# Manual on

# THE LAMINATING OF TIMBER PRODUCTS WITH LOW-TEMPERATURE, PHENOLIC-TYPE RESIN GLUES

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Prepared by
Forest Products Laboratory
Madison, Wisconsin
and
Gamble Brothers, Inc.
Louisville, Kentucky

In Cooperation
with the
Office of Production Research and Development
of the
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UNITED STATES DEPARTMENT OF AGRICULTURE
FOREST SERVICE
FOREST PRODUCTS LABORATORY
Madison, Wisconsin
In Cooperation with the University of Wisconsin

## Foreword

This manual provides information useful and necessary in the production of high-quality laminated timbers for ships, barges, and other purposes having similarly severe requirements of use. It is based on accumulated research experience and on special information developed by the Forest Products Laboratory and by Gamble Brothers, Inc., in pilot plant studies on laminated ship-timber gluing financed by the Office of Production Research and Development, of the War Production Board at the plant of Gamble Brothers, Inc., Louisville, Kentucky.

Experience to date has shown the great importance of careful selection of glues and control of fabricating details in order to produce laminated timbers of the necessary high quality and glue durability.

It is the purpose of this publication to provide a summary of the needed information and references to more detailed publications on various aspects of the problem

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Table of Contents

## A. LUMBER AND GLUE FOR LAMINATING

## B. LAMINATING WHITE OAK SHIP TIMBERS WITH LOW-TEMPERATURE PHENOLIC-TYPE RESIN GLUES

# A. LUMBER AND GLUE FOR LAMINATING

## 1.0. GROWTH AND STRUCTURE OF WOOD

### 1.1. Growth of wood

In most woods three regions may be readily distinguished on the end surface of a log: (1) the bark, (2) a light-colored layer next to the bark, called the sapwood, and (3) an inner zone, usually darker than the sapwood, called the heartwood. In the structural center of the log is a small, soft core known as the pith. These zones are shown in figure 1.

Sapwood and heartwood are similar in cellular structure (5)[1]. In the growing tree (fig. 2) the sapwood contains some living cells and takes an active part in the life processes of the tree. Most of the sapwood cells, however, are inactive and function only as channels for the movement of sap and as strength elements in the tree trunk. The heartwood consists entirely of nonliving cells.

A tree grows in height and spread of branches by the addition each year of new growth at the tips of the twigs. Each year new cells are also produced on the outer side of the sapwood of the trunk and branches by a thin layer of cells, called the cambium, located between the bark and the sapwood. As a tree increases in diameter by the addition of new layers of sapwood cells, dead as well as living branches are gradually embedded in the wood of the trunk and become known as knots. Normally a knot starts at the pith and increases in diameter from the pith outward so long as the branch is alive.

The inner sapwood changes to heartwood at substantially the same rate as that at which new sapwood cells are formed by the cambium. The principal changes involved in the transformation of sapwood to heartwood are the death of the living cells of the sapwood and the infiltration of various materials into the cell walls and cell cavities which usually darken the wood and, in many species, make it more resistant to decay, stain, mold, and insect attack. In some species, such as those of the white oak group, the larger cells (pores) become partially or completely plugged with ingrowths, known as tyloses, shortly before the change from sapwood to heartwood takes place. There is no substantial change in strength with change of sapwood to heartwood.

In most trees grown in a temperate climate, the cells formed at the beginning of each year's growth are larger than those formed later in the season and, consequently, well-defined concentric growth layers of wood, known as annual rings, can be seen on a cross section of a log, as shown in figure 1.

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[1] Underscored numbers in parentheses refer to publications listed under "Literature Cited", which give more detailed information.

Springwood is the wood formed during the early part of the growing season and occurs on the inner side of the annual ring. In such woods as oak, it is more porous than the summerwood that makes up the outer part of the annual ring. In such woods as Douglas-fir and southern yellow pine, springwood is much lower in density than summerwood. In general, springwood is lighter, softer, and weaker than summerwood although in some woods, such as birch and sweetgum, there is no distinct difference between springwood and summerwood.

## 1.2. Hardwoods and softwoods

Woods can be grouped in two general classes: hardwoods, such as oak and maple, that come from trees with broad leaves; and softwoods, such as fir and pine, that come from cone-bearing trees with needle-like or scale-like leaves. The terms hardwoods and softwoods do not refer to mechanical hardness since some of the so-called softwoods (southern yellow pine) are harder than some of the so-called hardwoods (basswood) (4).

The cellular structure of these two classes of wood is fundamentally different, however, as indicated by figure 3. That of hardwoods is characterized by the presence of larger cells, constituting pores or vessels, scattered among the smaller fibers. In softwoods the bulk of the wood is composed of tracheids. These are fibrous cells that serve the combined purpose of the pores and wood fibers of hardwoods (7, 8).

## 1.3. Wood rays

Most of the cells in wood, including vessel segments, fibers, and tracheids, are vertical elements, that is, their long dimensions extend in the direction of the grain and in a standing tree are vertical. In addition to these vertically arranged cells, there are strips of horizontally elongated cells in wood that extend radially from the bark inward, and are known as rays or wood rays. In oak the larger rays are distinctly visible as broad lines on the cross section and as large flakes from a fraction of an inch to several inches long on radial surfaces. In all other native commercial species the rays are much smaller.

## 1.4. Plain-sawed and quarter-sawed lumber

Wood can be cut in three distinct planes with respect to the annual layers of growth: lengthwise tangent to any of the annual rings, exposing the tangential or so-called plain-sawed, slash-grain, or flat-grain surface; lengthwise along any of the wood rays, exposing the radial surface, also known as the quarter-sawed, edge-grain, or vertical-grain surface; and crosswise, exposing the transverse or end-grain surface (figure 4). Usually the faces of the so-called quarter-sawed or edge-grain lumber are not cut strictly parallel with the rays, and often in plain-sawed boards the surfaces next to the edges are far from being tangent to the rings. In commercial practice, lumber with rings at angles from 45° to 90° with the wide faces is called quarter-sawed while material with rings at angles from 0° to 45° with the wide faces is called plain-sawed. A board may be plain-sawed in one part and quarter-sawed in another part of its width.

## 1.5. Identification of woods

Identification of most species of wood by general appearance is possible only after long experience. Specific differences in cellular structure, some of them microscopic, together with such characteristics as color, odor, taste, weight, and hardness, are the bases for the technical identification of wood. Two keys that permit the systematic identification of such important shipbuilding woods as white oak, Douglas-fir, and southern yellow pine are available (12).

# 2.0. PROPERTIES OF WOOD

## 2.1. Weight

The weight of wood per unit volume when dried to a uniform moisture content is a fairly reliable indication of its strength and shrinkage. In general, heavy woods are stronger and shrink more in drying than do light woods. The weight of wood is usually expressed as so many pounds per cubic foot or per thousand board feet at a stated moisture content.

## 2.2. Wood-moisture relations

Moisture content-- Moisture, sometimes known as "sap", in green or wet wood, is held in two ways. Part of it is bulk liquid contained in the cell cavities and is known as free water, and part is absorbed or "imbibed" water held in the cell walls. Some free water is present in both the heartwood and sapwood of most living trees, although the amounts may differ greatly. More moisture is usually contained in green sapwood than in heartwood. Contrary to common belief, the variation during the year in the amount of moisture in a standing tree is slight.

The amount of moisture in wood, termed the moisture content, is ordinarily expressed as a percentage of the weight of oven-dry wood. If, for example, the moisture content of a dry board is 10 percent, there are by weight 10 parts of water to 100 parts of oven-dry wood. If the moisture content of a green board is 150 percent, the moisture constitutes 3/5 and oven-dry wood 2/5 of the total weight of the board. The term "moisture content" obviously is relative and does not give a measure of the absolute amount of water present unless the density of the wood is taken into consideration. An oak board at 20 percent moisture content, for example, contains more water than a spruce board of the same dimensions at the same moisture content.

The trade terms "air-dry", "shipping-dry", and "kiln-dried" have no specific meaning with regard to moisture content. Air-dry lumber may have a moisture content ranging from 6 percent in the arid Southwest during the summer months to 24 percent in parts of the Pacific Northwest during the winter. In general, the average moisture content of thoroughly air-dry lumber is approximately 12 to 15 percent. Lumber that is partially dried to reduce freight charges is known as shipping-dry lumber and may have a moisture content of 30 percent or more. Kiln-dried lumber is commonly reduced to a moisture content of 4 to 12 percent, depending on the requirements for its use, although kiln-dried softwood lumber in common grades is sometimes only partially seasoned to 15 to 22 percent moisture content.

Measurement of moisture content-- Two methods most commonly used for the determination of moisture content in wood are the oven-drying and the electrical methods. The oven-drying method is more exact and is applicable over a wider range of moisture content values, whereas electrical moisture meters, although somewhat limited in range and accuracy, offer a rapid means of estimating moisture content. Electrical moisture meters do not read below 7 percent moisture content and hence are not of much value in avoiding the use of over-dry lumber for laminating purposes. Descriptions of these methods and of the equipment needed to carry out moisture content determinations are given in several publications (18, pp. 3-6, 11, pp. 208-210, and 2).

Fiber-saturation point-- A portion, or even all, of the free water contained in the cell cavities can be removed without reducing the amount of water in the cell walls. The point at which the cell cavities are emptied of water while the moisture content of the walls remains unchanged is called the fiber-saturation point. Further drying removes moisture from the cell walls themselves. It is at the fiber-saturation point, usually between 25 and 30 percent moisture content for most species, that the changes in the properties of the wood caused by drying usually begin to take place.

Equilibrium moisture content-- Any piece of wood that is placed in an atmosphere in which temperature and humidity are held constant will give off or take on moisture from the surrounding atmosphere until the moisture in the wood has come to a balance with the atmosphere. The moisture content of wood at the point of balance is called the equilibrium moisture content for those conditions (15, pp. 6-8).

Accurate determination of the equilibrium moisture content of wood at different dry-bulb temperatures and relative humidities is easily accomplished through the use of figure 6. At 80°F. and 50 percent relative humidity, for example, this graph shows that the equilibrium moisture content is 9 percent. If the temperature is raised to 180°F. and a relative humidity of 50 percent is again established, the wood will reach equilibrium at 6 percent moisture. Relative humidity may be readily determined from wet- and dry-bulb hygrometer readings and from tables of dry-bulb temperature and wet-bulb depression (15, pp. 9-10), or from plotted values presented in figure 7.

Shrinkage of wood-- The drying of wood below its fiber-saturation point is accompanied by shrinkage. In all species of wood, flat-grain lumber experiences the greatest amount of shrinkage across the face (tangential) and, quarter-sawed lumber approximately 1/2 to 2/3 as much (radial), when dried to the same moisture content. Normal wood experiences very little change in length as it becomes dry. Subsequent absorption of moisture results in swelling of the wood, and, if absorption is carried to the fiber-saturation point or higher, the amount of swelling will generally equal the original amount of shrinkage. Shrinkage of wood is discussed in detail in several publications (15, pp. 11-16 and 11, pp. 193-198).

2.3. Strength of wood

Basic strength properties-- In its broadest sense, strength includes all the properties that enable wood to resist different forces or loads. In a more restricted application of the term, strength may refer to any one of the different mechanical properties of wood. When used in this way, the name of the property should be stated. A wood that is exceptionally strong in resisting one kind of load, such as endwise compression, may be inferior to other woods in bending strength, stiffness, shock resistance, or hardness.

Comparative strength values for native American woods are available (14, pp. 5-13). These strength values are based on tests of small clear specimens of wood that eliminate the effect of defects.

Unlike metals which have generally uniform strength in all directions, wood does not have the same strength across the grain as parallel to the grain. The ratio of tensile strength parallel to the grain compared with that across the grain is commonly as high as 40 to 1, and the ratio of compressive strengths in these two directions is often as high as 7 to 1.

The position of the growth rings influences a few of the strength properties of wood. There is little if any difference in strength, however, between quarter-sawed or plain-sawed stock when loaded as a beam, nor is there any technical basis for the common belief that plain-sawed lumber bends more readily than quarter-sawed stock. Some properties, such as compressive strength across the grain, are considerably affected by the direction in which the load acts across the fibers. Greatest loads in compression across the grain can be supported when they are applied to the flat-grain surface, intermediate loads can be carried on the quarter-sawed surface, and lowest strength results when loads are applied at an angle of 45° to the annual growth rings (11, p. 56).

Specific gravity (or density) as related to strength-- The specific gravity of wood substance, the material of which the cell walls are composed, is about 1.5 regardless of species. Consequently, the specific gravity of a piece of dry wood is an excellent index of the amount of wood substance it contains and hence is an index of its strength properties. While a general relationship exists between specific gravity and strength properties among different species, specific gravity affords a still better index of strength where only one kind of wood is involved. The heaviest pieces of a species of wood may be 2 to 3 times as heavy as the lightest ones.

Although the number of rings per inch is sometimes of assistance in evaluating the strength of wood, it is not so reliable as specific gravity. Among the ring-porous hardwoods, such as oak, wood of fairly rapid growth is likely to be excellent in weight and strength. Softwood species, such as Douglas-fir and southern yellow pine, show a wide range of density and strength at different rates of growth, but usually the strongest material is associated with a moderate rate of growth. Exceptionally rapid or slow growth is likely to be accompanied by low density and correspondingly low mechanical properties (11, pp. 59-60).

Moisture as related to strength-- Wood increases in most strength properties as it dries below the fiber-saturation point. The increased strength of dry over green wood is believed to be chiefly due to the strengthening and stiffening of the cell walls as they dry out. In drying wood from green to 5 percent moisture content, the end crushing strength and bending strength of small clear pieces may be doubled or tripled. The increase in strength with seasoning is not so great in large timbers containing defects. In them the increase in strength is, to a large extent, offset by the influence of defects that develop in seasoning.

The various strength properties are not equally affected by changes in moisture content. Whereas some properties, such as crushing strength and bending strength, increase greatly with drying, others, such as stiffness, increase only moderately, and still others, such as shock resistance, may even show a slight decrease. This last effect is due to the fact that dry wood does not bend so far as green wood before failure, although it will sustain a greater load, and shock resistance or toughness is dependent upon both strength and pliability (11, pp. 61-62).

## 2.4. Bending of wood

When a piece of wood is bent, the fibers on the inside of the curve are in compression and those on the opposite side are in tension. The radius to which dry lumber can be bent before breaking is dependent upon the species, moisture content, thickness of material, and the defects present. The breaking radius for individual boards varies considerably from the average. In general, hardwoods will bend to more severe curvature than softwoods.

When wood is both wet and hot, its plasticity is increased. This effect is more evident in the hardwoods than in the softwoods. Such hardwoods as elm, hickory, and ash are particularly adaptable to bending, after steaming or soaking treatment in hot water, to a radius as small as 3 or 4 times the thickness of the piece. Bending of steamed lumber to sharp curvatures requires careful selection of dense, clear, straight-grained stock and careful manipulation during the bending process.

## 2.5. Durability of wood

If it is kept continuously dry (below 20 percent moisture content) or submerged in water, neither sapwood nor heartwood of any species will decay. When exposed to warm moist conditions favorable for the development of decay organisms, however, the untreated sapwood of practically all woods is short-lived. Under these conditions the durability of heartwood of different species varies over a wide range. The heartwood of black locust, for example, is extremely durable; that of white oak and dense Douglas-fir is not quite so durable; tamarack is intermediate, and cottonwood is very low in resistance to decay. A classification of common woods based on decay resistance of the heartwood is given in another publication (11, pp. 41-43). Impregnation with suitable preservatives will greatly prolong the life of nondurable woods under severe exposure conditions.

## 3.0. NATURAL DEFECTS IN WOOD

Irregularities in wood that tend to lower its strength, durability, or usefulness are known as defects. Certain defects, such as knots and decay, greatly affect the strength of wood; pitch streaks, that occur in some coniferous woods, and knots may impair the gluing characteristics of a surface; still other defects may affect a combination of properties. Cross grain, for example, influences strength, shrinkage, and gluing properties.

### 3.1. Decay and stains

The strength of wood is seriously impaired by decay (11, pp. 66-67). Although all decay organisms do not act alike, certain types of decay, even in their early stages when evident only as slight discolorations of the wood, may cause a considerable lowering in shock resistance. In the later stages of decay, all the mechanical properties deteriorate. Discolorations caused by staining fungi are not in themselves serious defects, but the conditions under which they develop favor the growth of wood-destroying fungi and there is danger that the stain may mask decay infection.

### 3.2. Cross grain

The term "cross grain" refers to any deviation of fibers in a wood member from the lengthwise direction of the member. Cross-grained material is weak as a result of the relatively low strength of wood in tension perpendicular to the grain as compared to tension parallel to the grain. In addition to their reduced strength, members containing cross grain are undesirable from the standpoint of warping and lengthwise shrinkage and swelling. Methods for the recognition and measurement of spiral and diagonal grain, the chief types of cross grain, are given in another publication (11, pp. 64-65).

### 3.3. Knots

The weakening influence of a knot is due in large part to the distorted grain around the knot. In fact, the distorted grain lowers the strength fully as much as does the knot itself. Knots are serious in their effects on the bending strength of wood. A knot located on the tension face of a beam has about twice the weakening effect of a similar knot on the compression side. The effect of knots depends on their size, location, shape, and soundness. Knots are harder to machine than the surrounding wood and may project from the surface when shrinkage occurs. Furthermore they are more resistant to compression at right angles to the grain than the surrounding wood, and are apt to cause an objectionable lack of uniformity in the distribution of pressures used in laminating operations. The end-grained surfaces presented by knots also are not favorable for strong and durable glue joints. Intergrown and encased knots are briefly discussed elsewhere (11, pp. 63-64). A knot that is cut through transversely or obliquely is known as a round knot or oval knot and one cut through lengthwise is known as a spike knot (fig. 5, A, B, and C). A tight knot is one so fixed by growth or position that it will firmly retain its place in the piece. An intergrown knot is necessarily a tight knot. A sound knot is solid across its face, as hard as the surrounding wood, and shows no signs of decay. Ordinarily, the size of knots refers to the average of maximum and minimum diameters.

### 3.4. Shakes and splits

A shake is a longitudinal separation in wood extending, in general, between two annual rings. A split is a lengthwise separation of the wood extending from one surface through the piece to the opposite surface or to an adjoining surface. In beams, the principal effect of shakes and splits is to reduce resistance to longitudinal shear, or the sliding of one part of the member upon another.

### 3.5. Pitch and bark pockets

Pitch pockets are openings within or between the growth rings of certain coniferous woods, such as Douglas-fir and southern yellow pine, containing pitch and sometimes bark as well. Ordinarily their dimensions at right angles to the annual rings are less than 1/2 inch although they may extend for several inches longitudinally and tangentially. Unless they are large or numerous, and involve considerable distortion of the grain, pitch pockets are ordinarily not serious in their effect on strength. A large number of pitch pockets in or close to the same annual growth layer, however, indicates a lack of bond and may be equivalent in effect to a shake. A bark pocket is a patch of bark partially or wholly enclosed in the wood and, of course, may occur in any species. Its effect is similar to that of a pitch pocket of the same size.

### 3.6. Compression failures

Compression failures appear as more or less pronounced wrinkles or as fine white lines extending across the fibers on a side-grain surface (fig. 5, D). Their presence indicates that the wood has at some time been excessively compressed. Compression failures may occur when standing trees are severely bent or when logs or sawed stock are roughly handled. They weaken wood particularly in tension and shock resistance, and a member containing compression failures is apt to produce brash-appearing and sudden failures.

### 3.7. Bird pecks and mineral streaks

A bird peck is a small hole or patch of distorted grain resulting from birds pecking through the growing cells of the tree (fig. 5, E). These defects frequently occur in horizontal rows around the tree and may result in the formation of mineral streaks. Mineral streaks are dark brown or black streaks, frequently with a green tinge and often contain mineral matter in sufficient quantities to dull sharp-edged tools. Mineral streaks are frequently infected by fungus and wood containing them checks more easily in seasoning than does normal wood. Evidently mineral streaks are often, if not always, due to some injury to the living tree.

### 3.8. Worm holes

The effect of worm holes on strength depends on their size and frequency. A worm hole not over 1/16 inch in diameter is known as a pin hole; a medium hole is over 1/16 inch but not more than 1/4 inch in diameter; and a large hole is one over 1/4 inch in diameter. Although the lose of strength associated with a pin worm hole is usually slight, the possibility of extensive damage to the interior of a piece by powderpost beetles should be recognized. These insects may seriously damage the sapwood of white oak and other hardwoods with no apparent injury other than small emergence holes on the surface.

### 3.9. Brashness

Wood that is low in shock resistance and fails at relatively low loads in bending by an abrupt break across the fibers without splintering is known as brash wood. Frequently, brash material is of low density and can be avoided, where strength is important, by the rejection of exceptionally light-weight pieces. In hardwoods, such as oak and hickory, brash material is often characterized by very slow growth. Not all brash wood, however, is low in density. Two of the most frequent causes of brashness in stock of satisfactory density are decay and compression failures. Reference has been made to both of these defects in previous paragraphs.

## 4.0. SEASONING OF LUMBER

Lumber is seasoned to improve its suitability for use. Properly controlled seasoning of lumber reduces the amount of seasoning defects that may otherwise develop in drying or in service, lessens the liability of wood to decay while air drying, and, particularly important from the standpoint of laminating, reduces the moisture content to the level most satisfactory for gluing operations.

### 4.1. Air drying and kiln drying

Lumber may be air seasoned or kiln dried. The principles involved in air seasoning are discussed in another publication (15, pp. 16-24). Commercial methods of air drying and storing dry lumber are presented in the same bulletin, (15, pp. 32-55) and in other publications (16, 17).

