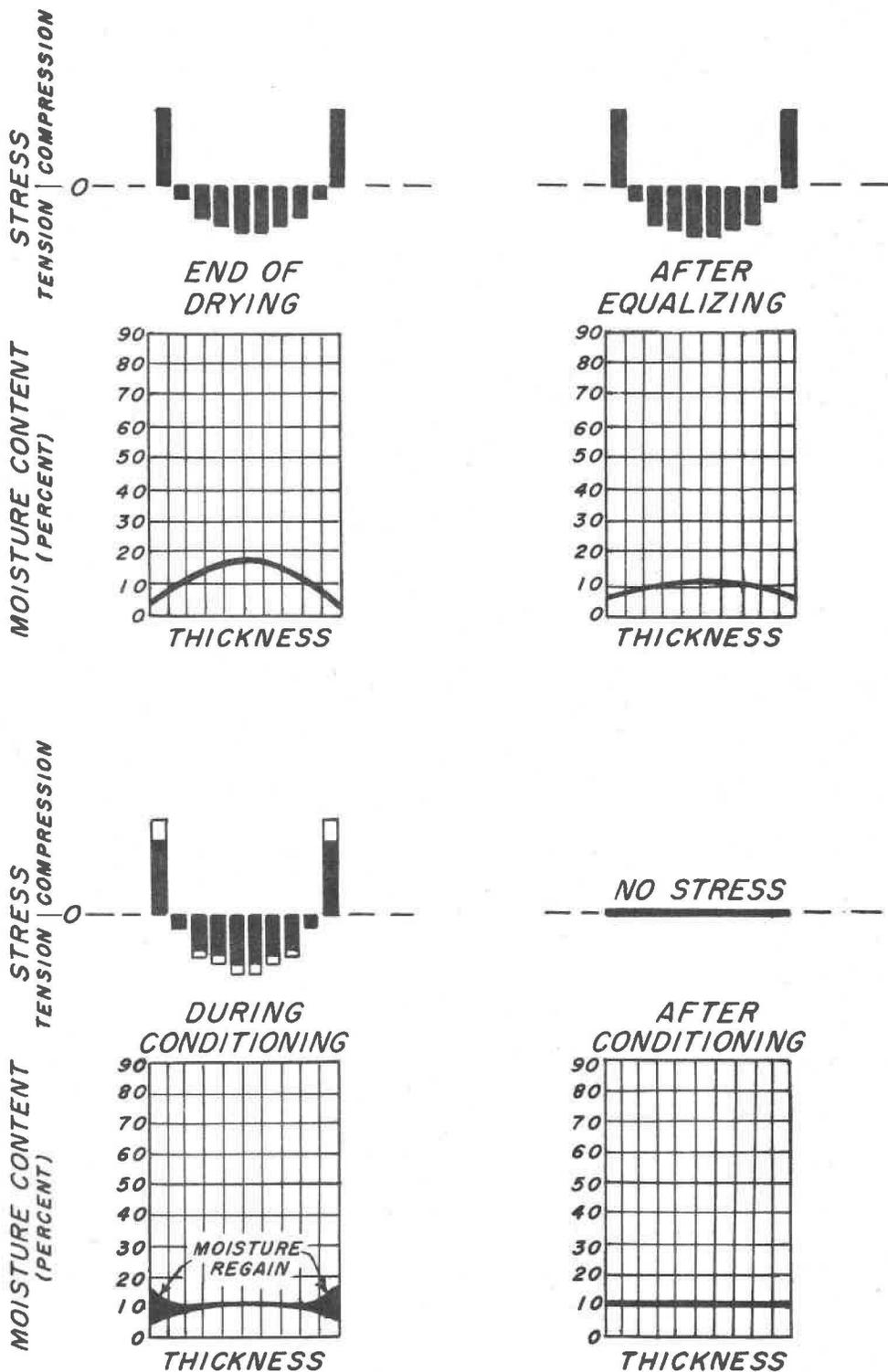
M 108 163

Figure 9. --Set curves for slices from two 2 - by 7-inch red oak boards of heartwood at 110° F.



X 97261 F

Figure 10.--Effect of temperature on board shrinkage of five red oak heartwood boards.



ZM 108 161

Figure 11. --Moisture-stress relationship during four stages of equalizing and conditioning.