When the requirements for a particular purpose demand a lower moisture content than can be obtained through air seasoning, kiln drying is necessary. Kiln drying also permits a considerable reduction in drying time. Successful kiln drying depends in large part upon the proper regulation of temperature, humidity, and circulation. The principles governing the control of these factors are covered in another bulletin (18, pp. 7-31. Whenever wood dries, moisture will become unevenly distributed throughout the piece and unequal shrinkage will occur, which may be detrimental unless kept within permissible limits. Drying stresses set up as a result of irregular shrinkage and methods of stress detection and stress relief are discussed in other publications (18, pp. 31-33, 37-43, and 9). Recommended kiln drying schedules for commercial practice together with details of kiln operation are also presented (18, pp. 43-95).

## 4.2. Seasoning defects

Most seasoning defects result from drying stresses that accompany uneven shrinkage. Such defects include surface and end checks, warp, casehardening, honeycomb, and collapse. These defects are discussed in other publications (18, pp. 33-36, 11, p. 204, and 15, pp. 24-27).

## 4.3. Seasoning requirements for lumber for laminating purposes

Careful control of moisture content and internal stress is essential to the success of the laminating operation. In preparing white oak laminating stock for gluing, specific limits are placed on the average moisture content, on the variation in moisture content between boards, and on the distribution of moisture in each board. The moisture content must average between 8 and 15 percent, and the maximum difference in moisture content permitted between individual boards to be used in the same laminated member is 3 percent. A further requirement specifies that the difference in moisture content between shell and core in any board shall be not more than 2 percent. Shell and core specimens are prepared as indicated in figure 8. These limitations call for close control of kiln drying and for the maintenance of proper storage conditions prior to gluing.

# 5.0. WOODWORKING GLUES

## 5.1. Types of glues

Prior to the development of the synthetic resins, the glues most commonly used in woodworking included the animal, vegetable (starch), casein, vegetable-protein, and blood-albumin types (6, 19, pp. 2-9). In the last decade, however, an incrasing number of synthetic-resin glues have been made available (10). The resin glues in most common use at present are the urea-formaldehyde, and phenol-formaldehyde glues. Melamine, resorcinol, and vinyl-ester resins represent glues that are promising but are not yet so well known.

With the exception of the vinyl-ester resins, the synthetic resin glues that have been named are classified as thermosetting; that is, once the glue has set it will undergo no softening even though the temperature is raised above that required for the original setting up to temperatures that will char wood. Thermoplastic glue joints, on the other hand, must be retained under pressure until cool in order to harden and strengthen the glue, and subsequent heating above the softening range will destroy the glue bond.

Some thermosetting glues are formulated for hot-pressing at temperatures in the neighborhood of 240° to 320°F., others, such as those of the low-temperature phenol type, set at intermediate temperatures and can be cured in a properly controlled dry kiln, and still others contain a catalyst that accelerates the setting reaction sufficiently to permit complete cure at room temperatures. The latter are commonly called cold-setting resins and are typified by some glues of the urea-resin type.

Although the dry joint strengths of all common woodworking glues are sufficient for most purposes, the low water resistance of vegetable, vegetable-protein, and animal glues limits them to uses that do not involve severe exposure to moisture.

## 5.11. Casein glues

Casein glue is classed as "water resistant" on the basis of its relatively high resistance to moisture in comparison with vegetable and animal glues. Its basic constituent is the dried casein of milk which, combined with alkali-producing chemicals, is water soluble. The further addition of lime causes the glue to set and retain a considerable portion of its strength even when submerged in water for a short period of time. In prolonged laboratory tests of plywood continuously soaked in water, however, casein glue joints have failed completely. Under exposures involving high humidity, casein glue joints weaken rapidly. Relatively recent introduction of casein glues containing sufficient toxic chemicals to prevent development of molds and other micro-organisms has considerably improved the strength and durability at high humidity.

## 5.12. Urea-formaldehyde glues

Urea resins are available as dry powders or as suspensions in water that ordinarily contain from 60 to 70 percent solids. The powder forms are prepared for use by mixing with water to produce suspensions of approximately the same concentration. Some urea-resin powders are formulated for use especially as cold-setting glues and include an incorporated catalyst. Other types serve either for room temperature setting or hot-press operations depending upon the particular catalyst added by the user.

Those urea-resin glues that are formulated for hot-pressing generally set at temperatures in the range of 220° to 260°F. The rate of setting of cold urea resins is reasonably rapid at a room temperature of 75°F. (3) (pressure can usually be removed after 4 hours) and is appreciably accelerated at higher temperatures. Setting temperatures below 70°F. are not recommended for urea glues.

Urea-resin glue joints in most woods are highly water resistant at ordinary temperatures. Tests of birch plywood have shown that glue joints of this type retain good strength values after several years of continuous soaking in water. These glues, however, are less satisfactory in resisting the effect of high humidity and deteriorate considerably when continuously exposed at high humidities. They are subject to pronounced weakening in water at temperatures above 150°F. and weaken more gradually when exposed in dry air at similar temperatures.

Although highly resistant to continuous soaking when used to glue some woods, cold-setting urea resins have performed unsatisfactorily in laboratory water-exposure tests when used to glue certain woods, including white oak and Douglas-fir. These results are confirmed by reports of partial delamination of experimental white oak laminated ship keels within 9 months when exposed in salt water.

Some urea-resin glues have been developed primarily to improve the resistance of the glue joints to hot water. These glues may be combinations of urea resin and resorcinol or melamine resins and are variously referred to as "fortified" or "modified". These special urea-resin glues appear to be somewhat more resistant to deterioration at high temperatures than either the cold-setting or hot-press ureas, but exposure tests indicate little improvement, if any, in their resistance to high humidity.

## 5.13. Phenol-formaldehyde glues

The phenol-formaldehyde glues may be classified, on the basis of setting-temperature requirements, as hot-press and low-temperature glues. In general, phenolic-resin glues are formed by the reaction of phenol or cresol with formaldehyde. For the production of woodworking glues, the reaction is stopped at an intermediate stage to obtain a product that can be powdered and suspended in water or some other solvent, such as alcohol. After the resin has been applied to the surfaces to be glued, the setting reaction is carried to completion by the application of heat.

As a class, phenolic-resin glue joints are extremely durable over a wide range of moisture and temperature conditions. They are resistant to attack by micro-organisms and are highly durable under such adverse conditions as continuous soaking in fresh or salt water, continuous exposure at high humidity, cyclic exposures involving wetting and drying, and exposure to high temperature at low and high humidities. The strength of phenolic-resin glue joints properly glued and cured is largely limited by the ability of the wood to resist the conditions of exposure.

Hot-press phenolic glues-- Most hot-press phenolic glues are nearly neutral in reaction and are available in film, powder, and liquid forms. When the glue is spread as a liquid, pressing may be done immediately or it may be delayed for several days. Platen temperatures for gluing with hot-press phenolic-resin glues of either film or liquid form in the usual hot-press operation are normally from 240° to 320°F.

Low-temperature phenolic glues-- Several phenolic, melamine, and resorcinol resins and combinations of them that set at substantially lower temperatures than those required for hot-press phenolics have been developed recently. Most of these glues contain either acidic or alkaline catalysts to accelerate the rate of setting at relatively low temperatures. Some of them cure at temperatures of 150° to 200°F. and present indications are that glues of this type may soon be available that will set at even lower temperatures.

In general, highly acid low-temperature phenolic glues appear to cause deterioration of the wood under certain conditions of exposure, resulting in reduced strength and shallow wood failures in the vicinity of the glue lines. Approximately neutral- or slightly alkaline-catalyzed low-temperature phenolic glues do not show this effect.

5.14. Melamine-formaldehyde glues

Melamine-resin glues are available both as hot-press and low-temperature types. Their characteristics and properties are similar to phenol-formaldehyde glues of the same type, except that temperatures required for curing the hot-press melamines are somewhat lower than for hot-press phenols.

5.15. Resorcinol glues

The properties and characteristics of resorcinol glues have not yet been fully investigated. They are represented by the manufacturers as developing cure and a high degree of water resistance at room temperatures and are finding application in the laminating of timbers. The indications are that they can also be cured more rapidly and as satisfactorily as under conditions suitable for low-temperature, phenol-formaldehyde glues.

5.2. Glues for use in laminating timbers for severe exposure

The selection of glues for use in laminating timber products, such as ship timbers, is necessarily based on their curing requirements and on the ability of the glues to withstand severe conditions of exposure. On this basis, the choice of glues for ship timbers is limited at present to those of the low-temperature phenol, resorcinol, and melamine-formaldehyde types. The durability of the non-resin glues and of urea-formaldehyde resins is inadequate, and the temperature requirements for curing the hot-press resins are not readily met by the use of generally available plant equipment.

Although some phenolic-resin glues have been formulated with the idea of curing them at room temperatures, wood joints made at room temperature with these mixtures have not proved sufficiently strong and durable to recommend their use for laminating timbers under such conditions with the denser species of wood when maximum joint strength and durability are essential. If, however, the laminations are spread and pressed at room temperature and the assembly then heated in a curing chamber while still under pressure, maintaining a relative humidity necessary to prevent dimensional change in the wood during the heating period, the joints made with some of these glues are high in strength and durable under severe conditions.

Low-temperature, phenolic-type glues[2]

Glues of the low-temperature, phenolic type may be furnished in either a liquid or powder form with separate catalyst. The degree of acidity (or alkalinity) of low-temperature, phenolic-type glues, expressed on the

[2] Glue and gluing requirements presented in this section are based on Bureau of Ships Ad Interim Specifications 52G12(INT) and R39-0-7(INT).

basis of pH of the set glue film, varies with different glues from highly acid (pH 1.3) to mildly alkaline (pH 8.4). Acid-type glues that set to a film with pH less than 2.5 are not acceptable for ship timber use. At the present time glues having the characteristics necessary for the construction of laminated ship timbers are all of the liquid type. Some glues of this type are combinations of phenol and resorcinol resins.

Storage life-- The length of time that a glue may be kept in storage in the original container and still be usable (storage life or shelf life) and the storage conditions required are important in low-temperature, phenolic-type glues. Storage life, for example, varies with different glues from as short a period as 35 days to more than 3 months at 80°F. A storage life at 80°F. of at least 30 days is required. The glue should be maintained in cold storage at some temperature between 40° and 70°F., preferably at 55° ± 5°F., and it should be used within the shelf-life period guaranteed by the manufacturer at the storage temperature used.

Working life-- The liquid working life of low-temperature, phenolic glues after mixing must be at least 2-1/2 hours at 80°F. Manufacturer's instructions with regard to working life at different temperatures should be observed, and use of the glue permitted during this period only.

Moisture content requirements-- Low-temperature, phenolic glues produce the strongest glue joints if the moisture content of the wood at the time of gluing lies somewhere between 8 and 15 percent. The moisture content in any assembly, however, should be uniform as well as within this range.

# B. LAMINATING SHIP TIMBERS WITH LOW-TEMPERATURE PHENOLIC-TYPE RESIN GLUES

## 6.0 SELECTION AND PREPARATION OF LUMBER FOR LAMINATING

### 6.1. Limitation of defects

In preparing lumber for laminating it is essential to consider all defects that will impair the quality of the glue bond, interfere with the proper shaping of curved members, or reduce the serviceability of the finished product. Considerations that will affect the size and position of allowable defects include:

a. The strength requirements of the finished member.

b. The severity of curvature in bent members. Sharply bent assemblies require a better grade of stock than do flat or slightly bent members.

c. The dimension of the finished piece. A bent boat frame, for example, finished to 1-inch width permits fewer defects than a keel 8 inches wide.

d. The strength and durability requirements of the glue joints.

e. Position of scarf and edge joints. Edge and scarf joint lines should be free of defects.

f. Character of subsequent machining. Depth of stock removed in final shaping determines the removal of surface defects and the exposure of interior defects.

g. Durability expected of laminated timber against deterioration and decay of wood (sapwood, for example).

The presence of large holes, loose and unsound knots, dote, wane, and similar defects indicates decreased strength of the wood at such points. Shake, splits, and such seasoning defects as severe surface checking, honeycomb, and collapse indicate rupture and weakened wood. Areas of cross grain, end grain around knots, and sound or loose knots do not glue well due to the exposed end grain. These natural and seasoning defects must be avoided in laminating members when the maximum strength is required.

In most laminated members, however, the requirements are somewhat less than those in which only clear stock is suitable. The specifications covering the items to be produced will generally describe the quality of product required and the defects which may be permitted. In selecting lumber for laminating high-strength ship timbers, the more critical curved parts bent to the maximum curvature permitted require clear and straight-grain lumber free of defects except small holes not over 1/16 inch in diameter and sound tight knots not over 1/4 inch in diameter, while uncurved members will permit 1/4-inch holes and 3/4-inch sound knots. Intermediate curvatures should permit intermediate sizes of defects since such defects do not interfere with the bending of the laminations to the required curvature.

Sapwood, when used under conditions of high moisture content, is readily susceptible to attack by wood-destroying fungi. It is also attacked by insects. When placed in a laminated assembly, the decay of a single board of sapwood may cause failure of the entire member. When it is required that the wood be durable, the amount of sapwood in any lamination therefore should accordingly be limited.

## 6.2. Moisture content of lumber

The moisture content of lumber at the time of gluing is of importance in the fabrication of laminated products. Low-temperature, phenolic glues develop the strongest glue joints when the wood at the time of gluing has a moisture content within the range of 8 to 15 percent. Any change in moisture content after gluing and curing causes swelling or shrinking of the wood. Such dimensional change develops in the glue lines and wood stresses that favor delamination and reduce the load that the member can carry in service. The ideal moisture content for the lumber at the time of gluing is that which will produce strong glue joints and will be as near as practicable to the average moisture content of the laminated timber in service. A moisture content of 11 to 12 percent in the lumber is probably the most practical for most plants that are laminating timbers for ships and other outdoor use.

The uniformity of moisture content between the laminations of any one assembly and throughout the cross section of each board is also important. If adjacent laminations differ widely in moisture content at the time of gluing, subsequent moisture equalization changes will cause them to swell or shrink differently, with the consequent development of stresses in the glue line, of delamination, and of distortion of the finished member. An extreme range in moisture content, between laminations not greater than 3 percent is recommended. Stresses will also be created if the interior portion of any one board differs greatly in moisture content from the outer portion or shell. This difference should not exceed 2 percent.

## 6.3. Determination of moisture content

Moisture content of the lumber should be determined before machining operations are performed. Determinations should be made both for average moisture content and for uniformity between boards.

Moisture content determinations will normally have been made in connection with the kiln-drying operation. It is desirable to make moisture content determinations for each kiln charge of lumber. At least 10 such samples should be taken from each 5,000 board feet of lumber. Samples should be selected at random from various points in the kiln truck.

Immediately prior to laminating, a resistance-type moisture meter may be used for spot-checking the moisture content of surfaced stock. Constant use of this instrument is strongly recommended to avoid inclusion of wet or extremely dry lumber in a laminated member. Electrical moisture meters, however, do not read below 7 percent moisture content so that they are not usable in measuring the moisture content of extremely dry lumber.

## 6.4. Selection for grain in stock used for laminating

It has been shown in section 2.2 that flat or plain-sawed lumber will shrink more across the width of the board than will quarter-sawed lumber (11, pp. 193-198). For example, a flat-sawed board of white oak 12 inches wide having 6 percent moisture content will expand approximately 3/4 inch when soaked to saturation, while a quarter-sawed board treated similarly will expand about 1/2 inch. This possible difference in amount of expansion can produce a severe stress on the glue line in a laminated member with changes in moisture content and can be minimized by reasonable care in the selection of lumber for laminations. At some stage in the preparation of the stock, therefore, the lumber should be segregated into two groups. All quarter-sawed stock, including all boards in which the annual rings run at an angle of more than 45° from the wide face of the board, should be put in one group. Plain-sawed lumber, having annual rings parallel or within 45° to the wide face of the board, should be placed in the second group. Boards containing both quarter-sawed and plain-sawed grain should be classified according to their predominant grain. These groups should be kept segregated in all subsequent operations and the two classes of stock should not be mixed in any single laminated assembly. This sorting can be done at any time prior to final surfacing, if stock of full length and width is used, but should be done prior to edge gluing and scarfing if these operations are necessary. It will usually be convenient to sort as the stock leaves the rough planer.

## 6.5. Cutting and ripping of laminated stock

The use of a rough planer is essential as a first step in the machining of lumber for laminating. This operation will help to disclose natural and seasoning defects and, in the long run, will conserve time and material by eliminating unsuitable stock in the beginning. Rough planing is also desirable to reduce stock to reasonably uniform thickness. This is advantageous for accurate work in later ripping, edge-gluing, scarf-gluing, and surfacing operations. In order to keep in balance any seasoning stresses that may be in the lumber, the rough planing should remove an equal light cut from each face. A double surfacer will usually do the most effective work.

The sequence of operations in cross cutting and ripping to eliminate defects and reduce stock to desired lengths will be determined by the layout and facilities of the individual plant.

When stock is being ripped for edge gluing, it will be economical in time and material to select a number of standard widths to which stock may be ripped. For example, assume that stock is being prepared for a member 8 inches wide. The proportion of 8-inch stock would be small, especially if produced from hardwoods. The narrowest piece that is practical for edge gluing may be 1-1/2 inches. If the additional ripping width are 2, 2-1/2, 3, 4, 5, and 6 inches, there then will be numerous combinations of widths which, when edge glued, will produce the desired widths. These combinations are 6-2; 5-3; 4-4-; 1-1/2 - 5 - 1-1/2; 2-4-2; 2-1/2 - 3 - 2-1/2; 1-1/2 - 4 - 2-1/2. With such a variety of combinations possible, maximum utility of lumber can be accomplished. Furthermore this permits the cutting back of long strips to remove defects, and reducing them to other usable lengths 4 feet and longer, which, when edge glued and end scarfed, can become part of a laminated member.

Before proceeding with the manufacture of the material for laminating, careful planning is necessary. Some parts will be such that they will require all one-piece stock. Some parts will require lumber to be all of one standard length that can be obtained from the average run of the lumber for width and length. Some parts will require a clear section within a length. If all these factors are thoroughly studied before proceeding much material can be saved. Softwood lumber is usually available in longer and wider dimensions than are hardwoods in the grades used for laminating ship timbers, requiring less edge and scarf-joint gluing.

## 6.6. Preparation of edge and scarf joints

In preparing lumber for edge gluing, properly planed or sawed joints may be used. Successful gluing of sawed edges of lumber requires that the ripsaw be in first-class condition, the chain-ways true, and the saw round and jointed. A disadvantage to the use of edge jointers for this purpose is the difficulty of securing a perfectly straight edge for the full length of long strips. The use of a cutterhead, either in jointer or molder, moreover, involves a loss of material greater than the loss when joints are sawed. Either a planed or sawed edge should be square.

### Preparation of scarf joints

Lumber to be used in laminating is scarf-jointed primarily to obtain full length laminations and for the purpose of securing better utilization of raw material and for building into the assembly certain required qualities of grade. The full advantages from the use of scarf joints can be secured only if scarfs are prepared and glued in advance of final surfacing. This procedure makes it possible to plan in advance of the laminating operation the location of defects in relation to curves in bent members. Likewise it gives opportunity to match the grain and the location of edge joints in adjacent boards, minimizing the development of stresses in the final product. Assembly time for the final gluing operation can thereby also be materially shortened. Advance scarfing with subsequent final surfacing, moreover, helps to insure uniform thickness of stock for the full length of each lamination and prevents open joints which are certain to develop adjacent to butt joints in bent assemblies. When laminations are in one piece, the entire job of laying up the final assembly is greatly speeded.

There are several methods of making scarf joints. Common types are plain scarf, finger scarf, and serrated scarf. All of these require a relatively long slope to develop maximum tensile strength in the joint. A well-glued, plain-scarf joint in oak, for example, might require a slope of 1:15 to produce such strength, while in Douglas-fir and yellow pine a slope of 1:12 would be equally efficient. Steep slopes have the advantage that they result in less waste but they are also weaker and may contribute little or nothing to the final strength of the laminated member. There is also the risk that they will break when long laminations are handled in assembling and in bending to curved form. Scarf joints introduce an added stiffness to the board at the scarf area increasing somewhat the difficulty of drawing such areas of the lamination into bent members.

Plain scarfs can be produced by tilting-head saws, single-end tennoners, shapers, planers, or other methods depending on the ingenuity of the fabricator. There is no fast scarfing machine on the market today that develops high production.

Plain scarfs and serrated-scarf joints should be cut so that the sloped surfaces of both ends of the board are in parallel planes. This will permit successive boards to be fitted together as they come from the machine without being turned over, and will also permit cross cutting any board and bringing the scarfed ends together without turning over either piece.

## 6.7. Resawing and surfacing

Before scarfed lumber is resawed or surfaced, it is necessary to remove any surplus glue from the surfaces of the scarfs in order to provide the reasonably smooth face essential for accurate final machining. Unless this glue is removed, skips in dressing and other irregularities in surfacing will result.

The operation of resawing to thinner material, especially in stock over 6 inches in width, will induce some degree of cupping if there is any casehardening in the lumber. It is well to proceed with the final surfacing as soon after resawing as possible in order to equalize these stresses. This can be done by taking the heaviest cut from the outer surface with the resawed side down in the planer. Cup in the boards after final surfacing prior to assembly should not exceed 1/32 inch for each inch in width for boards under 1/2 inch in thickness and 1/64 inch for boards over 1/2 inch in thickness. If cupping exceeds this in the finished lamination, the stock should be bulk piled and allowed to equalize. Badly cupped stock is difficult to spread with glue and prevents the application of uniform pressure to the glue line. Poor bonding is likely to result.

The surfacing of the stock preparatory to assembly is one of the most important operations the fabricator of laminated timbers is called on to perform. The final product may be good or bad depending on the accuracy and care with which this part of the work is done.

All finish surfacing can best be done on a double cabinet surfacer with ballbearing cutterheads, and the final surfacing should be a comparatively light cut, not more than 1/16 inch maximum from each face. Knives should be kept well sharpened to prevent compressed fiber due to dull knives.

Matchers and molders cannot hold the accuracy of adjustment necessary for the proper surfacing of stock and should not be used. It is necessary to hold the variation in thickness between the two surfaces and throughout the entire length and width of each individual lamination to within 0.01 inch. The recommended rates of feed are from 30 to 60 feet per minute with from 20 to 30 knife cuts per inch. The rate of feed will be governed largely by the number of knives cutting. The surfacing job should be of such quality that revolution marks are hardly perceptible.

The use of single surfacers for this type of surfacing is not recommended because of the greater difficulty in maintaining uniform pressures against the bed, particularly with stock having a slight tendency to cup.

During the surfacing operation, stock should be frequently gaged with a slip-on thickness gage on both edges throughout the length of the piece. These gages are inexpensive and should be not less than 3/4 inch in width to prevent rocking. Narrow gages will not give the desired degree of accuracy. The fit on the stock should be an easy sliding fit and should be just tight enough so that no side or rocking motion is perceptible.

Clipping at the ends of the board usually indicates improper adjustment of pressure bars, knives ground below the normal cutting circle of the head, or improper setting of the feed rolls.

## 7.0. LAYOUT OF ASSEMBLY FOR LAMINATING

### 7.1. Location of scarf and edge joints

Well-glued, scarf joints in lumber do not develop maximum strength except with long slopes. The more abrupt the slope, the weaker the joint. Since existing ship timber specifications permit scarfs as steep as 1 in 4, the location of the scarfs must be controlled to produce laminated members adequate in strength and durability. In a laminated assembly, scarf joints should be staggered in adjacent laminations to the maximum practical distance. In general, it may be practical to consider that spacing between scarf joints in any group of three consecutive laminations, measured center to center horizontally, should be not less than 24 times the thickness of the stock. A safe rule-of-thumb for arrangement of scarf joints is to permit, in any group of three consecutive laminations, no joints closer than 12 inches center to center if laminae are 1/2 inch or less in thickness nor closer than 18 inches in stock 1/2 inch to 1 inch thick. Scarf joints in boat keels should slope downward toward the stern. Since such timbers will be variously machined in ship yards, all scarf joints, including those in the center of the member, should slope uniformly in one direction.

Edge joints, properly made, do not in themselves materially reduce the strength of stock used for laminating. Coincidence of edge joints in adjacent laminae, however, increases the possibility of vertical cleavage if any imperfect joints are present. When the laminations are laid up, therefore, such joints should be offset as much as possible, never by less than the thickness of the lamination. This practice will be made easier, when edge-glued boards are scarf jointed for length, if edge joints are arranged to form a continuous line the full length of the lamination. Alternation of edge-glued and solid boards in successive laminations is good procedure.

## 7.2. Thickness of laminations

In any curved laminated timber, the radius of curvature of the inner or concave face will be shorter than the radius of the outer lamination. In thick bent assemblies this difference may be considerable and may make necessary the use of thinner stock for the inner portion of the timber.

The minimum radius to which dry, straight-grained, clear lumber can be bent without breaking is approximately 40 to 60 times its thickness, varying with the species of wood. In general, hardwoods bend to somewhat shorter radii than do softwoods for the same thickness. In laminating high-strength bent timbers from boards, however, it is recommended that the laminations be bent to a radius not less than 1.6 times the breaking radius.

Table 1 shows the minimum bending radii recommended for different thicknesses of lamination when gluing high-strength laminated timbers.

Table 1

| Thickness of lamination | Recommended minimum radius of curvature |
|---|---|
| Inches | Inches |
| 1/4 | 18 |
| 5/16 | 24 |
| 3/8 | 30 |
| 17/16 | 36 |
| 1/2 | 43 |
| 5/8 | 58 |
| 3/4 | 73 |
| 13/16 | 79 |

In order to obtain maximum utility of stock or to fabricate a laminated timber to exact dimension, it may sometimes be desirable to use more than one thickness of stock even in flat assemblies. Arrangement of the different thicknesses will be governed largely by the end use to which the timber will be put and by the character of machining operations to be performed upon it. The thinner laminations ordinarily would be placed in the position entailing the least subsequent face machining.

In determining the allowable thickness of stock for curved timbers no distinction need be made between solid and scarf-jointed lumber, provided only that the scarf joints are strong enough to withstand the stress of bending.

7.3. Setting jigs or forms

Patterns to be used for curved laminated assemblies should be of a rigid type that will not bend or become deformed with use or with a change in moisture conditions.

Arrangement of adjustable "arms" on the bed in clamping jigs necessarily must be such that boards will follow the line of the pattern when clamped to the jig. Any irregularity in the alignment of the jig arms or any departure of the arms from the line of the pattern will be imparted to the laminated member. Jigs, therefore, must be designed to prevent movement or twisting of the arms while stock is being bent and pressure applied. In setting up jigs to be used for bending curved assemblies, it will usually be advisable to carry the line of the curve well beyond the net length of the finished timber. Failure to set at least one arm on the bed of the jig beyond this length is a frequent cause of distortion in the finished timber. This practice is particularly desirable in patterns having a short curve line near the end of the assembly.

In setting adjustable jigs for curved laminated assemblies that permit little tolerance in the shape of the finished product, it is necessary to add the thickness of the caul to the width of the pattern on the jig side. Otherwise, the radius of the finished timber will be in error by the thickness of the caul.

Spacing between jig arms may be varied with the degree of curvature. In flat assemblies, a spacing of 4 feet is not excessive if the cauls and stock are heavy enough to prevent sagging or bending of the package during the curing process. In curved timbers, the spacing of jig arms must be decreased as the bending radius is shortened. Required spacing may be as close as 9 inches on sharp bends of 30-inch radius or less. Proper spacing can best be judged by observing the fit of the pattern and the behavior of the laminations as they are clamped into position.

Bending curved assemblies may be done over either male or female forms. In heavy assemblies, the female type of jig will have considerable advantage in permitting the bending of laminations to the form one at a time. By pressing one end against a head block, the board can be bent and forced into the curve, and then temporarily held in position by nailing or fastening at the other end. When clamping is begun, (drawing the assembly into the desired form and applying retaining clamps to provide gluing pressure) the fastened or nailed end must be released to permit slippage of the laminations. When the male type of form is used, the entire assembly is usually bent as a single unit. Choice of bending forms, therefore, will be governed largely by the type of timber to be laminated.

7.4. Spring back tolerance

A constant problem in forming curved timbers by laminating is the prevention of "spring back" when the assembly is removed from the bending jig. When the assembly can be cured in place, in the jig itself, appreciable spring back does not develop. Under other conditions special precautions are necessary to prevent it.

A partial cure or precure in the jig, sufficient to set the glue so that it will withstand internal stresses, will permit removal from the clamped assembly without appreciable spring back.

In assemblies having abrupt curves near the end of the pattern, it may be necessary to add enough length to the stock so that pressure may be applied well beyond the pattern on a tangent to the curve. If the work is moved before curing it is advisable to use cradles or slings that will support the load at several points and to lay the assembly on its side so that the weight of the stock and clamps will not change the curvature.

## 8.0. LAMINATING PROCEDURE

The procedure described in this manual is for producing laminated timbers in which the glue joints will be strong and durable even when used for structural parts of ships and barges or for outdoor exposure. According to present knowledge, such durability will be furnished most satisfactorily by the use of phenolic-type glues. The laminating procedure described in the following pages relates particularly to the use of low-temperature-setting phenolic-type glues.

### 8.1. Preparing the glue

Low-temperature phenolic-resin glues are furnished in liquid form and are preferably kept in cool storage to provide a practical period of useful life. The glue manufacturer marks on each shipment the period of time that the glue can be satisfactorily held in storage and also the recommended storage temperature. The glue should not be permitted to become heated above the recommended storage temperature for an appreciable length of time; otherwise some curing action results and the glue may become thickened to such an extent that it cannot be properly mixed and spread on the lumber to be glued. Such periods of heating may occur in transit from the glue manufacturer to the purchaser, or even at the fabricator's plant, and each such exposure will decrease the period of time during which the glue is satisfactory for use. Slight thickening of the glue in storage may be reduced in some low-temperature phenolic-resin glues by the addition of a small amount of alcohol, and thus permit satisfactory use of the glue without decreasing the quality of the glue joints. However, the approval and specific directions of the manufacturer of the glue should be followed in adopting this procedure.

Low-temperature phenolic-resin glues may also be affected by freezing temperatures (32°F. and less). At such low temperatures some ingredients may settle out of the glue and be difficult to remix, especially in barrel lots. Transit and storage conditions that avoid 32°F. and less are recommended.

Manufacturers of low-temperature phenolic-resin glues furnish a catalyst (powder or liquid, and sometimes an added filler) that is to be mixed with the liquid glue just before using. The catalyst, the instructions for the amount to be added, and the manner of mixing may be different for each glue and are furnished by the glue manufacturer. No other extenders, fillers, or other materials should be added to the glue ingredients or mixture.

When mixing the glue, it is usually measured and weighed in steel or galvanized metal containers. The chemical reaction that brings about the setting or cure of the glue when the catalyst is mixed with it and when the heating treatments are applied may be seriously affected if chemicals from other glues, or from other sources, or if oils, greases, and the like are allowed to contaminate the equipment. It is essential that glue measuring, mixing, and spreading equipment be kept thoroughly clean to avoid damage to the glue.

## 8.2. Gluing edge joints

The glue used in edge gluing boards to produce full width laminations should develop as great glue joint strength and durability as the glue used in laminating the timber. The edges to be glued should be prepared as previously discussed (par. 6.6). The glue may be spread on the edges with a single roll spreader using a normal glue spread.

Various types of clamping equipment may be used for edge gluing of jointed stock. The conventional wheel or tractor type of clamp carrier is satisfactory for use provided the stock is held under pressure for initial cure of the glue long enough to permit handling the edge-glued stock upon removal from the carrier without damaging the glue joints. The carrier should be aligned to assure straight glued edges. This type of clamp can be enclosed and heated, and thus speed up the initial curing of the glue. When using 4/4-inch lumber, low-temperature phenolic-resin glue used for edge gluing can be cured sufficiently in 4 hours in this type of clamp carrier if a temperature of 150°to 160°F. is maintained in the stock. Clamping edge-glued stock can also be accomplished with piling clamps, which permit the assembly of such stock on trucks and moving into heated chambers for initial curing. Low-temperature phenolic-resin glues cure too slowly at room temperature to develop sufficient strength within a few hours to permit handling the stock. The use of heated chambers for this initial curing is recommended.

In assembling edge-glued joints it is important to provide sufficient gluing pressure along the entire glue line. Best distribution of pressure is obtained if the wider boards are placed on the outside, next to the clamps, and if the narrower strips are placed inside the pack, and if clamps can be spaced at as much as 18 inches when the outside boards are not less than 4 inches wide. Edge-glued stock should be allowed to stand for 24 hours after curing in clamps before surfacing for scarf jointing or laminating.

Sufficient initial cure of the glue in this process should be obtained to permit handling of the stock without damage to the glue line, and the full cure of the glue will be developed later when the laminated beam is cured.

Tightening of clamps should begin at the center of the package and proceed toward each end.

## 8.3. Gluing scarf joints

Where scarf jointing is necessary, it will normally follow the edge-gluing operation. Where permanent scarf joint strength will be required in the laminated member, the glue used for scarf jointing also should be as strong and durable as that used for laminating the timber, and should be applied to both faces of the scarf. The initial cure of the joint should develop enough strength to permit handling the laminations and bending them to the required curvature without damage to the scarf joint. Full cure of the joint will be developed when the laminated timber is cured.

The scarf joint is most satisfactorily glued under the combined application of heat and pressure. Several methods of heating may be possible. With the development of phenolic-resin (or equal quality) glues that can be cured rapidly at low temperatures, the use of hot plates applied under pressure to both outside faces of the scarf joint area of the lamination to produce sufficient initial cure may be possible.

The boards, at the time of gluing the scarf joints, must be in a plane and aligned to a straight guide. Assembling boards on edge for scarf jointing should produce laminations that are satisfactorily straight. Table supports with dowels in the top to hold the boards in vertical position have also given satisfactory results. Some gripping device to avoid end and side slippage at the scarf joint is desirable. The use of the serrated scarf makes the lining up of the scarfed areas easier and avoids side slippage. It also offers an advantage in the final surfacing of the lamination since it shows as a serrated line on the surface of the board and results in less chipping or tearing of the grain.

The practice of gluing scarf joints at the time of laminating, by placing the unglued scarfed boards into the assembly, does not insure accurate fit in the scarf or sufficient pressure at the glue line of the scarf to produce a strong glue joint. It also fails to bend the ends of the laminations to the curvature desired and increases the assembly time in laminating a long timber. It is important, therefore, that scarf-joint gluing be performed as a separate operation prior to laminating.

## 8.4. Gluing laminated assemblies

Much of the success in fabricating satisfactory laminated timbers depends on following proper procedure when gluing the assembly, particularly with reference to spreading the glue, placing the laminations into proper position, and applying adequate pressure uniformly and quickly to avoid initial setting of the glue before application of the pressure is completed.

In the normal laminating procedure, the lamination has been edge glued (if edge gluing is necessary), followed by scarf jointing (if necessary) and then has been finish surfaced just prior to gluing.

The glue to be used for laminating should be a low-temperature phenol, meeting the requirements of Bureau of Ships Specification No. 52-G-12 (Glue, phenol-formaldehyde, low-temperature setting) or equal. Not all low-temperature setting phenol-formaldehyde glues will produce suitable glue joints for laminated ship timbers, and a list of acceptable glues for the laminating should be furnished by the purchaser with the order.

When only a small amount of glue is needed, some low-temperature phenolic-resin glues may be mixed by hand. A mechanical glue mixer is, however, preferable. A suitable paddle speed for such a mixer is about 60 revolutions per minute. Higher paddle speeds have a tendency to develop foam in the glue.

A variable-speed mixer is advantageous, since slow stirring will avoid loss of powdered catalyst when first stirred into the liquid glue. When the powder is completely submerged in the glue, a shift to the higher speed of about 60 r.p.m. will more quickly produce a homogeneous mixture.

A total mixing time of 3 to 10 minutes is usually sufficient for low-temperature phenolic-resin glues, which are then ready for spreading.

The mixed glue should be applied to the laminations by spreading on each face of each lamination one-half of the glue required (except outer faces of outer laminations). This can be most satisfactorily done with a double-roll spreader in which the rolls are rubber covered and grooved and are fitted with "doctor" rolls to control the glue spread. Spreading glue on each face is desirable since it insures wetting of all the wood surface to be glued.

At the time of spreading glue, the lumber should preferably be at a temperature of 70° to 80°F., and should not be colder than 50°F. It should not be warmer than 100°F., to avoid too rapid initial curing of the glue before clamping can be finished. Usually 25 to 30 pounds of liquid mix low-temperature phenolic-resin glue per 1,000 square feet of joint area should be applied to each face of each lamination and some glue squeeze-out should take place during clamping. The glue spread can be determined by weighing a section of board of the same thickness as that being used for laminating before and after passing through the glue spreader. Dividing the weight of the glue added by the surface area covered will give the amount of glue spread per unit area.

The glue spread for each face can be determined by passing two sections of thin boards, whose combined thickness is equal to that of the laminations being used, through the glue spreader together and measuring the glue spread separately on each.

The mixed glue will have a longer working life if it is kept cool until spread on the wood. This is desirable if spreading is done in a room in which the temperature is above 80°F., and can be done by water jacketing or refrigeration, to a temperature of less than 70°F., but not less than 40°F. After spreading, the temperature of the glue will become the same as that of the lumber.

At room temperature the mixed glue may develop initial set in the spreader, both in operation and while standing idle, to the point where cleaning the glue from the spreader becomes difficult. Spreaders with glue on the rolls should not be left idle for more than 5 to 10 minutes at a time and in use should frequently be washed out and refilled with fresh glue. When used continuously, washing at 2-hour intervals may be satisfactory. In intermittent operation that includes idle periods more frequent washing is necessary.

If mixed glue is left in the spreader unused for several hours, it will cure to such an extent that it cannot be removed by washing with water. Low-temperature phenolic-resin glue can generally best be cleaned from a spreader by using cold or lukewarm water. The use of hot water or steam will develop cure of the glue before it can be washed off. Some low-temperature phenolic-resin glues are in an alcohol solution. Cleaning the glue spreader can then be more satisfactorily accomplished by adding alcohol to the water used for washing. In melamine glues, the addition of acetic acid to the washing water facilitates removing the glue.

The period of time between spreading glue on the first lamination and completing the clamping for gluing pressure is called "assembly" time. Assembly must be completed before the glue has developed an initial set, which is the result both of chemical reaction and of loss of moisture to the wood. The permissible assembly time will vary with each glue used, and will become less as the temperature at the glue line is increased. If the spread laminations are exposed to the atmosphere, water will evaporate from the glue surface and the allowable assembly time is reduced. Placing the spread laminations promptly together so that the glue surfaces are not exposed to the atmosphere (closed assembly) reduces the evaporation and permits a longer assembly time. Information on the permissible open and closed assembly times should be furnished by the glue manufacturer.

## 8.5. Gluing pressure and clamping procedure

In both bent and flat members, it is essential that adequate gluing pressure be provided over the entire area of the glue line. In gluing oak, comparatively high pressures are required. An average gluing pressure of 150 pounds per square inch of glue area is desirable and local pressures up to 300 pounds per square inch are not harmful to the glue joint. At no point should the pressure be less than 100 pounds per square inch. Softwoods can be satisfactorily glued with average pressures of 150 pounds per square inch and local pressures up to 200 pounds per square inch are not harmful.

The retaining clamps generally used on laminated work apply pressure by drawing up a nut on a threaded bolt. Torque wrenches can be used to measure the load applied to the nuts and the total pressure applied to the head can be calculated by formula provided that the threads are kept clean and lubricated (19, p. 73). Retaining-clamp bolts may be furnished with V threads or with square cut threads. The square cut threads will maintain a more uniform thread face in use than V threads and are preferred, especially when the pressure is determined by the use of torque wrenches. An equalizing-head retaining clamp serves to apply the pressure more uniformly over the width of the assembly than a clamp with solid cross bars.

It is usually not practical to place retaining clamps directly on the laminations so close together that they will distribute suitable gluing pressure directly to all parts of the glue line, and cauls are used between the laminated assembly and the retaining clamps to carry the pressure over the area between clamps. These cauls may be wood or metal and are placed on both sides of the work. Thick cauls, such as 2-inch wood planks are commonly used on flat laminated work and will permit spacing the clamps as much as 15 inches apart, while the use of 3/4 inch cauls will permit a clamp spacing of not more than 9 inches. In gluing bent laminated timbers, thick wood cauls cannot readily be used and sometimes the cauls cannot be any thicker than the laminations being glued. Then closer clamp spacing is desirable. A space not greater than 4 inches between clamps is recommended when the caul is 3/8 inch thick.

When laminations are glued in a bent assembly, it is necessary to apply pressure that will draw the laminations snugly into position. This process cannot be considered as applying full pressure on the glue line. It is advisable to use draw-up clamps to establish the bent form, and retaining clamps to furnish pressure on the glue lines. In drawing an assembly of laminations into bent form, the laminations must be permitted to slip over each other to permit wood-to-wood contact at all glue line areas. This can be accomplished by drawing the assembly snugly to the form at some central point in the curve, and drawing other positions of the assembly approximately, but not tightly, to form, and then on each side of the clamped central point progressively applying retaining clamps toward each end, drawing each draw-up clamp tightly to the form as the application of retaining clamps reaches that point. This procedure enables the bent laminations to slip endwise where necessary to produce a tight joint (fig. 21).

With some glues, clamping pressures fall off soon after assembly and it is recommended that the pressures be rechecked about 30 to 45 minutes after the first clamping.

## 9.0. CURING OF LAMINATED ASSEMBLIES

### 9.1. Time-temperature requirement for curing low-temperature phenolic glue

Low-temperature phenolic glues are sometimes described as "cold-setting", or more frequently, "low-temperature setting", indicating that such glues might cure at room temperature. While it is true that these glues will develop appreciable strength and cure at room temperatures, it has been found that at these temperatures the glue does not become completely cured. When the glued timbers are used in the construction of boats, where they are exposed to soaking in fresh and in salt water, or when they are exposed to the weather, the glue cured at room temperature is not sufficiently water resistant to prevent delamination. With one glue, for example, white oak glued beams cured under pressure for 20 hours in a room heated at 110°F. and later exposed to soaking and drying, developed complete delamination. Similar beams cured at 160°F. for over 20 hours, likewise delaminated, even though the glue joints soon after curing showed high shearing strengths. Curing this type of phenolic glue at higher temperatures develops some increase in strength and substantial increase in resistance to water and weather exposure. When cured at a temperature of about 190°F. to 200°F. for 10 hours, some of these glues are cured sufficiently so that well-glued timbers of white oak can be repeatedly soaked in salt water and dried without delamination. Glued Douglas-fir timbers, however, were cured sufficiently in 10 hours at 160°F. (measured at the center glue line) to resist delamination on exposure to repeated soaking and drying.

Further experiments in curing laminated white oak beams at 190°F. showed that highly acid-catalyzed low-temperature phenols with a film pH of 1.5 weakened the wood adjacent to the glue line, resulting, under soaking and drying exposure, in low shearing strength and eventual delamination with a thin layer of wood failure. This effect was also observed when gluing Douglas-fir with the same adhesive cured at 160°F. Such delamination is just as detrimental as in the glue line itself.