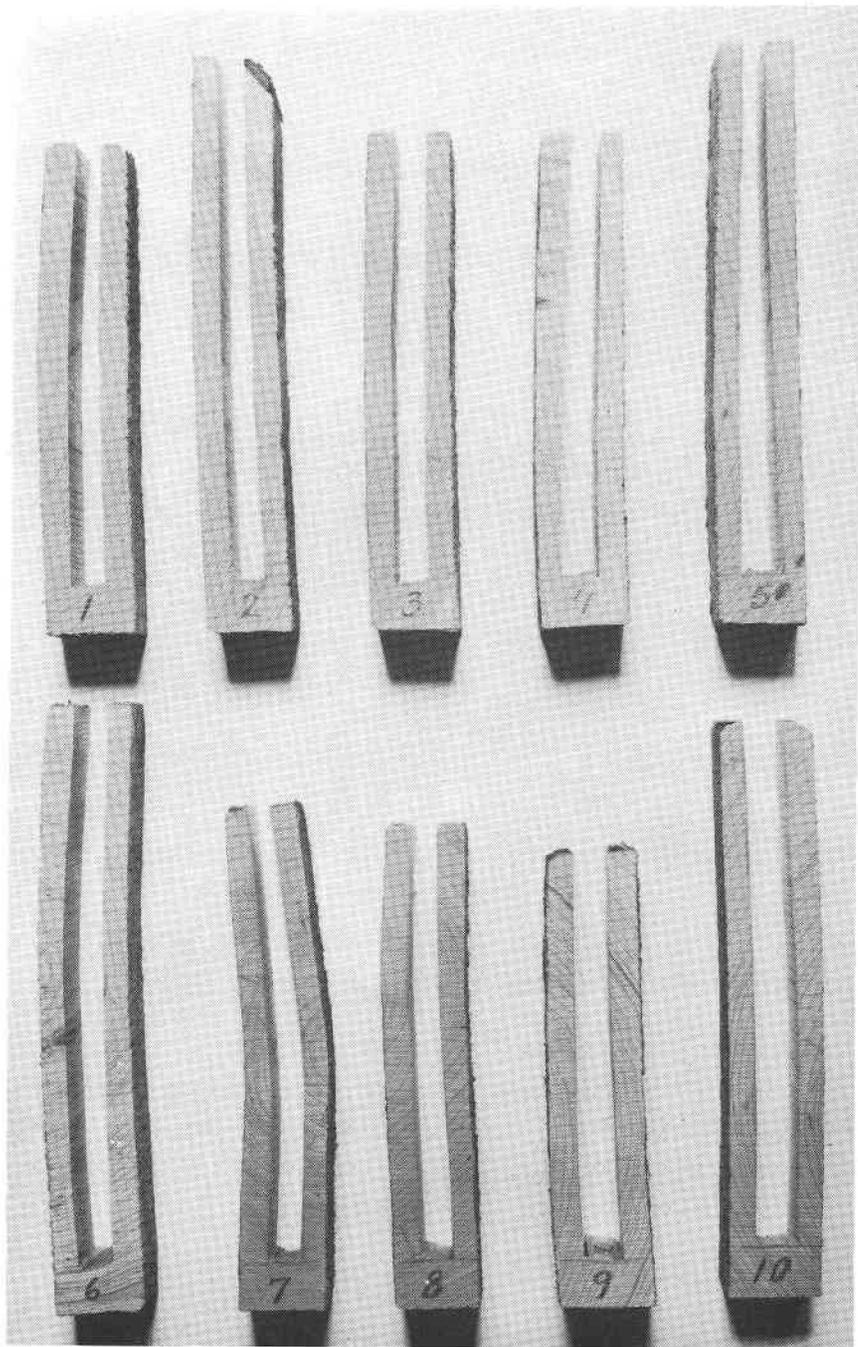
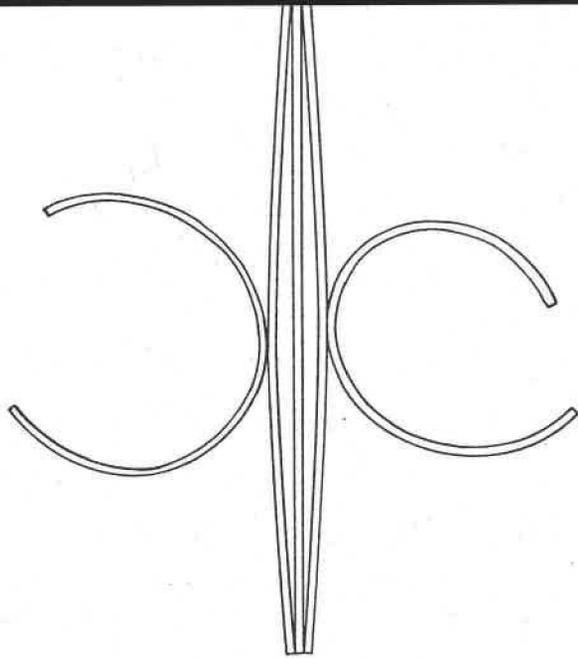