The minimum temperature and minimum time requirements for satisfactory curing will vary with glues and species of wood. These requirements should be included as a part of the information in the list of acceptable glues furnished by the purchaser with the order for the laminated timbers. At present, however, when gluing white oak, the minimum requirement appears to be 190°F. at the glue line maintained for 10 hours, and, when gluing Douglas-fir, 160°F. at the glue line maintained for 10 hours, for the low-temperature phenolic glue in approved use. This requires that the clamped assembly be heated until all portions of the glue line have reached such a minimum temperature, which is designated (T), then be held at or above that temperature for at least 10 hours. Extension of the curing period beyond the 10-hour minimum requirement will not be detrimental to the glue bond but such extension should not be carried to a point where it will seriously affect the strength of the wood. There are several methods of heating but the most satisfactory to date is to place the assembly under clamped pressure in a curing chamber that can be heated to and maintained at a temperature approximately 20°F. or more above the required glue line temperature (T). However, curing chamber temperatures above 215°F. are not recommended.

## 9.2. Transfer of heat in laminated assemblies

The rate at which heat will be transferred to the center of a laminated assembly varies somewhat with the species and moisture content of the wood, and a great deal with the dimensions of the assembly. The graphs in figures 9 to 20 show the rate at which such timbers of white oak and Douglas-fir in cauls and clamps heat in curing chambers maintained at the temperatures indicated. Heating periods required for other sizes can be calculated by the use of formulas (13).

The total period of curing can be divided into three parts:-

(a) Heating the assembly to bring all glue lines to the minimum temperature (T) required for curing the glue.

(b) Maintaining temperature (T) or higher for 10 hours at all glue lines.

(c) Cooling the laminated assembly. The length of time that the glue line areas are at or above temperature (T) during this period may be considered as a part of the 10-hour requirement given in (b).

While the outer area of an ordinary size of laminated ship timber assembly may be expected to heat rapidly along with the atmosphere of the curing chamber, a period of hours is required before the glue line at the center of the assembly will reach the temperature (T) required to cure the glue. When cooling, however, the outer area cools first and a period of hours again elapses during which the center remains at or above the temperature (T).

## 9.3. Relative humidity requirements for curing chamber

When wood is heated to 210°F. without humidity control for a number of hours, considerable drying of the wood takes place resulting in shrinkage on the outside of the assembly. This will result in opening the edges of the glue joints before the glue is cured, or in checking of the wood. Drying will be avoided if a high relative humidity is provided and maintained in the curing chamber. Under these conditions the glue joints will remain tight and the wood will not check. It is desirable to maintain a relative humidity that meets the equilibrium moisture content value of the wood in the laminated assembly. Figure 6 indicates, for example, that to maintain a moisture content of 10 to 12 percent a relative humidity of 80 to 85 percent is required. At a curing chamber temperature of 210°F., such a relative humidity requires a wet-bulb temperature of 199° to 202°F.

Humidity refers to the amount of moisture vapor in the atmosphere. Absolute humidity is expressed in terms of the weight of water vapor per unit volume of air. For example, at ordinary factory conditions the amount of moisture in the air may amount to 5 grains of water vapor per cubic foot. Relative humidity is the ratio between the amount of moisture present and the amount of moisture required to saturate the atmosphere at the same temperature. For example, if a factory operating at a temperature of 70°F. contains 5 grains of water vapor per cubic foot, its relative humidity is 61 percent since the atmosphere at 70°F. will contain 8 grains of water vapor when saturated (100 percent relative humidity). The moisture holding capacity of the atmosphere is greatly increased with increase in temperature (approximately doubled for each 20° rise in temperature). At 210°F. the capacity of the atmosphere rises to 255 grains per cubic foot, and a relative humidity of 80 percent requires about 210 grains per cubic foot. It is obvious that in order to provide sufficient humidity in a curing chamber to avoid drying of the glued assembly, it becomes necessary to add considerable water vapor to the atmosphere. This is most conveniently done by admitting live steam (jet or spray) into the chamber. A highly insulated and vapor tight chamber is recommended for this use.

## 9.4. Curing chamber operation

The curing chamber may use the principles of operation of the modern lumber dry kiln, in which heat is provided by steam-heated coils, humidity is provided by steam jets or sprays, and circulation of air is provided by mechanically operated fans. Temperature may be controlled by a thermostat operating on the heating coil, and relative humidity may be controlled by a wet-bulb thermostat operating on the steam spray line. It is possible to secure required control by hand-valve operation but the use of recording-controller instruments for both temperature and relative humidity is preferred.

Heated curing of the clamped laminated assembly glued with a low-temperature phenol should begin within 7 days after gluing, and during that time the assembly should be held in clamps at a temperature of not less than 40°F. When the assembly has been placed in the curing chamber and the heating process begins, it is desirable to heat the chamber at a rate that will require 2 to 3 hours to reach 210°F. This will ordinarily require the use of all heating coils available. The steam-spray supply should be throttled to avoid building up the humidity to the point where condensation will appear on the glued timber but the humidity may be raised as fast as this limitation will permit. Rapid circulation of air in the curing chamber is helpful in bringing about uniformity of curing conditions.

While recorder-controllers are useful in controlling the temperature and relative humidity in the curing chamber, they do not record the temperature inside the laminated timber. Thermocouples, however, may be placed at any desired points in the glue lines while laying the assembly, and the temperature in the timber at these points can be read at any time during the curing operation by means of a potentiometer (electrical thermometer). While curves shown in figures 9 to 20 indicate the temperature readings to be expected in the center of laminated assemblies during curing, they are subject to change whenever heating conditions in the chamber are varied, and often some correction must be made. The use of a potentiometer to check the interior temperatures during curing is recommended, particularly when laminating the first few timbers of any size or shape.

After the curing by heating of the timber has been completed, it is necessary to cool the timber to room temperature without appreciable drying, to avoid surface checking. Ordinarily, cooling is accomplished by shutting off the steam supply to the heating coils and to the steam spray. Water vapor will escape during the cooling period, however, usually so rapidly that the relative humidity becomes too low and drying and checking of the surface of the wood take place. It is important, therefore, to control the relative humidity during the entire cooling period. If this is attempted by admitting some steam spray into the chamber, heat also is admitted and cooling is retarded. A satisfactory method of rapid cooling is to inject a fine water spray or mist into the circulating air in the curing chamber during the cooling period. This introduction of water spray or mist, however, should not be permitted to wet the glued timber. Laminated timbers may be cooled satisfactorily from 210° to 100°F. as rapidly as at the rate of 1 hour per inch width of timber.

Cooling preferably should be carried to a temperature within 25°F. of room temperature before removing the timber from the chamber.

## 9.5. Thermal expansion

In the process of curing in the heated chamber, both the metal retaining clamps and the wood will increase in dimension due to thermal expansion. The coefficients of expansion for steel and wood are given as follows:

Thermal expansion of steel - 0.000006 per °F. (Marks' Mechanical Eng. Handbook).

Thermal expansion of oak across fiber - 0.000030 per °F. (Wood Handbook - p. 43) (11).

The thermal expansion for oak lumber is approximately five times that of steel. Thus, in heating the clamped assembly, the total thermal expansion of the wood (without change in moisture content) will be greater than that of the steel retaining clamps, and crushing of the cauls under the clamp heads results. The greater expansion of the wood will result in increased pressure on the glue line, but in the early stages of heating the clamps will heat faster than the wood assembly and there may be danger of reducing the pressure if the curing chamber is heated too rapidly. This is one reason why it is preferable to extend the heating period over 2 to 3 hours. Further, the initial setting of the glue may have taken place before the extra expansion of the wood develops an increased pressure, and by that time an increased pressure may no longer be beneficial to the glue line. Upon cooling, the wood contracts more than the clamps and the clamps will appear loose when curing and cooling have been completed. Loose clamps on cured and cooled assemblies is not an indication of inadequate pressure during the curing process.

## 10.0. SPACE REQUIREMENTS AND EQUIPMENT NECESSARY FOR LAMINATING STRAIGHT AND CURVED TIMBERS

### 10.1. Plant space requirements

The amount of floor space required for a plant to engage in the lamination of straight and curved timbers will depend on three major points: (a) Facilities for kiln drying, storing of kiln-dried lumber, and machining of material before laminating; (b) the anticipated daily production; (c) the size and the shape of the laminated material.

Assuming that plants intending to engage in this type of fabrication already have facilities for drying and storing lumber and have determined their expected daily output, the remaining factor that will determine the amount of floor space required will be the type of material to be manufactured.

If the material to be fabricated is to consist largely of lengths longer than those procurable from the standard lengths of lumber, provision must be made for the scarfing operation involving the long lengths to be manufactured. The required space must be long but it can be comparatively narrow.

Since the operations of scarfing, gluing of scarfs, and their curing precede final surfacing, it is not essential that these operations be done in the same space or department in which the final assembly is undertaken.

It is difficult to predetermine the total area required for laminating because the sizes of laminated timber to be produced and the production capacity must govern. As final assemblies are often heavy and awkward to handle, areas containing wide, clear spans and freedom from columns are desirable.

Space should be provided for inspection of lumber and the assembly to the final package size prior to the spreading of the glue. This will permit the spacing of scarfs and the assembling of the proper number of pieces for each package.

The ideal inspection and assembly of laminations before gluing may progress on roller conveyors that permit constant flow of material assembled in package form ready for spreading.

The space required for spreading is slightly more than twice the length of the longest member to be fabricated. Some saving in space can be made by mounting the spreader on casters so that flexibility in assembly is possible. By this method the spreader can be placed at the head end of the clamp bed or jig, saving some space in depth. If flat material is to be fabricated, and provision is made for curing in a separate chamber, it will be desirable to glue and clamp the assembly on movable trucks or dollies. The glued material clamped on the movable trucks or dollies is then moved to out-of-the-way convenient storage and accumulated until a sufficient quantity has been assembled to charge the curing chamber.

The space requirement when using fixed clamping beds or jigs is somewhat greater, but such plant layout has advantages if the material is to be cured on the bed. The beds may be in rows in order that heating facilities can be easily installed and the finished material may be easily removed by mechanical means from the clamping beds. The total space requirement for fixed-bed type of operation will depend upon the number of fixtures needed for the required curing cycles and the desired production capacity.

Separate curing chambers are desirable but on certain types of large curved members that are difficult to handle it will be necessary either to pre-cure or fully cure these members in the jigs in which they are formed, due to the danger of distortion when moved. The fabricator should anticipate this condition in laying out his plant facilities, and even though a separate curing chamber is provided, a certain number of adjustable fixtures should be so equipped that the packages may, if necessary, be cured in place in the jig.

As the weight of the finished laminated material with the clamps added may exceed a ton or more, consideration must be given to the handling problem.

Overhead hoists will be most effective, but floor cranes can also be used effectively, if of a design and size to span the curing beds. If trucks or dollies are used, a level floor is necessary. Otherwise distortion will develop in the package and it will take a permanent set. This danger is most pronounced in thin packages. Precaution should be taken at all times to see that the laminated packages in retaining clamps are evenly and well supported to prevent distortion.

## 10.20. PLANT EQUIPMENT

### 10.21. Dry kilns

The fabricator should have at his plant, or have access to, kilns of such design that lumber for laminating can be uniformly dried, stress free, to the high degree of accuracy and balance between shell and core necessary to meet the specifications and the requirements of good laminating procedure. Equipment for testing moisture content of lumber must be available.

Storage of kiln-dried lumber-- The fabricator should have facilities for the dry storage of kiln-dried lumber in enclosed and heated buildings.

## 10.22. Sawing equipment

The fabricator will require the following woodworking machinery to properly fabricate laminated material.

(a) Chain feed rip saws capable of ripping a true straight edge, suitable for the edge gluing of lumber.

(b) Cross cut saws for trimming boards and removing defects.

(c) Band resaw-- The need of a band resaw will be governed largely by the product to be made. If much curved material will be manufactured it may be considered essential, but the thickness requirements of flat stock do not make this machine a necessity. However, if stock is going to be made in multiple widths in order to take advantage of maximum economies in production, a resaw is essential for splitting the wide assembly into the final units.

## 10.23. Edge and scarf-joint gluing equipment

(a) Clamping equipment for edge gluing may consist of hand clamps, clamp carriers, piling clamps, or other types of screw device to apply and hold pressure satisfactorily on the edges of boards during the operations of edge gluing and precuring.

(b) Equipment for end scarfing of lumber may be a saw, shaper, tenoner, or any other device that will produce the fingered, plain, or serrated surfaces of the slope and uniformity required.

(c) Scarf gluing clamps may be presses, C-clamps or any suitable retaining device to apply and hold pressure during the gluing and curing of scarf joints.

## 10.24. Surfacing

(a) The rough planer is used for the initial surfacing of both sides of kiln-dried rough lumber.

(b) The cabinet surfacer is an essential piece of equipment. It should be a double cylinder, ball-bearing machine capable of being set to surface accurately within close limits. It should be not less than a six-roll machine.

## 10.25. Glue storage and spreading

(a) Storage facilities for glue-- Adequate storage facilities must be available to store glue at cool temperatures. Some means of refrigeration should be provided in order that temperatures of 40° to 60°F. may be maintained in the storage room.

(b) Glue spreaders-- The equipment for applying glue to the lamination faces should be a double rubber-roll resin-glue spreader, adequately adjustable, with doctor rolls to control thickness of spread. The rate of feed should be 50 to 100 feet per minute. Suitable weighing equipment is essential for checking glue spread. A single roll spreader is necessary for edge gluing.

## 10.26. Jigs, forms, and clamps

(a) Clamping, jigs, beds, and fixtures-- The type of jigs, beds, and fixtures necessary will depend largely on the type of laminating to be done. It is desirable that the jigs for bent work be readily adjustable to conform to various curvatures. The use of fixtures that are rigid and nonadjustable is apt to be costly unless large quantities of timbers of a given size and curvature are required. All jigs and fixtures should permit the finished package to be readily removed from the form, but must be sufficiently strong and rigid to withstand the pressures of bending curved work to the contour of the jig without deformation. Flat beds for clamping of straight timbers should be of such construction that the material can be prevented from slipping during the clamping operation.

Provision should be made for the mechanical handling of heavy members by overhead hoists, by floor cranes, or by other lifting equipment.

(b) Retaining clamps-- Retaining clamps should be sturdy and readily adjustable for differently sized packages. It is desirable that the clamps have some compensating device to adjust the pressure equally throughout the package cross section and to apply pressure equally across the faces. I-beam retaining clamps or other types of frame clamps can be used. The heads and bases should be sufficiently rigid to prevent distortion during clamping and should be capable of maintaining pressures up to 12,000 pounds total load per clamp.

## 10.27. Curing chambers

The curing of laminated timbers glued with available and approved low-temperature phenolic resins requires the accurate control of temperatures and humidities in the curing chamber. The closest approach in a woodworking plant to the kind of control required is by the dry kiln, which seldom, however, has been designed or constructed to maintain the high temperature and relative humidities required for this purpose. The principal defect in kilns is that they are not sufficiently vapor tight. Dry-kiln equipment, however, can be satisfactorily used if it is provided with:

(a) Heating coils ample to heat the chamber to 210°F. in a period of 3 or 4 hours. The heating system in a chamber not over 50 feet long and installed in a return-bend system will ordinarily, under thermostatic control, be able to provide a uniform temperature distribution. It is desirable to have the heating system subdivided into several sections so that only a portion of the heating coils need be used after the chamber has become heated. In long chambers, such as 100 feet or more, it is desirable to have a heating system for each end, separately controlled by thermostat, to maintain uniform temperatures.

(b) Highly vapor-tight and well insulated building construction. The vapor pressure within the curing chamber at 210°F. and 80 percent relative humidity is approximately 12 pounds per square inch, and structural openings, cracks, or permeable wall materials will permit considerable vapor leakage. It is desirable that the chamber structure have an inner face through which water vapor cannot pass readily. Painting the inside faces with a good grade of asphaltic kiln paint is very helpful. Outside faces should not be vapor tight. In addition to providing a vapor-tight construction, the chamber should also be well insulated against heat loss to avoid condensation on the interior faces of the chamber. The use of live-steam spray controlled by a wet-bulb thermostat is satisfactory and practical for supplying the required humidity.

The wall construction of a dry-kiln type of curing chamber may be of conventional hollow tile, brick, or similar materials. In smaller units, the use of a vapor-tight cement-asbestos board interior lining, over which insulating board is applied, and interior joints sealed with asphaltic plastic is satisfactory for use inside enclosed buildings. Provision for heating, humidifying, circulation of air, cooling and automatic instrument control in these small chambers are the same as for the dry-kiln equipment described.

(c) Forced air circulation system. The control of temperature and relative humidity uniformly to the curing requirement for the glue is much easier to maintain if there is mechanical equipment for producing definite circulation of the air in all parts of the curing chamber. The circulation of air in the curing chamber may be readily observed by releasing chemical smoke (titanium tetrachloride) into the chamber while cold with circulation system in operation. It may be possible to provide sufficient control of temperature and humidity during the heating and curing periods by natural circulation augmented by steam spray effect, but such circulation would largely disappear during the cooling process. The cooling process cannot be controlled to maintain a high relative humidity without the use of mechanically-produced circulation.

(d) Equipment to provide high humidity during cooling. While steam spray may be used to provide humidity during heating and curing, it is undesirable during cooling since it will admit heat also. The use of a water mist or fog injected into the circulating air by spray heads or by an air-operated spray gun is satisfactory.

Another successful type of curing chamber for interior use has been provided by enclosing the glued assembly, heating coils, and steam spray, with or without mechanical equipment for circulating the air, with a rubber-treated canvas that is highly vapor tight. The useful life of such canvas covering may be relatively short but may be practical in certain uses.

It is desirable to have the curing chambers located where escaping vapor will not interfere with moisture conditions in the plant.

10.28. Control instruments

There are certain instruments that may be considered essential to the fabricator of laminated material, as follows:

(a) Shear testing equipment for testing the strength of glued joints.

(b) Potentiometer (electric thermometer), essential for determining temperatures within the package during heating and cooling. This can only be done accurately by the use of thermocouples.

(c) Moisture meter. This should be of the resistance type and is desirable for rough checking lumber prior to laminating.

(d) Torque wrenches, for applying and testing the proper pressures on the gluing clamps.

(e) Compressometer or hydraulic jack with gage. This is desirable in order to check the pressures developed with various types of clamps in order to set torque wrenches properly.

(f) Scales. An accurate triple-beam balance, or its equal in accuracy, to be capable of weighing to 1/10 gram for determination of glue spread.

(g) Micrometers. For checking accuracy of surfacing stock before laminating. These should be screw type and not the dial indicator.

(h) Slip-on gage. For convenient and rapid checking of thickness of dressed lumber.

## 11.0. MACHINING OF LAMINATED ASSEMBLIES

The amount of machine work that it is necessary to perform on laminated assemblies will be largely governed by customer requirements.

After the retaining clamps have been removed, the first operation is the removal of the surplus glue caused by "squeeze-out". This operation can be satisfactorily performed with a hoe-shaped steel hand scraper. As the glue is brittle, it is removed with comparative ease. If the laminated member is to be surfaced on four sides, and a four-side matcher is available, the lumber can then be run through this machine, the ends trimmed, and the piece is then ready for shipping. If a four-side matcher is not available and the member shows any distortion, one edge should be squared with a power hand surfacer. After this has been done, the piece can then be put through a double surfacer for preparation for shipment. On some curved sections, it will be impossible to surface by mechanical means. Timbers of this kind will have to be machined by hand, and for this purpose power-driven hand tools are necessary.

In the interest of economy in manufacture, it will be advantageous in the fabricating of many laminated assemblies to make the assembly in multiple widths. A factor of importance in such fabrication will be the difference in time required to cure the larger package as compared to the smaller units. When assemblies are made in multiple widths, the edges should be surfaced before resawing.

In breaking down heavy timbers on the resaw, it is desirable to break them down to the lightest possible units by weight as soon as possible. For this purpose it is best to reduce by halving through each successive pass through the resaw.

The end trimming of timbers can most generally be done by a small electric-powered circular saw. On extremely bulky members of large size, hand trimming may be necessary.

Machining operations, other than four-side surfacing and end trimming, will depend upon customer's requirements.

## 12.0. TREATMENT, PACKING, AND SHIPPING OF LAMINATED MEMBERS

### 12.1. End coating

The customer for heavy laminated timbers will undoubtedly specify some particular type of end coating to be applied to the member after trimming and before shipping. This is desirable in order to avoid end checking of the finished piece. Resin varnish sealers, phenolic resin, lead and oil paints, and other coatings give satisfactory results.

### 12.2. Surface coating

The customer may require surface coating or treatment of laminated material to protect it against weathering, stain, or fungus attack. These treatments should, of course, be applied after all machining operations necessary on the assembly have been completed. Small members can be dipped in the specified coating before shipment but larger members will require brush coating, or spraying. Even though the customer does not specify protective coatings, it is well to give serious consideration to the use of some surface protection that will not interfere with the subsequent use or finishing of the laminated timber.

### 12.3. Bundling and wrapping

Since a finished laminated assembly may be considered a semi-fabricated product, reasonable protection should be given, particularly to the ends of the pieces, in shipping. Specific details for bundling and wrapping are usually included in purchaser's specifications.

### 12.4. Crating and bracing

The customer may require that certain types of laminated products be crated for shipping. The crating of curved sections presents some difficulty. Thin resawn material can be steel strapped to the inner and outer faces of a curved member, thus providing reasonable protection, especially if square cleated around the package at suitable intervals. Problems of this kind are usually arranged between the fabricator and the purchaser, depending upon the degree of protection that must be afforded the final products.

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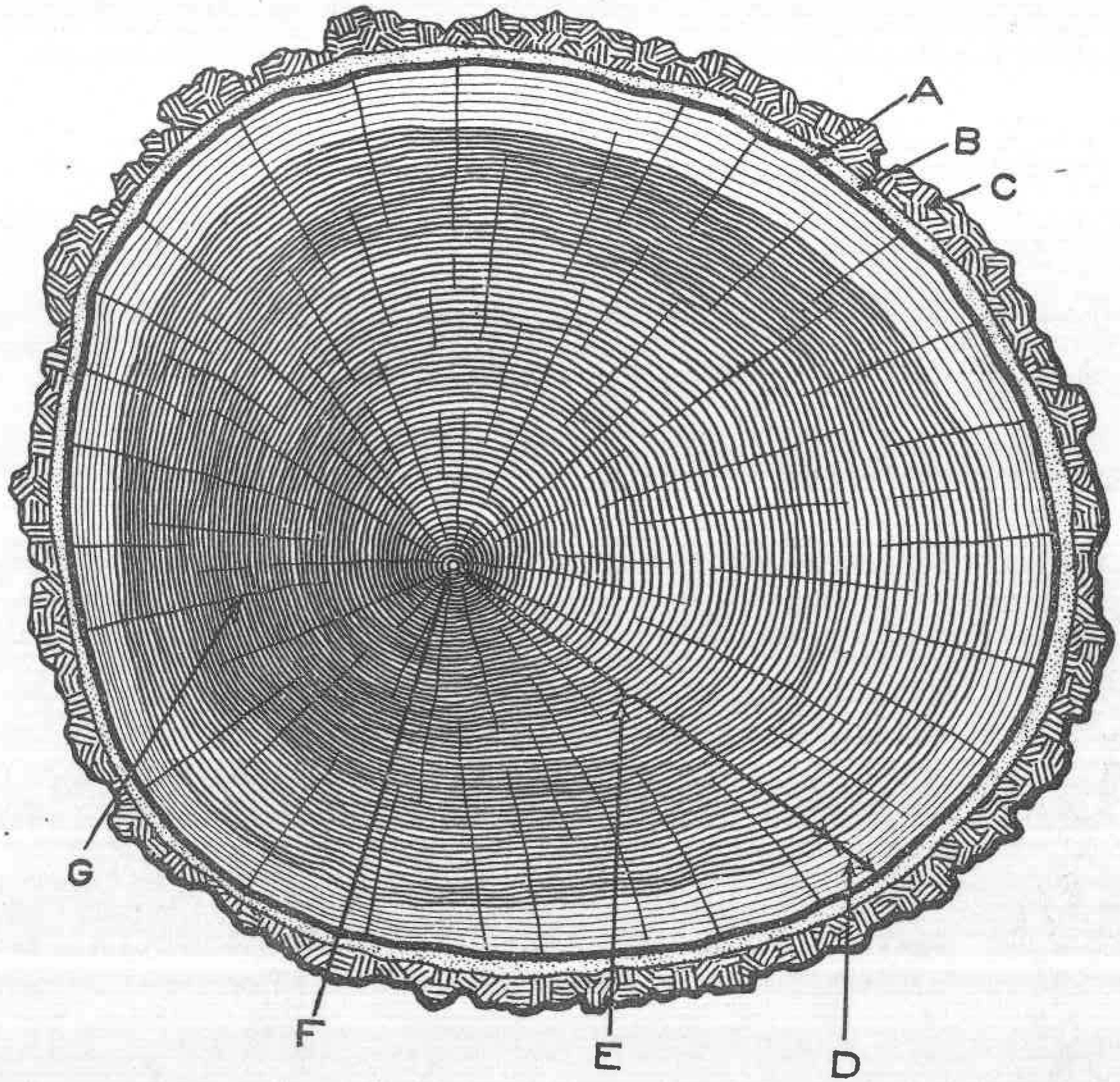


Figure 1.--The tree trunk: *A*, Cambium layer (microscopic) is inside of inner bark and forms wood and bark cells. *B*, Inner bark is moist and soft. Carries prepared food from leaves to all growing parts of tree. *C*, Outer bark or corky layer is composed of dry dead tissue. Gives general protection against external injuries. *D*, Sapwood is the light-colored wood beneath the bark. Carries sap from roots to leaves. *E*, Heartwood (inactive) is formed by a gradual change in the sapwood. *F*, Pith is the soft tissue about which the first wood growth takes place in the newly formed twigs. *G*, Wood rays connect the various layers from pith to bark for storage and transference of food.

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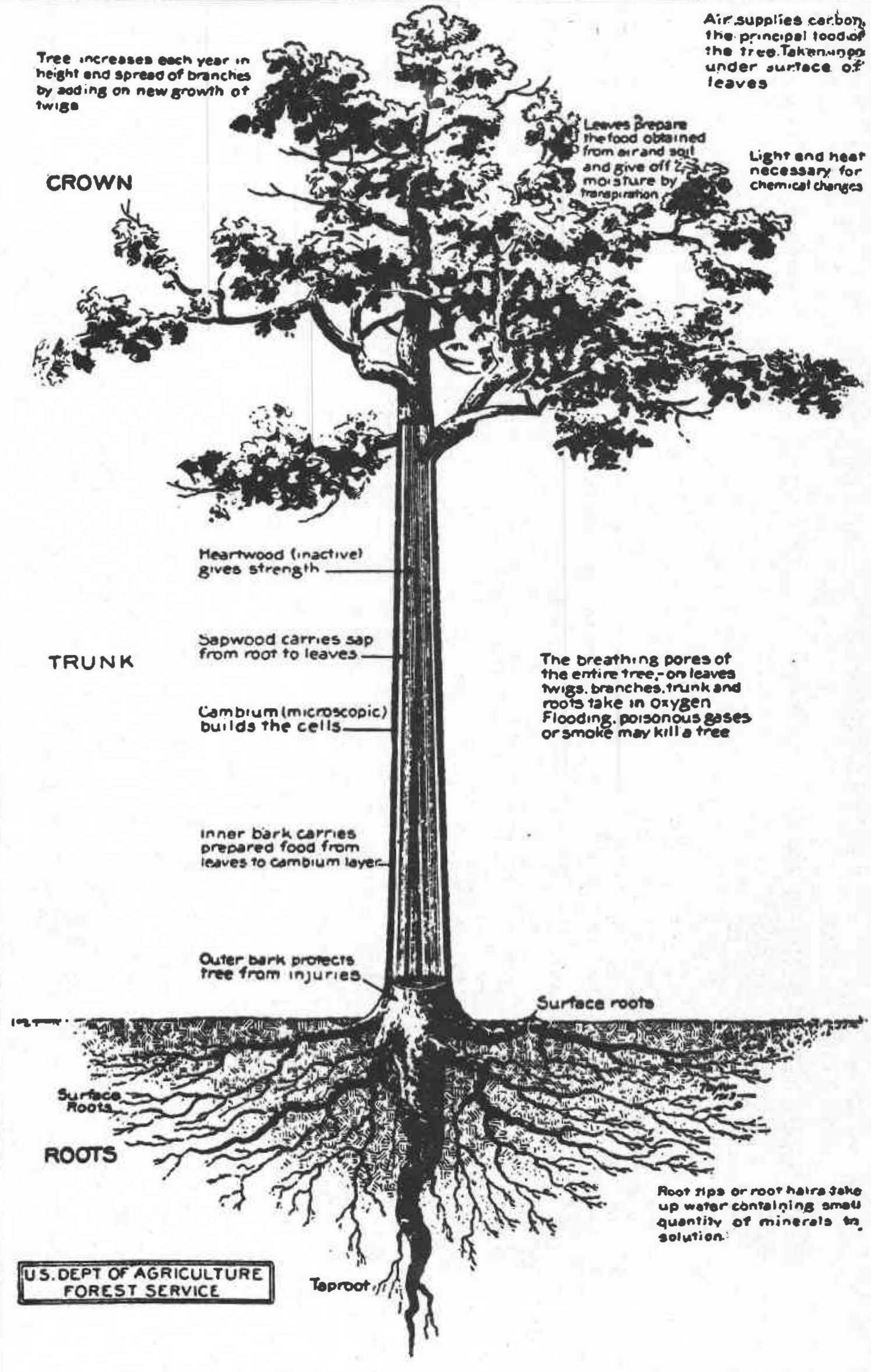


**Figure 2.-- HOW THE TREE GROWS**

The buds, root tips and cambium layer are the growing parts of the tree. Water containing a small quantity of minerals in solution is absorbed by the roots carried up through the sapwood to the leaves and there combined with carbon from the air to make food. This food is carried by the inner bark to all growing parts of the tree, even down to the root-tips.

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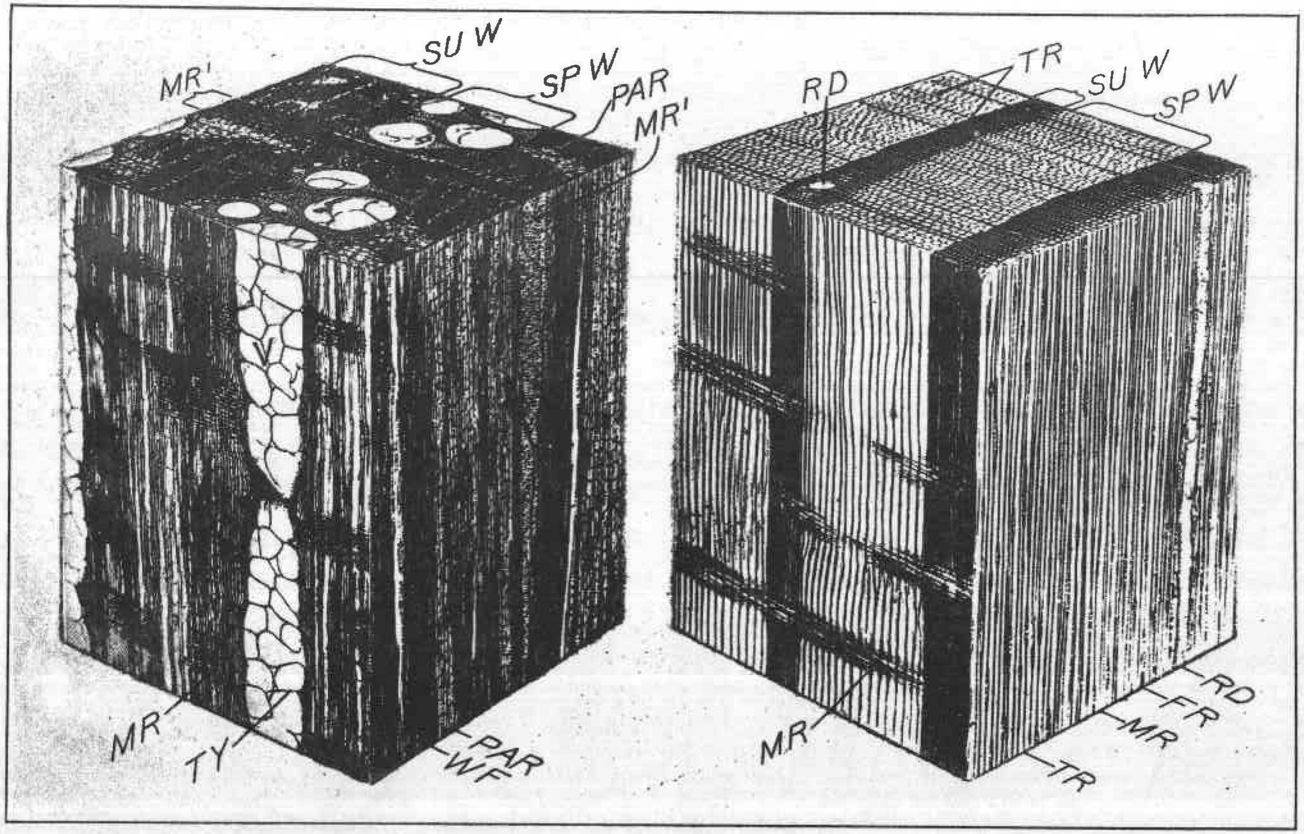


WHITE OAK. SHORTLEAF PINE.

Fig. 3 PHOTOGRAPHS OF CUBES OF WOOD MAGNIFIED ABOUT 25 DIAMETERS.

In each cube the top view represents the transverse or end surface, the left view the radial or "quartered" surface, and the right view the tangential or "bastard" surface. *SPW*, springwood; *SUW*, summerwood. To the left a hardwood showing: *V*, vessels or pores; *TY*, tyloses in a vessel; *PAR*, parenchyma cells; the dark areas, *WF*, wood fibers; *MR*, small medullary ray; *MR'*, large medullary ray. To the right a coniferous wood, showing: *TR*, tracheids, which comprise the bulk of the wood; *RD*, resin ducts; *MR*, ordinary medullary rays; *FR*, fusiform ray containing a horizontal resin duct. The medullary rays are continuous from the starting point to the bark, and the vessels are continuous longitudinally, although the illustrations show them interrupted.

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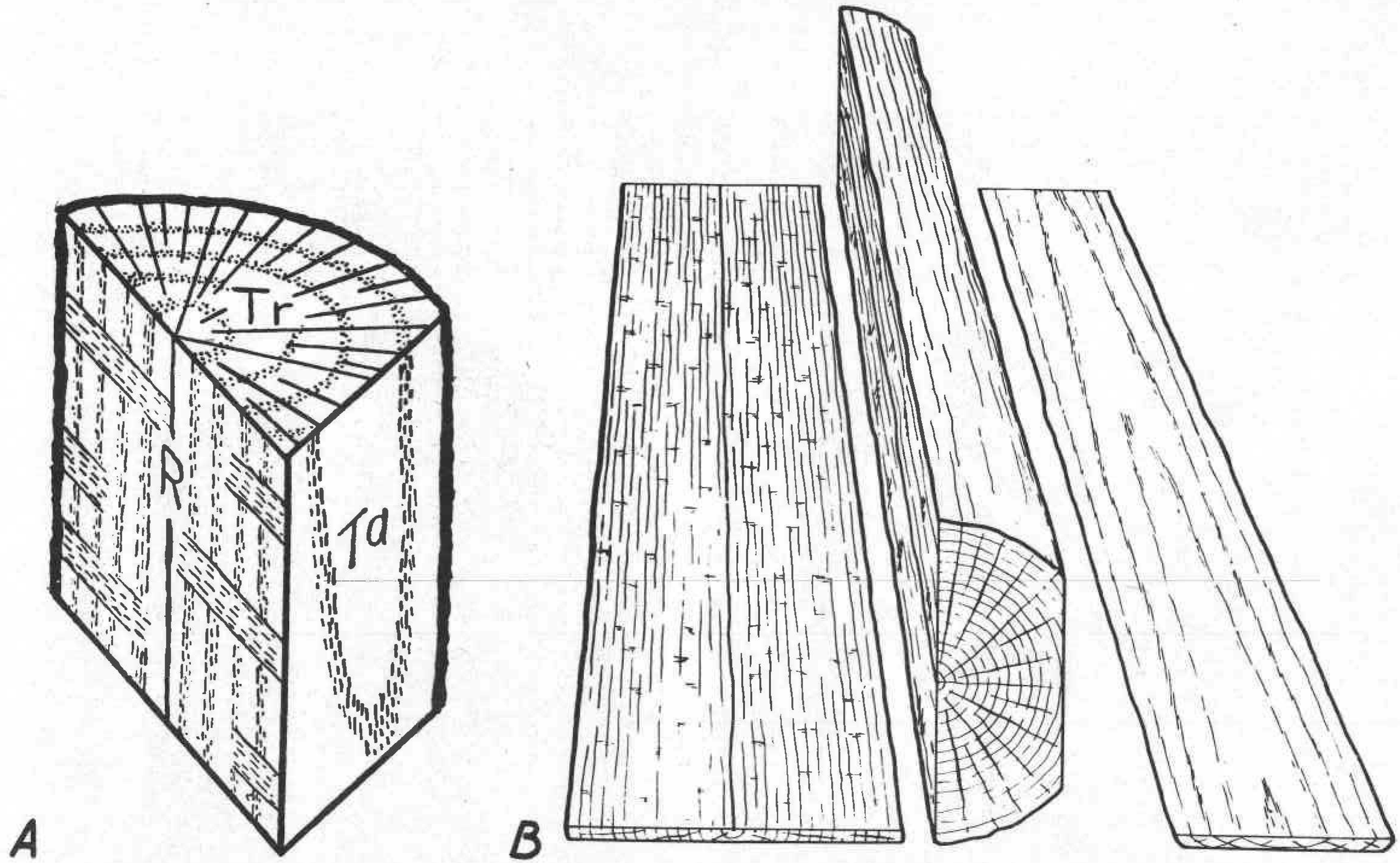


Figure 4.--A. A block of wood showing, Tr, transverse surface; R, radial surface; Ta, tangential surface. B. Quarter-sawed (left) and plain-sawed (right) boards cut from log.

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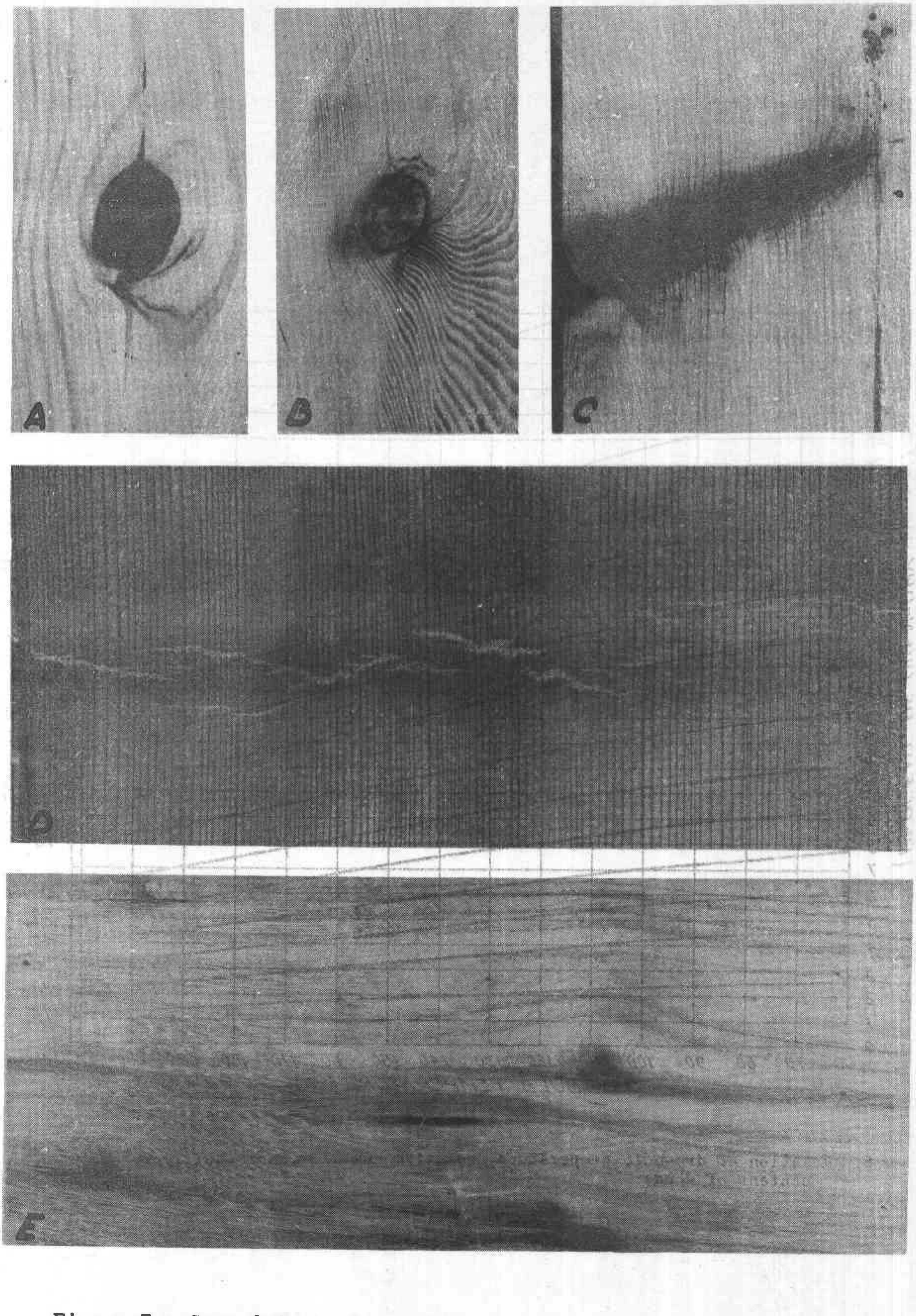


Figure 5.--Some defects in wood. A. Round intergrown knot. B. Oval encased knot. C. Spike knot, intergrown for most of its length. D. Pronounced compression failures. E. Bird pecks.