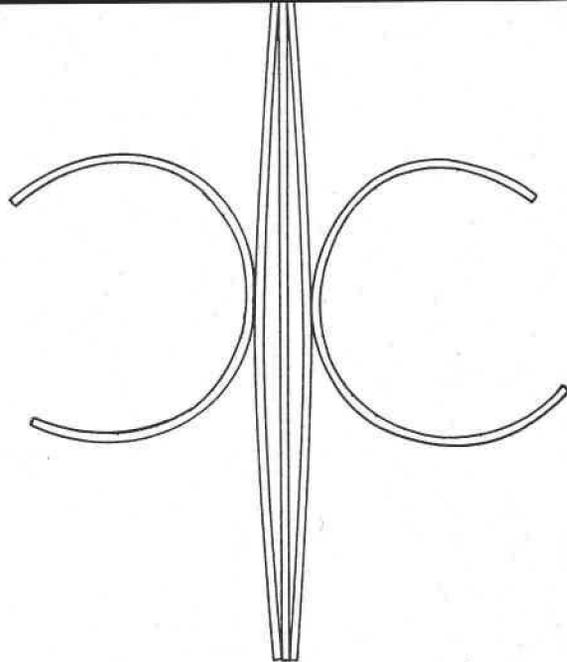
Figure 12. --Stress sections from properly conditioned cherry lumber.