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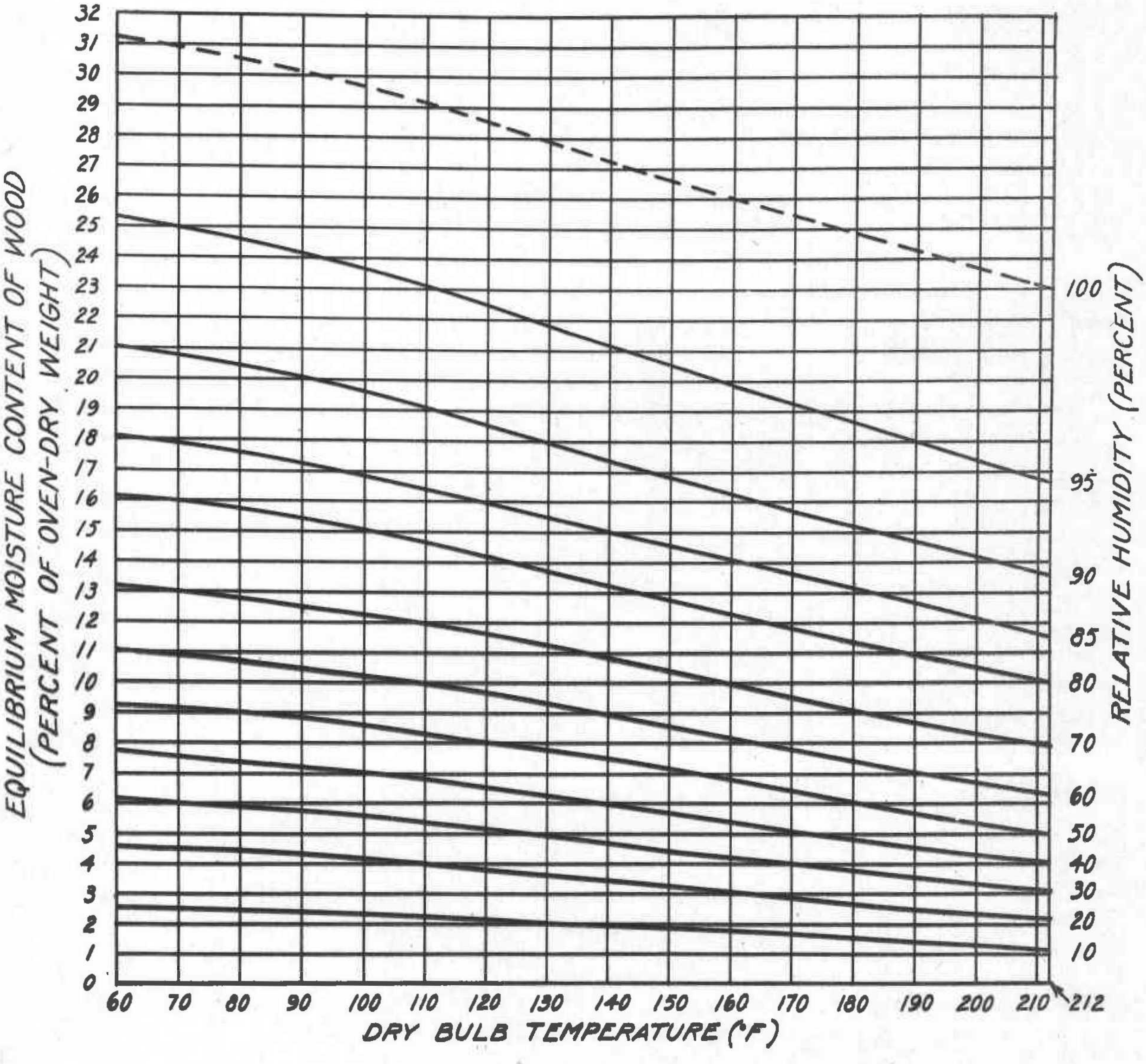


**Figure 6.--Relation of dry-bulb temperature, relative humidity, and equilibrium moisture content of wood.**

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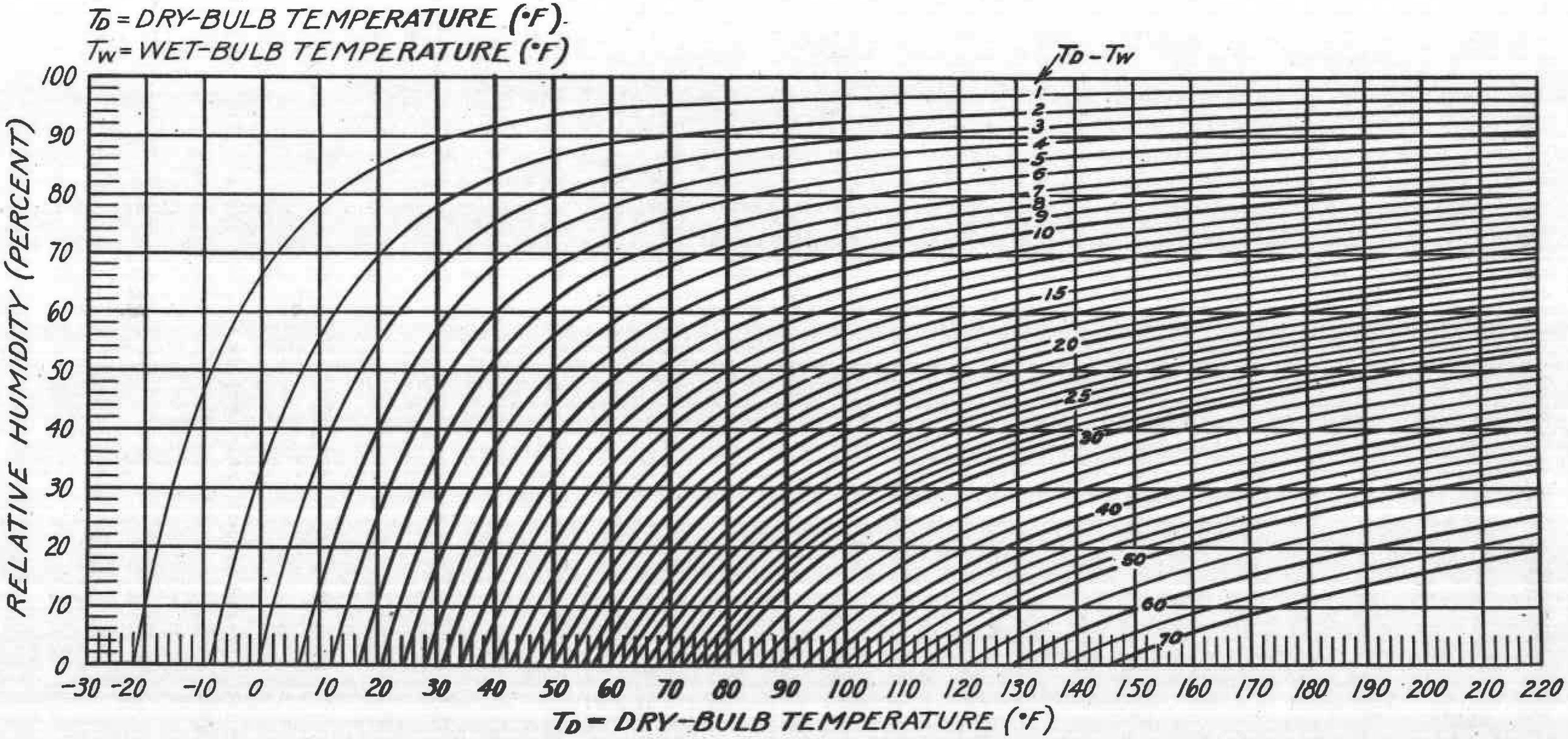


**Figure 7.--Relation of dry-bulb temperature, wet-bulb temperature, and relative humidity.**

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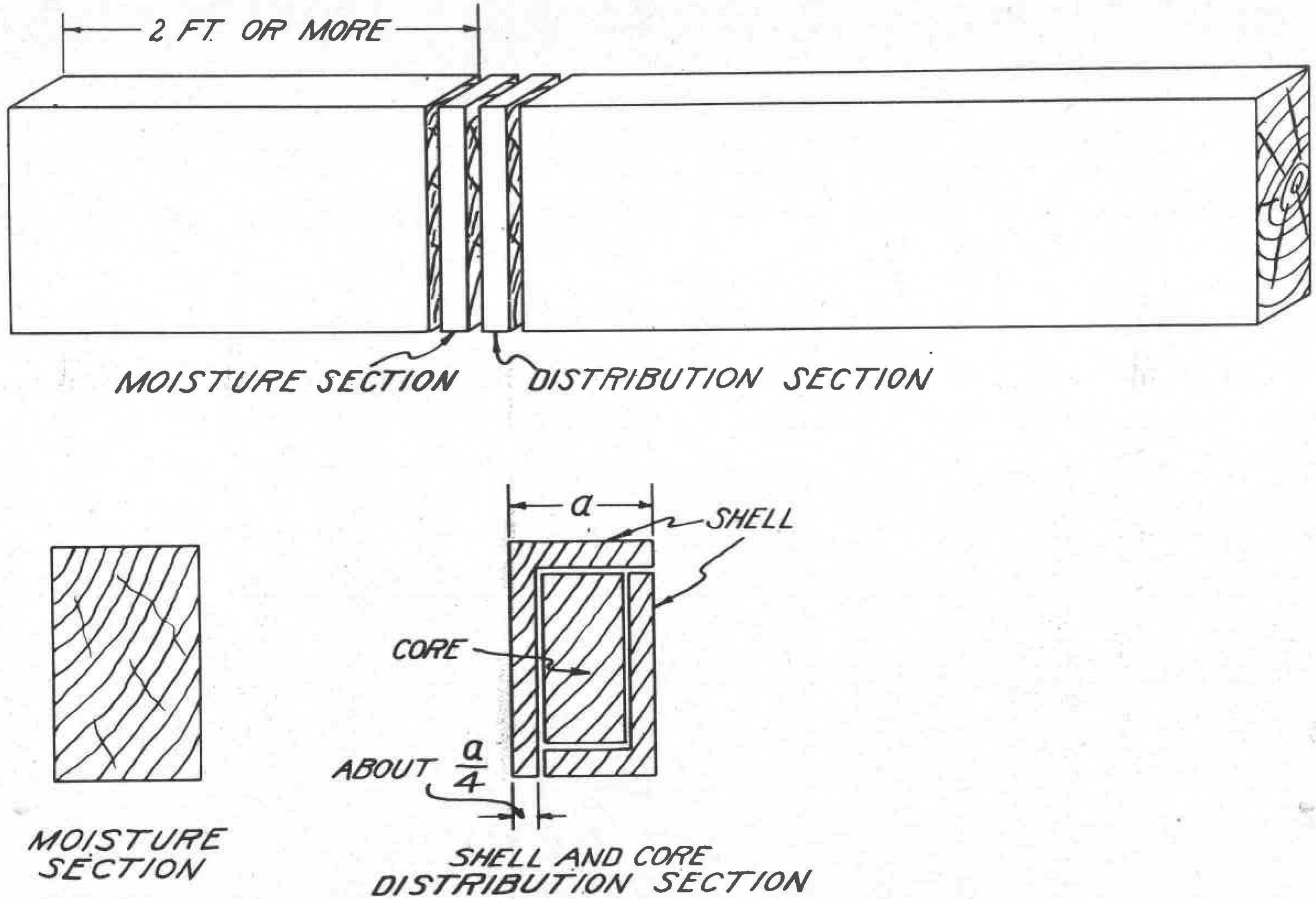


Figure 8.--Method of cutting sections from a piece of wood for moisture-content and moisture-distribution determinations.

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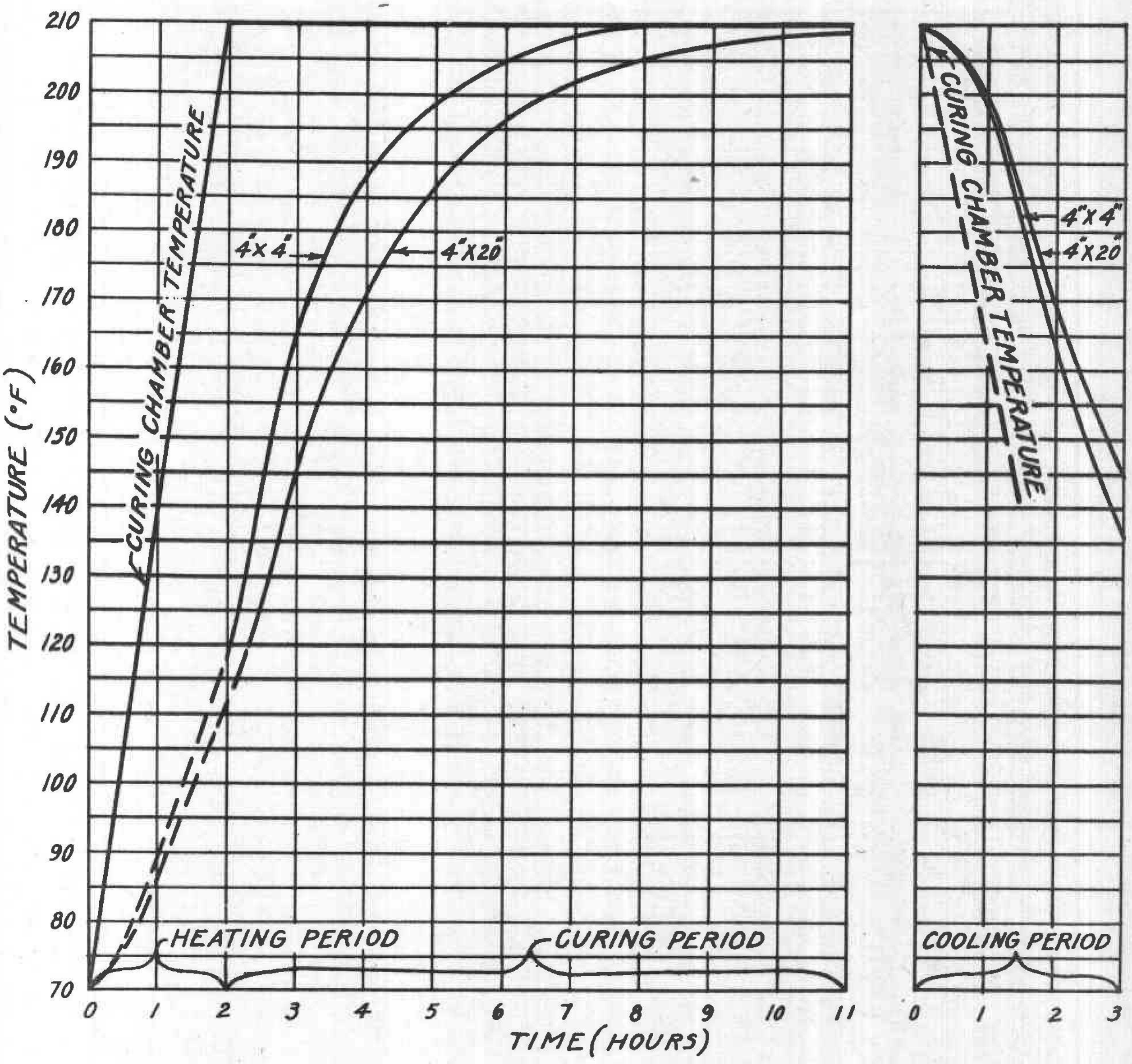


Figure 9.--Glue line temperature at center of laminated white oak beams having laminations 4 inches wide, curing chamber held at 210° F. and 80 percent relative humidity.

Z M 51748 F

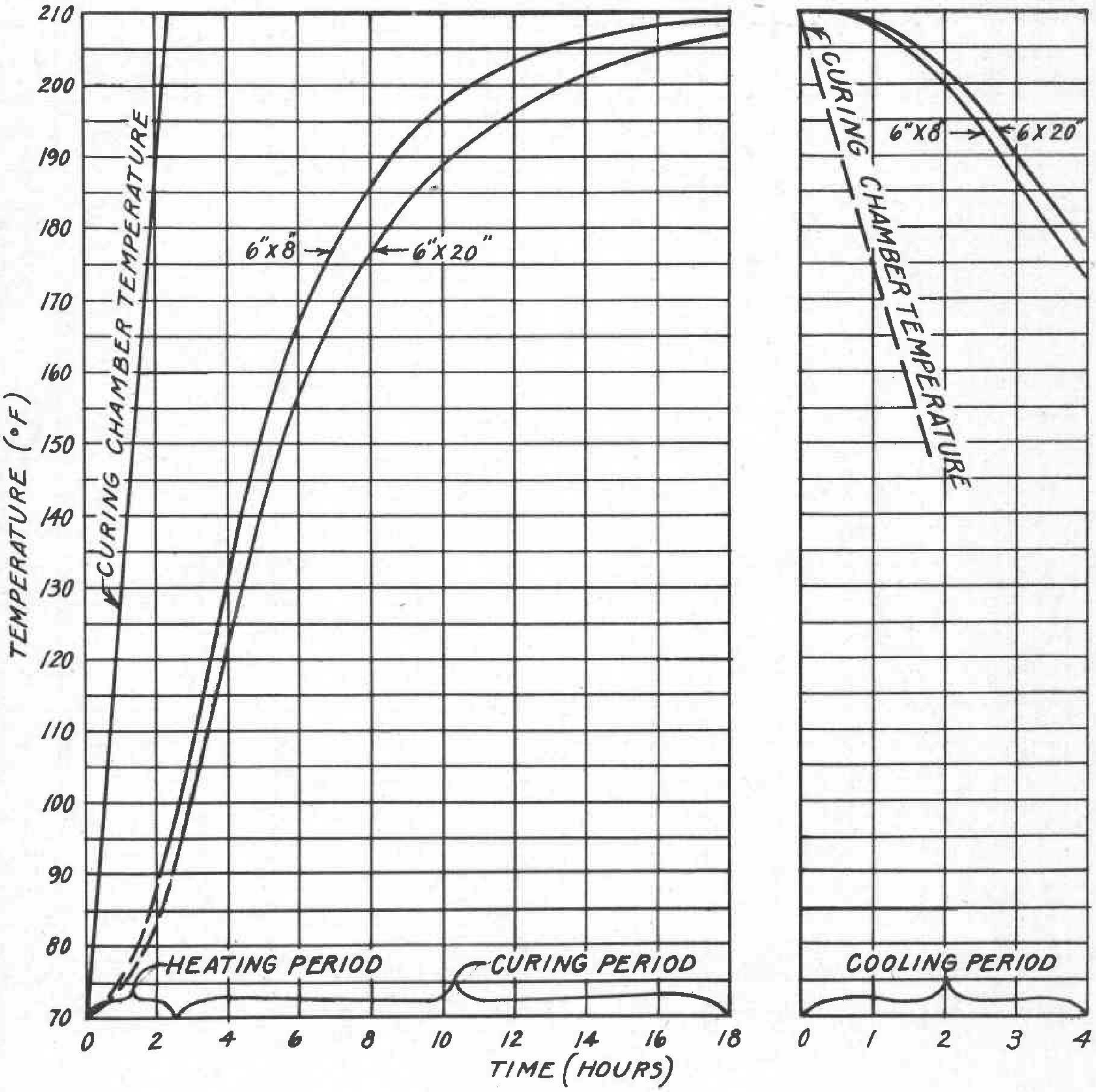


Figure 10.--Glue line temperature at center of laminated white oak beams having laminations 6 inches wide, curing chamber held at 210° F. and 80 percent relative humidity.

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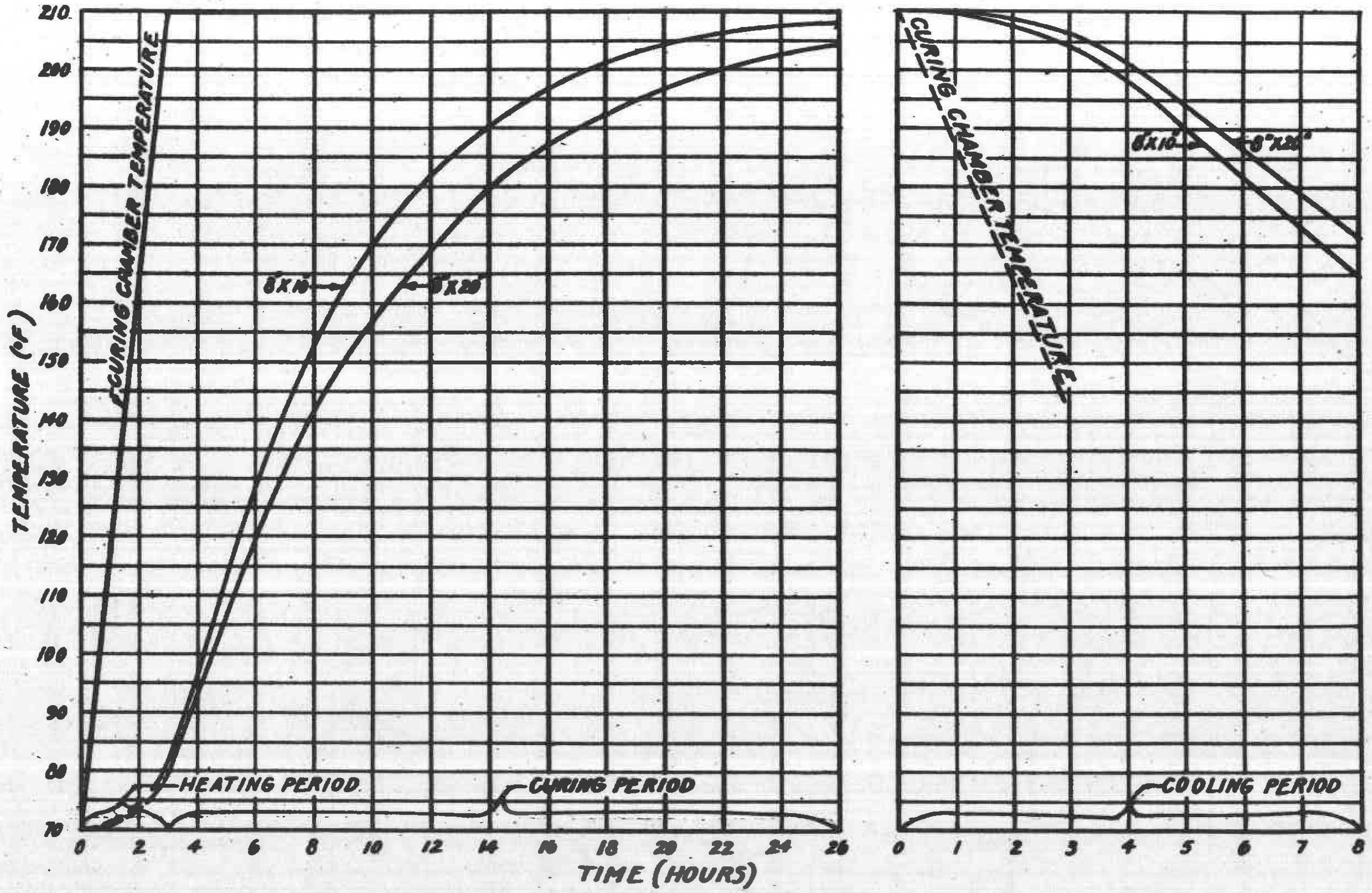


Figure 11.--Glue line temperature at center of laminated white oak beams having laminations 8 inches wide, curing chamber held at 210° F. and 80 percent relative humidity.

Z M 51750 F

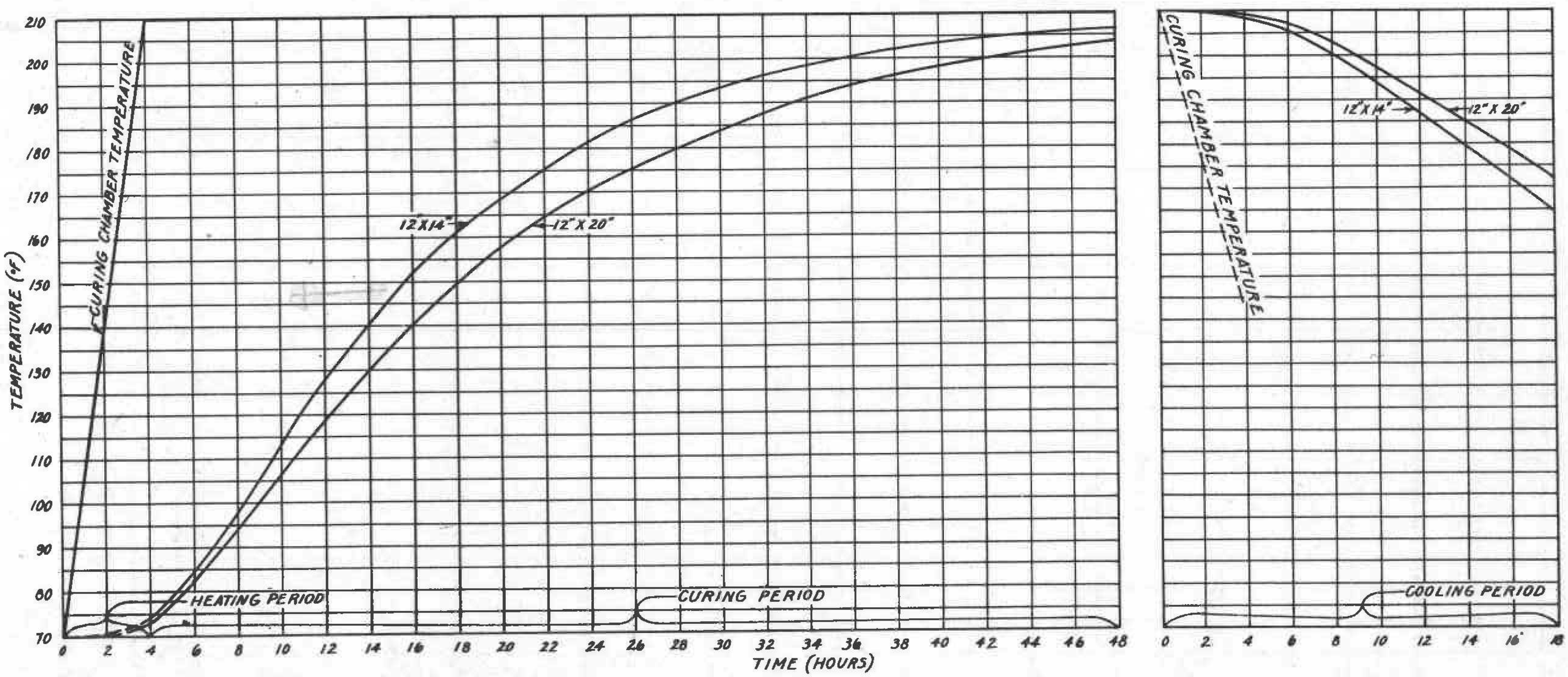


Figure 12.--Glue line temperature at center of laminated white oak beams having laminations 12 inches wide; curing chamber held at 210° F. and 80 percent relative humidity.

Z M 51751 F

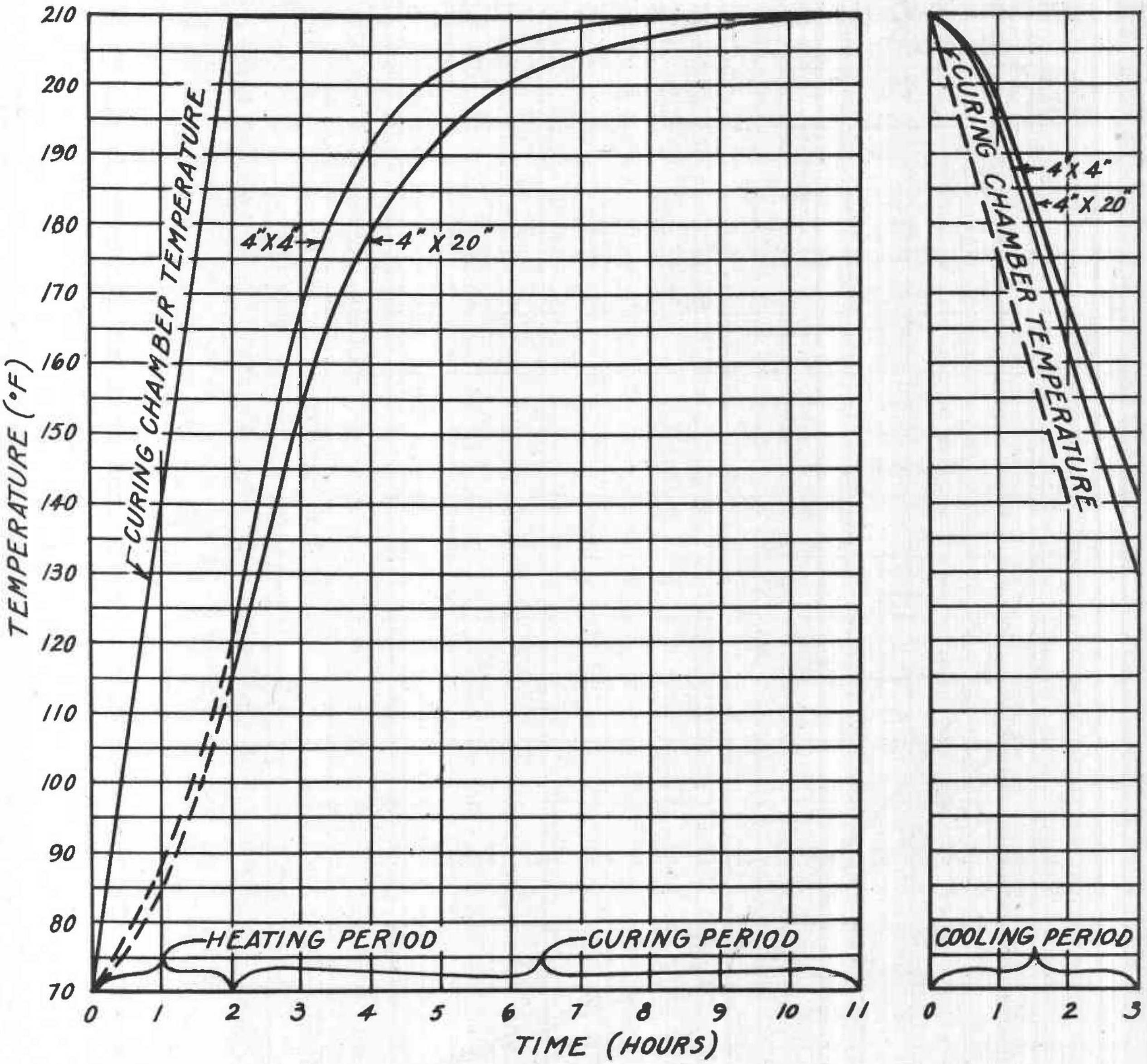


Figure 13.--Glue line temperature at center of laminated Douglas-fir beams having laminations 4 inches wide, curing chamber held at 210° F. and 80 percent relative humidity.

Z M 51752 F

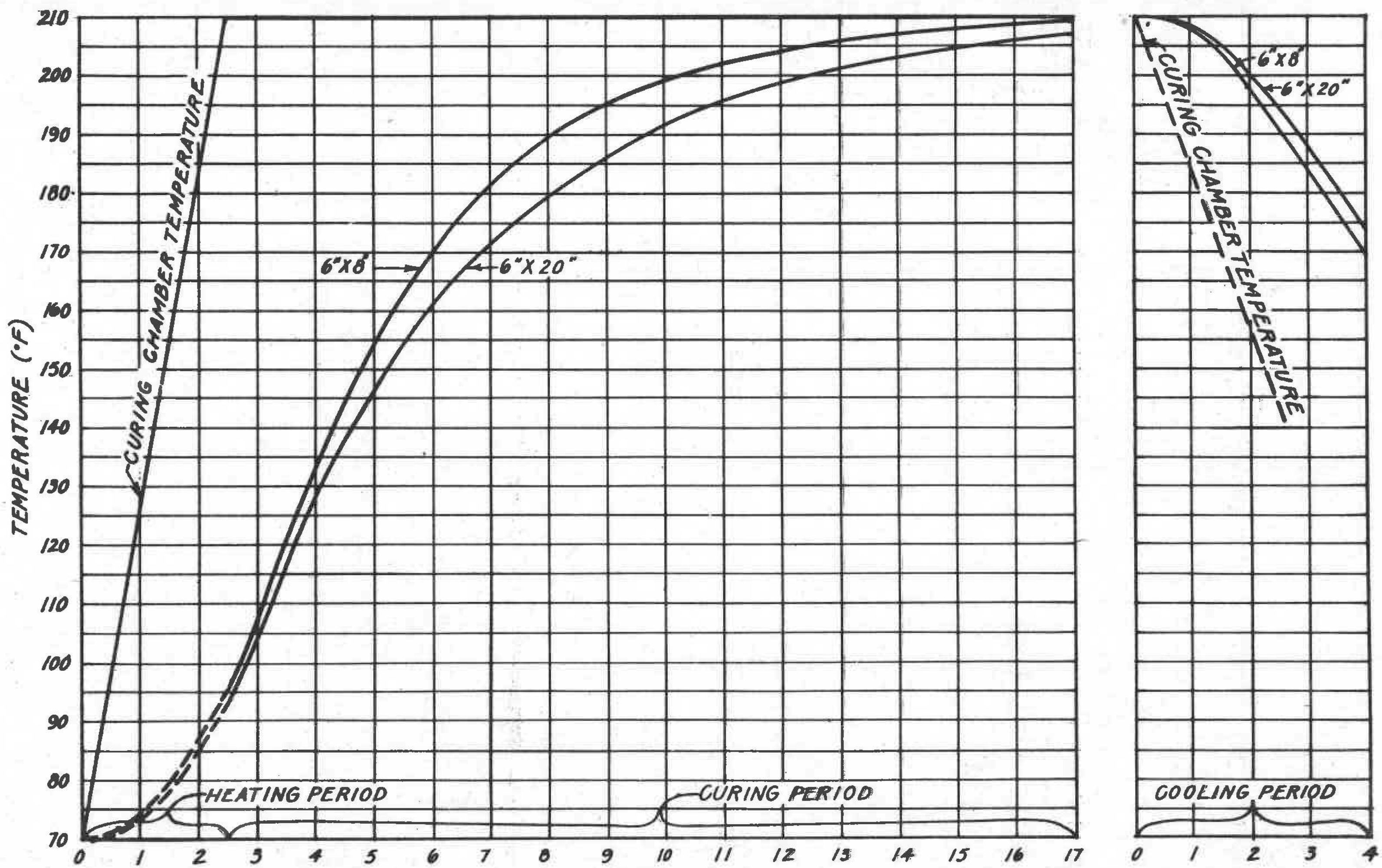


Figure 14.--Glue line temperature at center of laminated Douglas-fir beams having laminations 6 inches wide, curing chamber held at 210° F. and 80 percent relative humidity.

Z M 51753 F

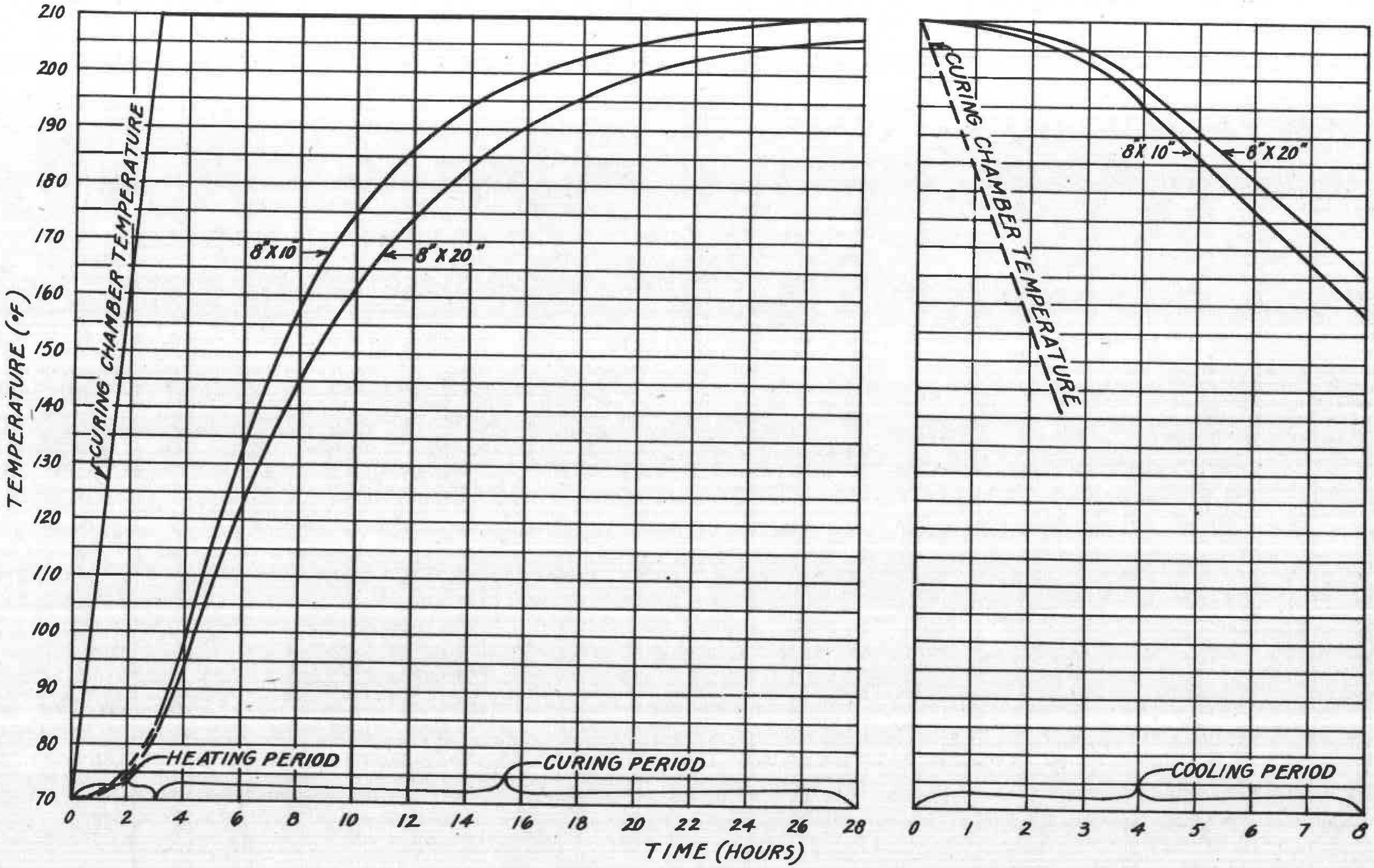


Figure 15.--Glue line temperature at center of laminated Douglas-fir beams having laminations 8 inches wide, curing chamber held at 210° F. and 80 percent relative humidity.

Z M 51754 F

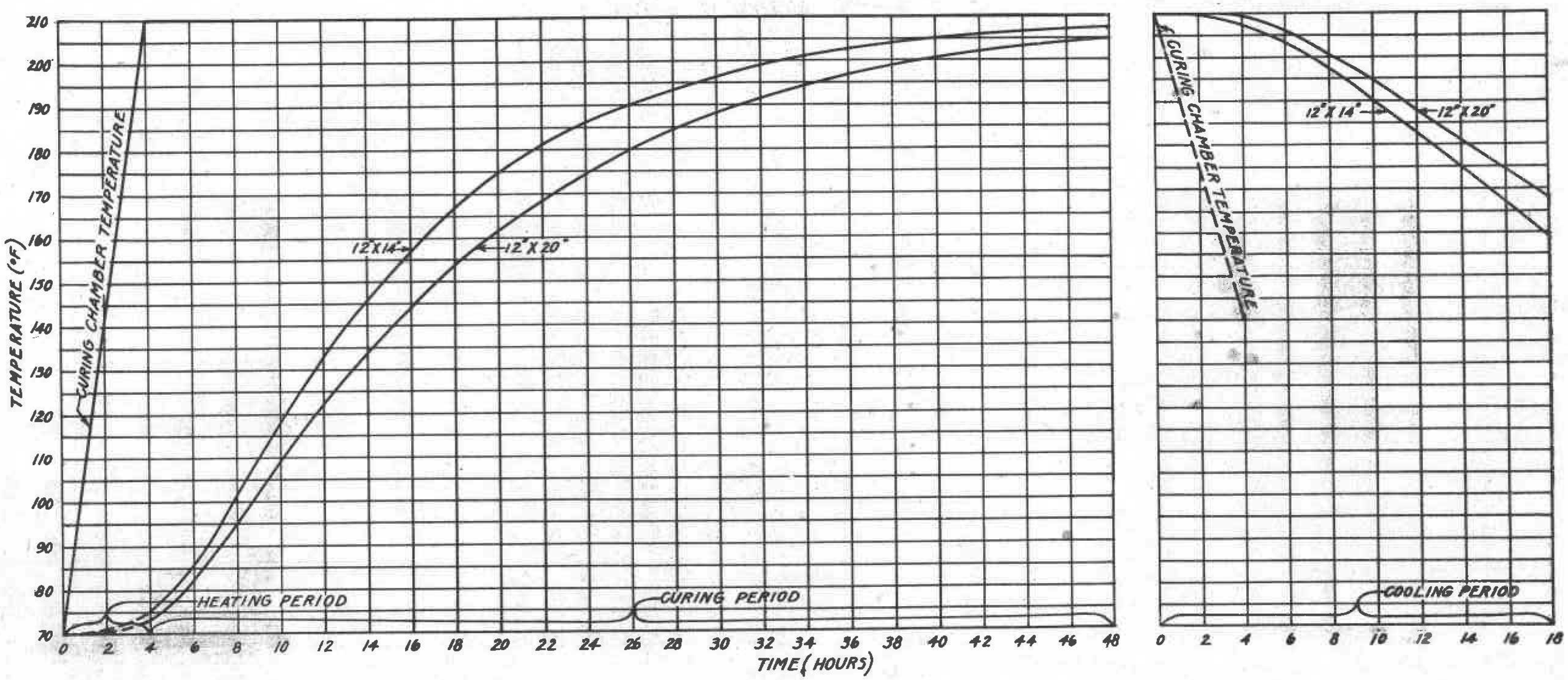


Figure 16.--Glue line temperature at center of laminated Douglas-fir beams having laminations 12 inches wide, curing chamber held at 210° F. and 80 percent relative humidity.