ZM 88561 F

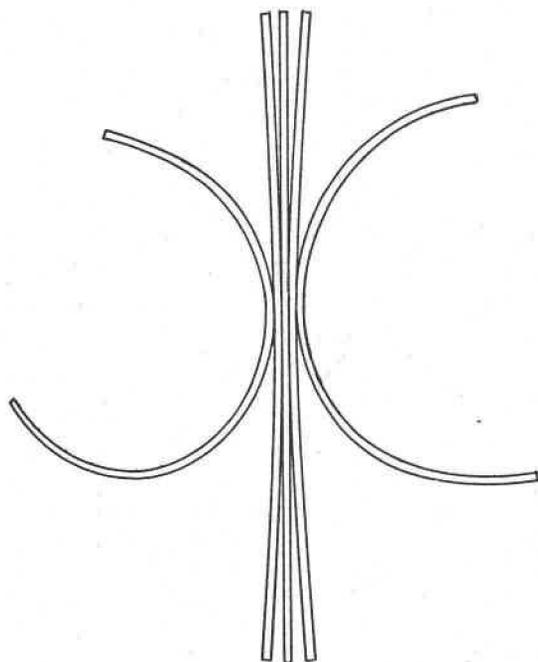
Report No. 1652



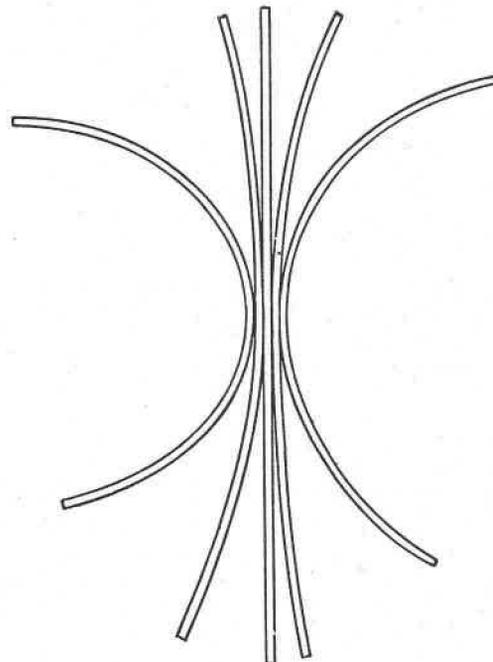
*3/4 HOURS
STEAMING*



*1 1/2 HOURS
STEAMING*



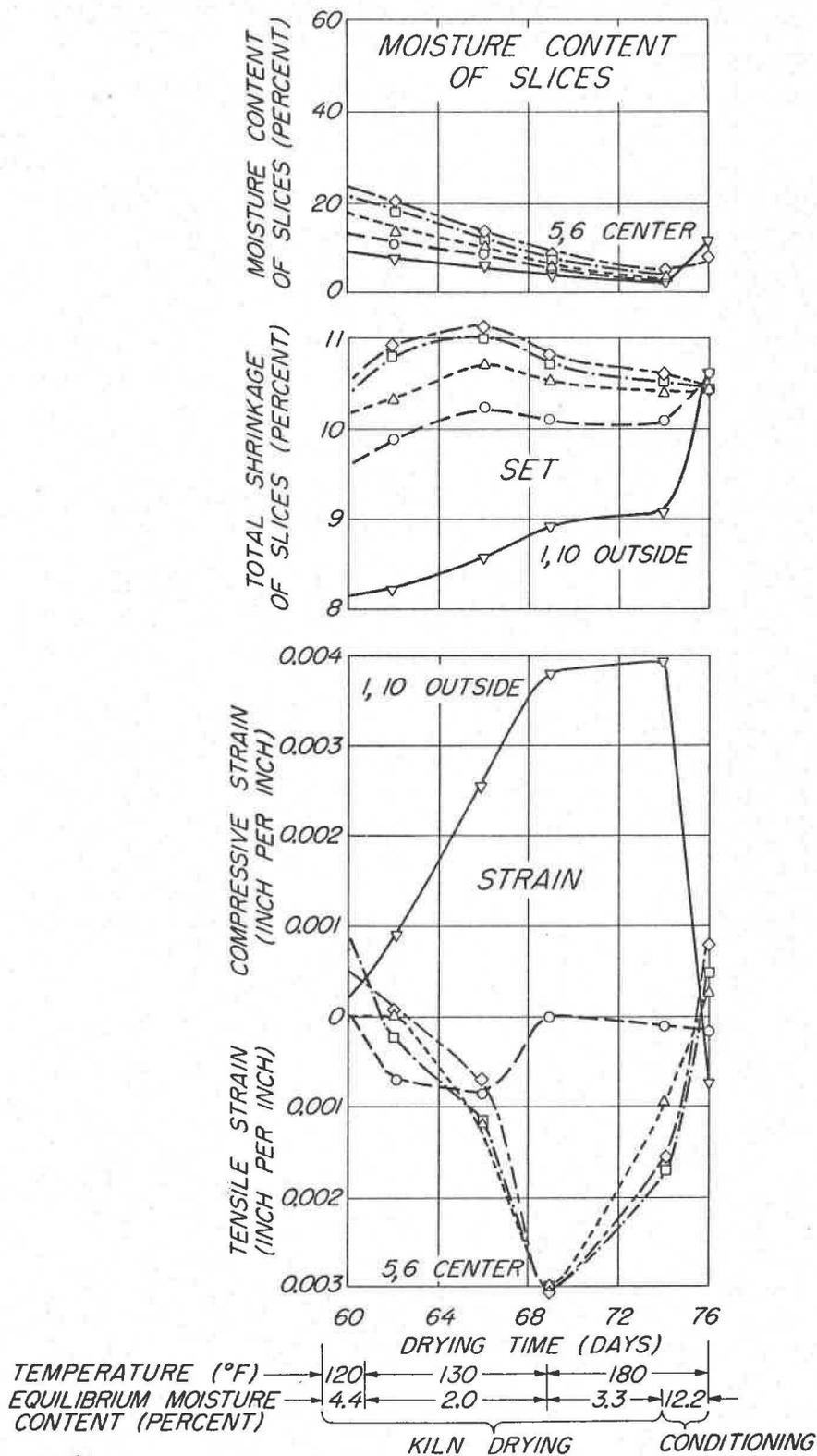