Z M 51755 F

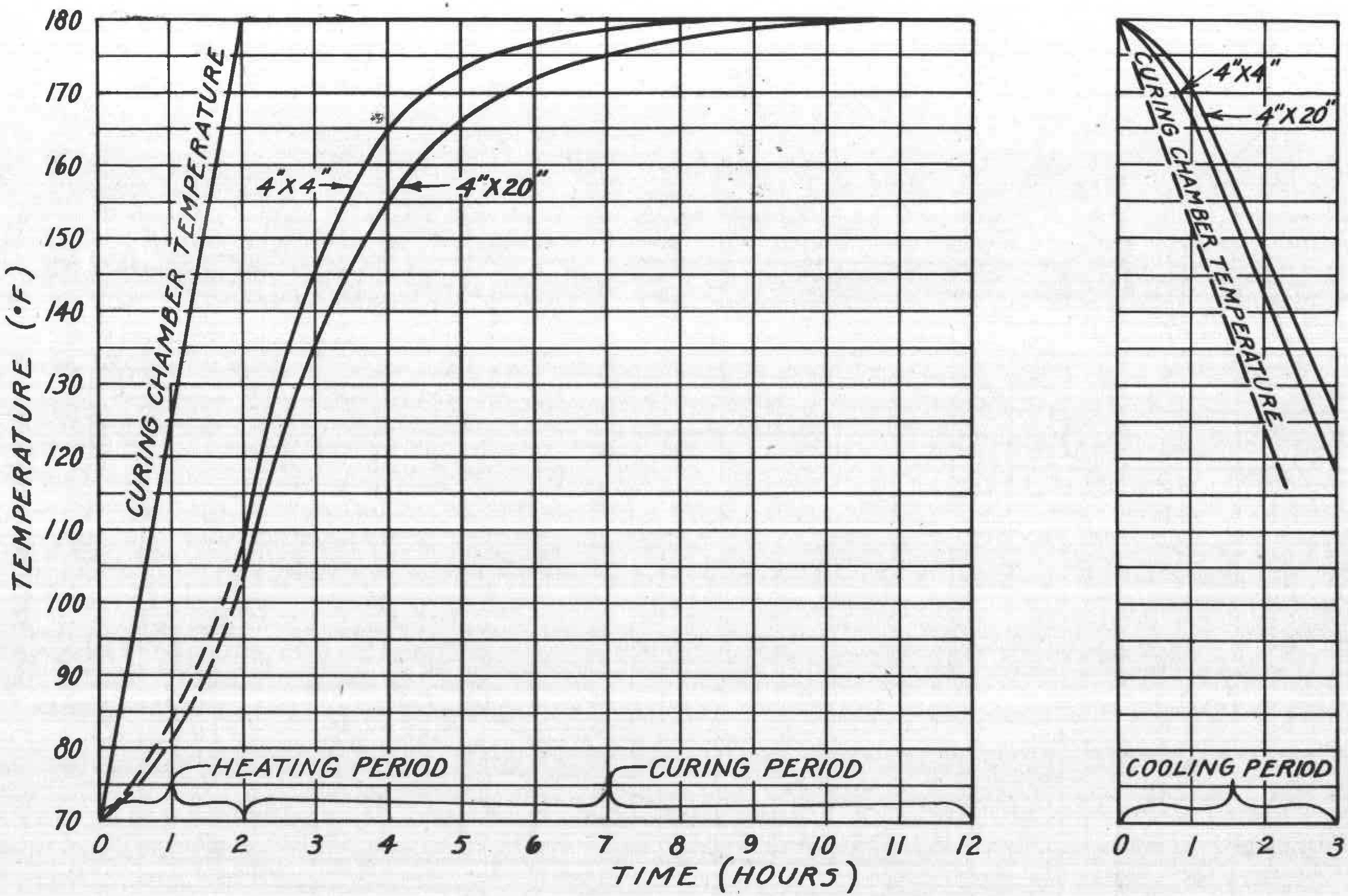


Figure 17.--Glue line temperature at center of laminated Douglas-fir beam having laminations 4 inches wide, curing chamber held at 180° F. and 80 percent relative humidity.

Z M 51897 F

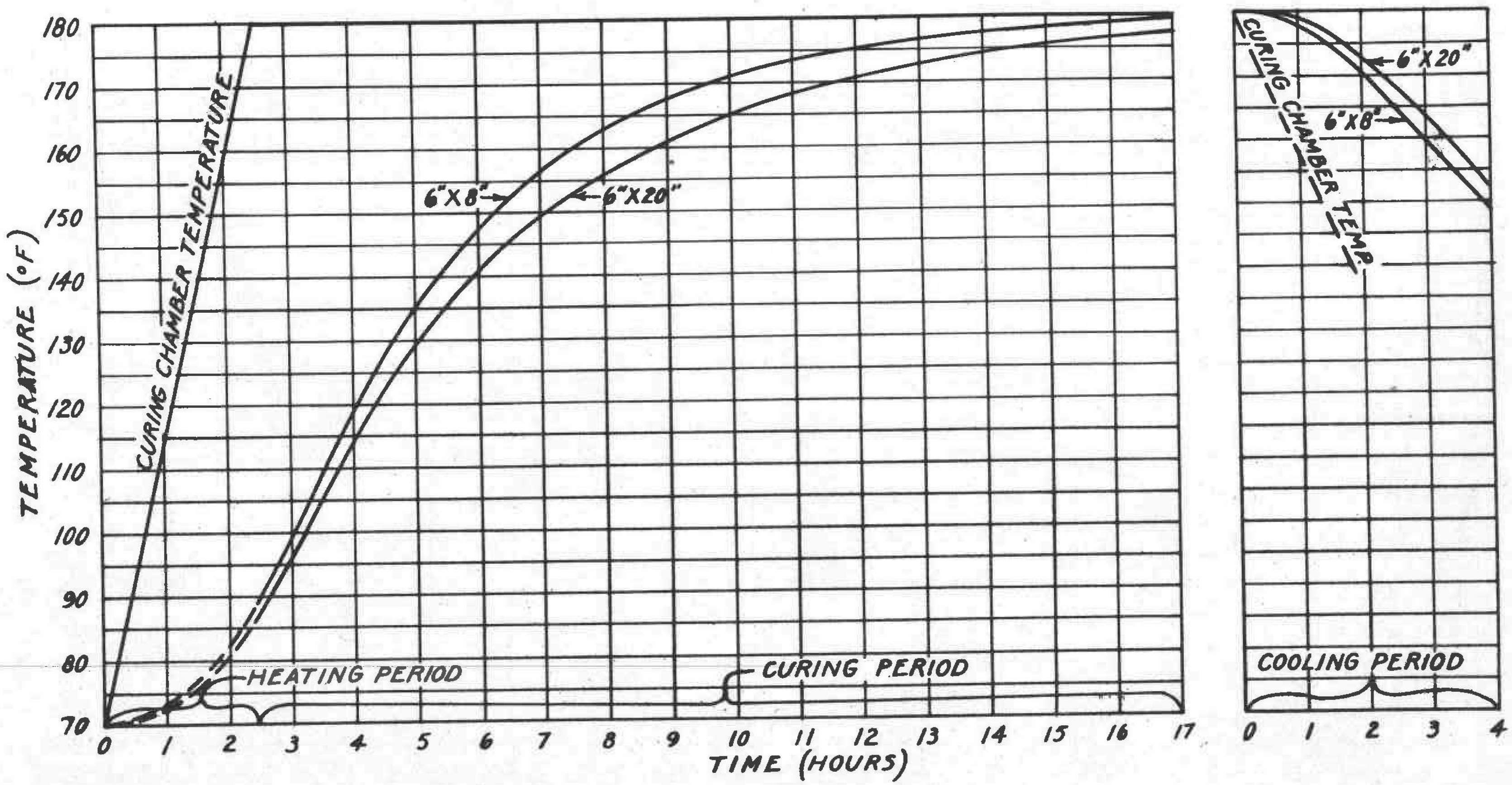


Figure 18.--Glue line temperature at center of laminated Douglas-fir beam having laminations 6 inches wide, curing chamber held at 180° F. and 80 percent relative humidity.

Z M 51898 F

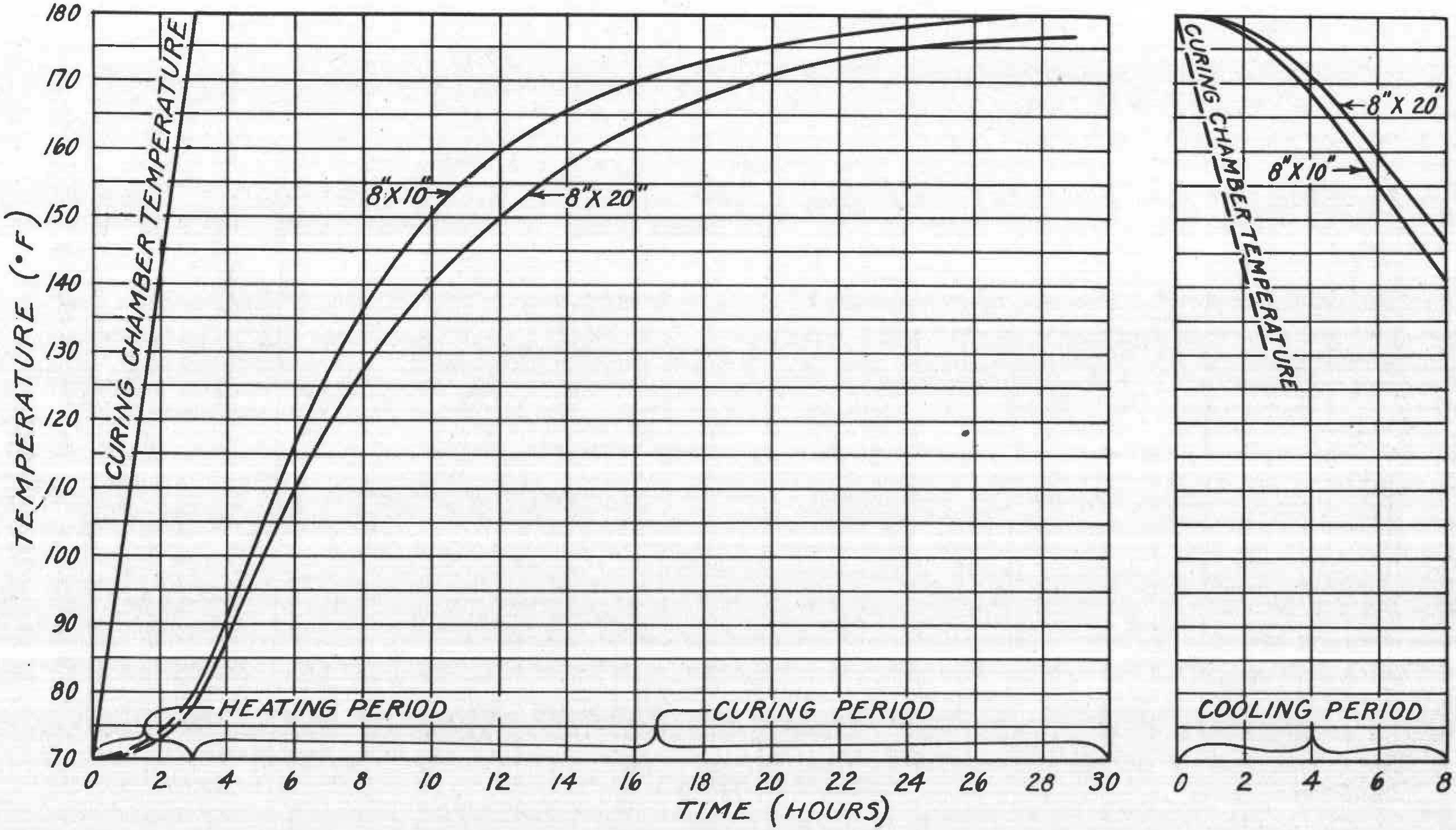


Figure 19.--Glue line temperature at center of laminated Douglas-fir beam having laminations 8 inches wide, curing chamber held at 180° F. and 80 percent relative humidity.

Z M 51899 F

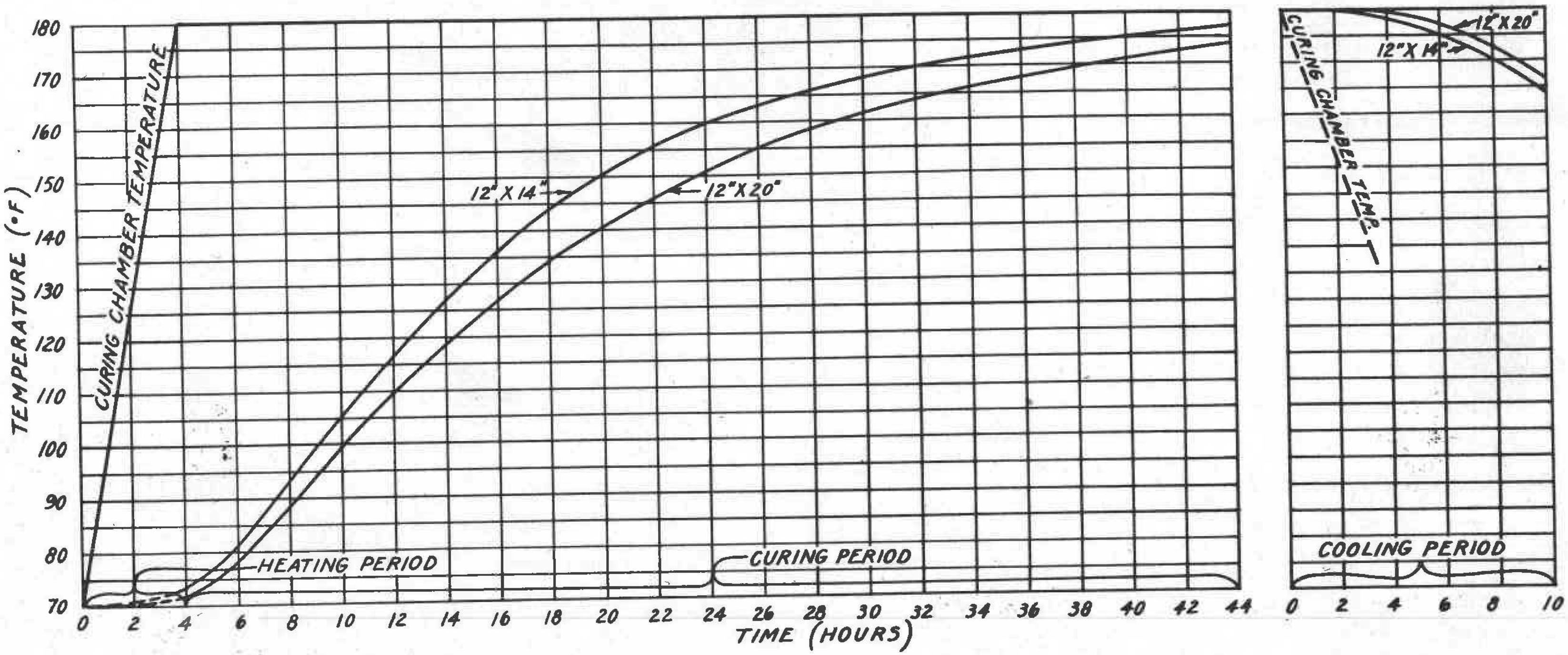


Figure 20.--Glue line temperature at center of laminated Douglas-fir beam having laminations 12 inches wide, curing chamber held at 180° F. and 80 percent relative humidity.

ZM 51900 F

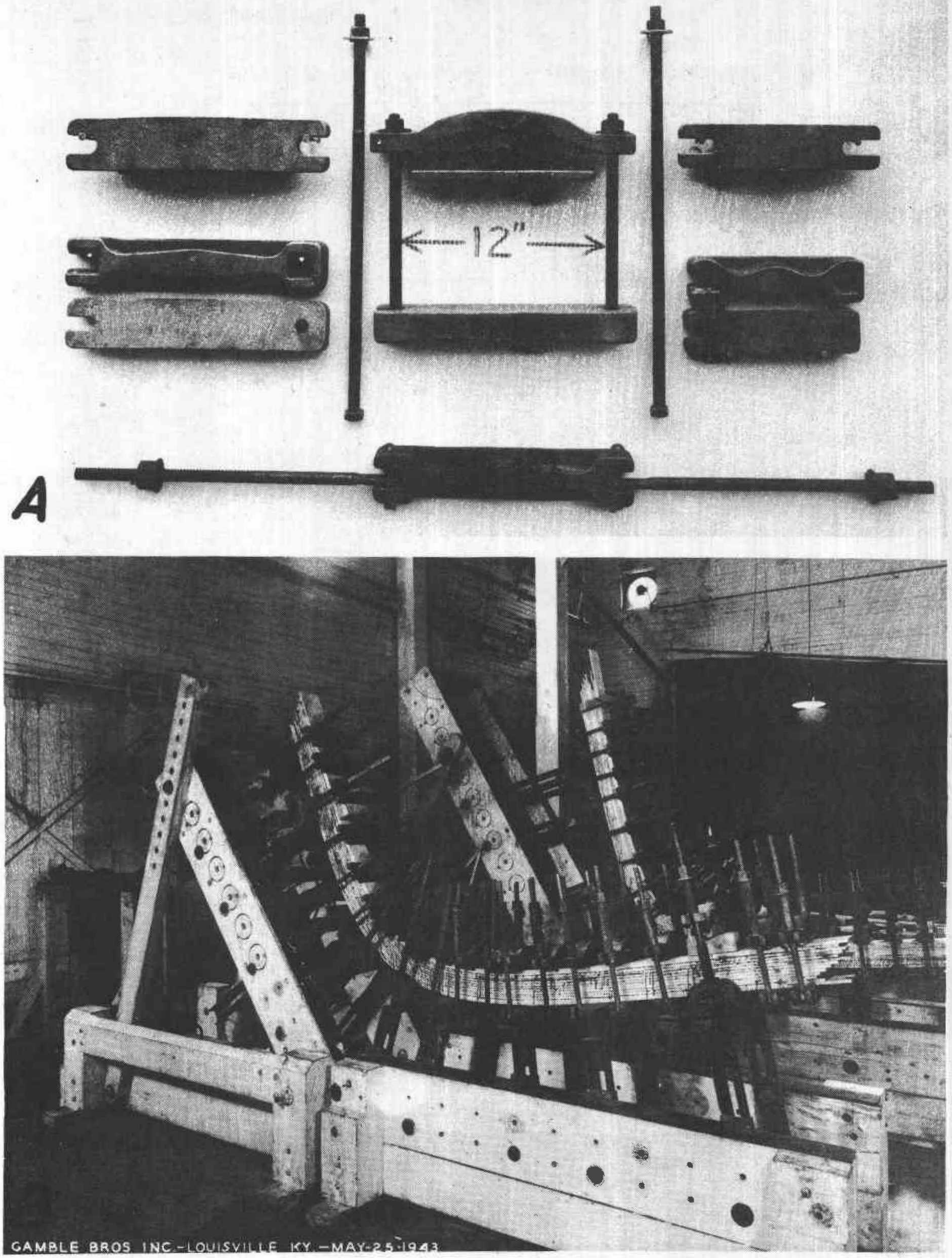


Figure 21.--A, equalizing head type of retaining clamp used in applying pressure to laminated assembly. B, bent laminated assembly in universal jig. Draw-up clamps provide additional gluing pressure.

Z M 51901 F

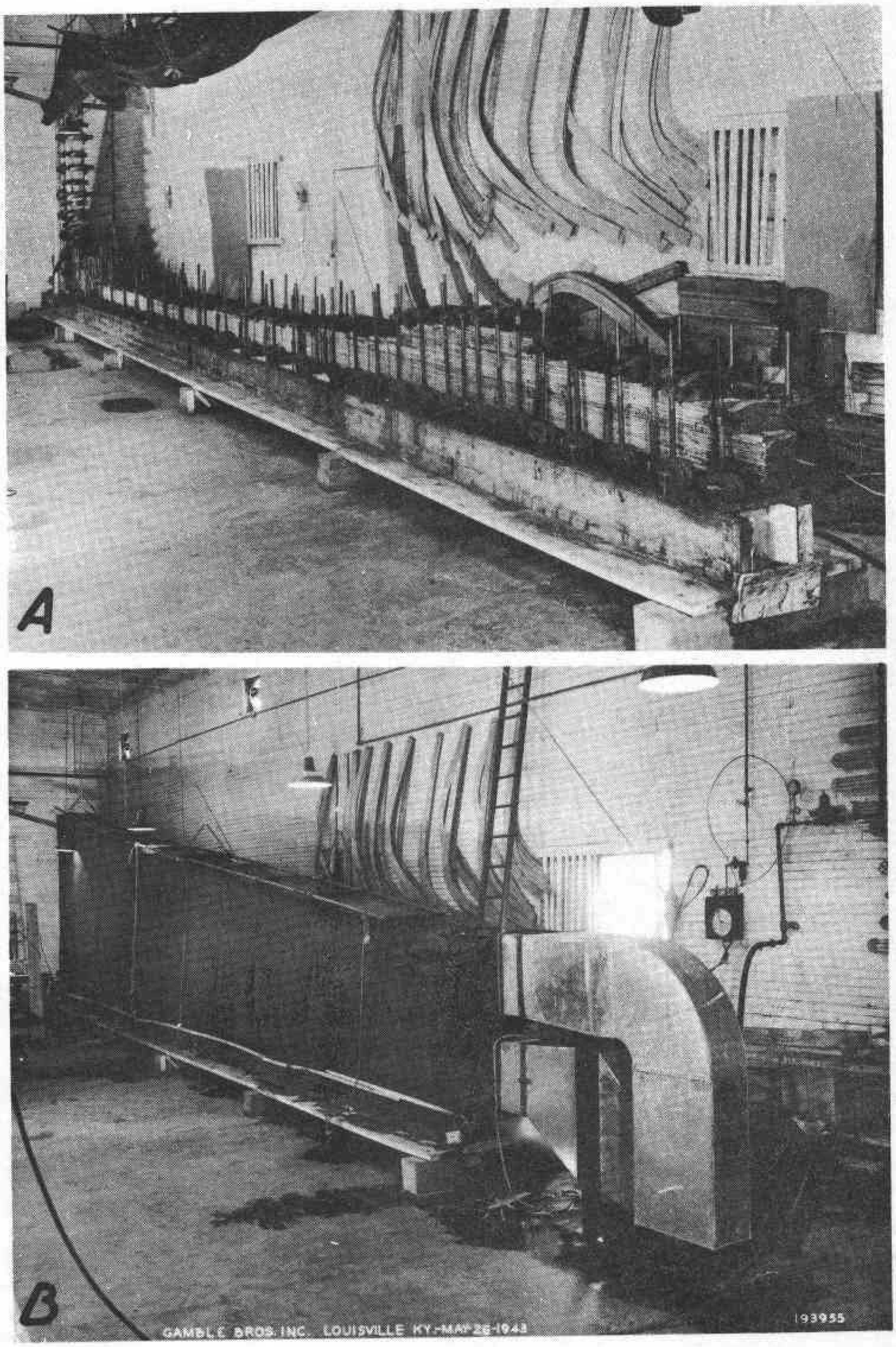


Figure 22.--A, bent laminated glued assembly clamped in solid form, ready for curing operation. B, canvas canopy dropped over laminated assembly to serve as curing chamber. Fan at end furnishes recirculation of air. Heating coils and steam spray in chamber, thermostatically controlled, provide necessary temperature and humidity conditions for curing glue. Canvas, specially treated, provides vapor-tight construction.

Z M 51902 F