*3 HOURS
STEAMING*



*6 HOURS
STEAMING*

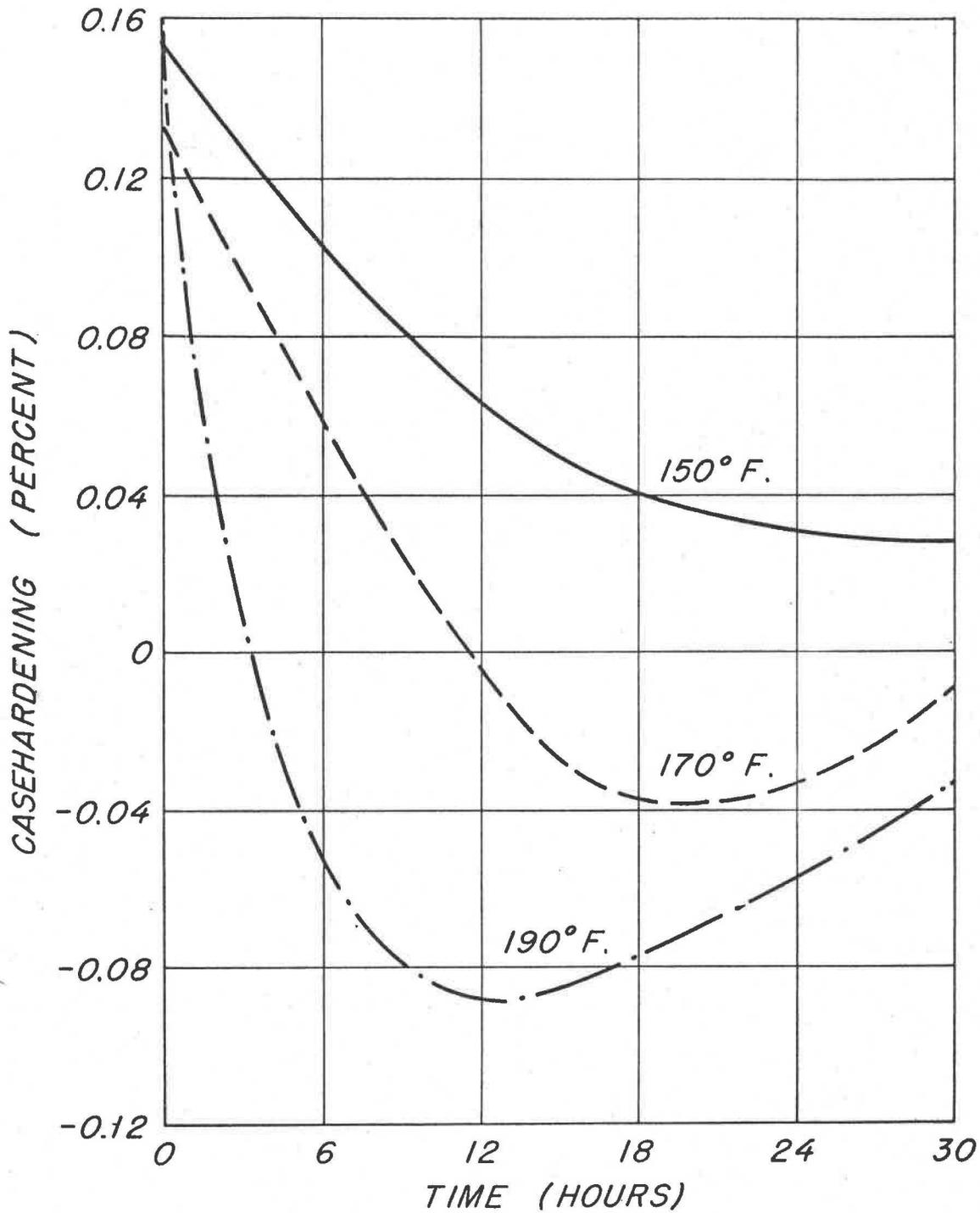
M 108 217

Figure 13. --Reversed stresses in a sap gum board as a result of steaming for periods shown.



M 107 741

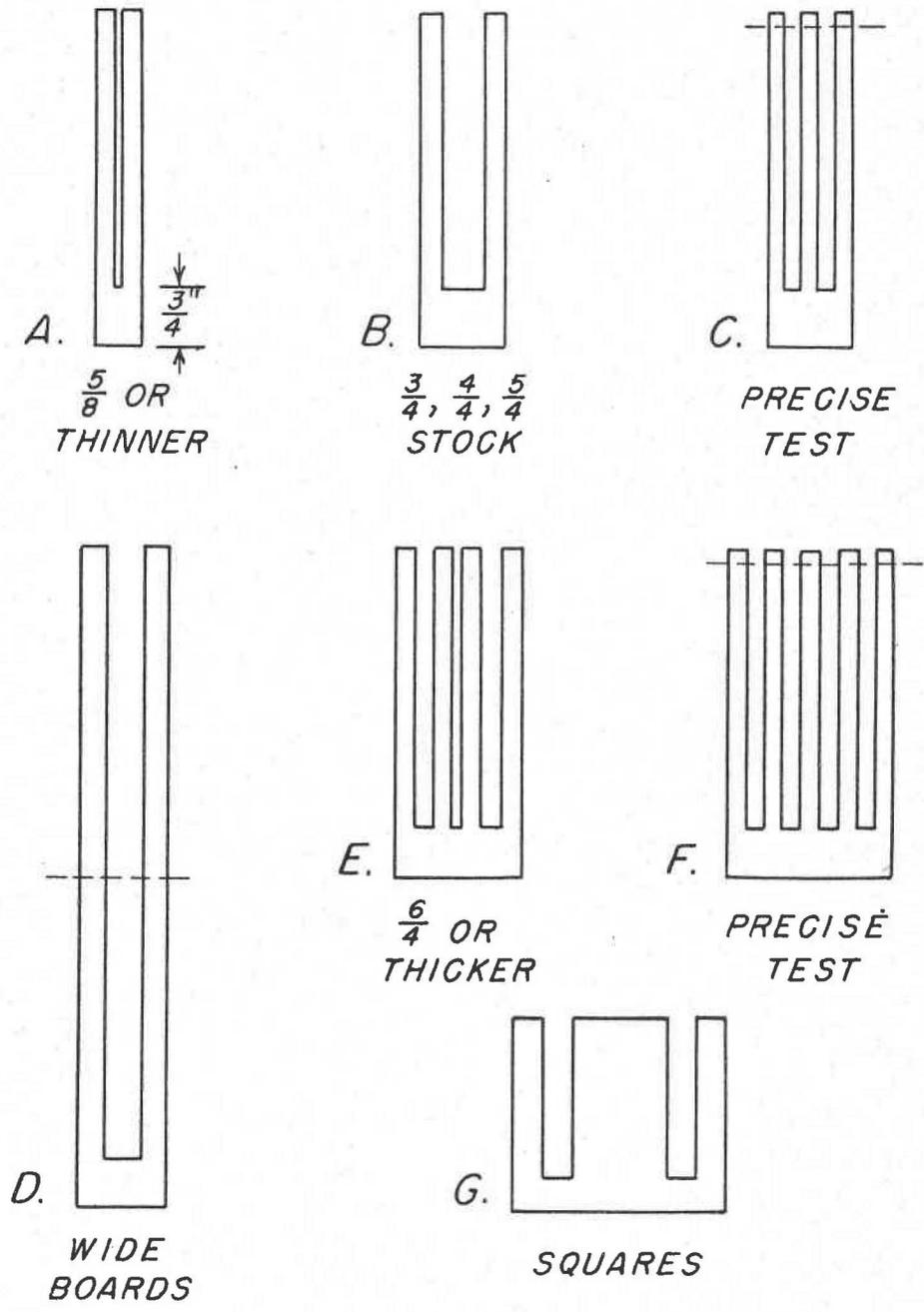
Figure 14. --Relief of stresses in a red oak heartwood board by high-temperature, high-humidity treatment.



M 107 742

Figure 15. --Stress relief and reversal in yellow birch at 9 percent EMC.

Report No. 1652



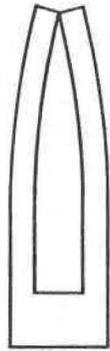
M 108 159

Figure 16. --Method of cutting stress tests.

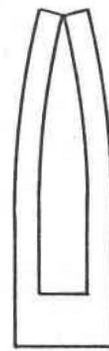
REACTION
WHEN SAWED

CONDITION AFTER
ROOM DRYING

A

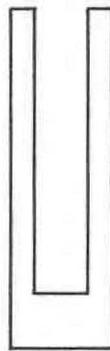


PRONGS
TURN IN

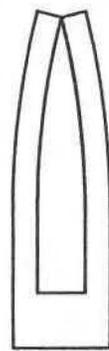


CASEHARDENED

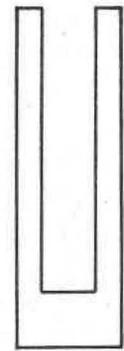
B



PRONGS
STRAIGHT

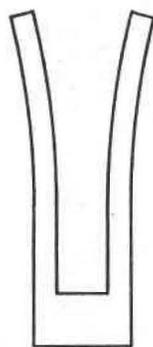


CASEHARDENED

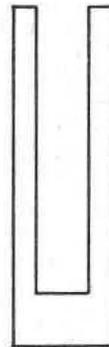


STRESS
FREE

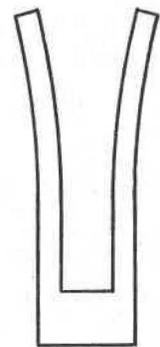
C



PRONGS
TURN OUT



STRESS
FREE



REVERSE
CASEHARDENED

Figure 17. --Stress-test results.