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Drying Rates of Thin Sections of Wood at High Temperatures

Herbert O. Fleischer
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DRYING RATES OF THIN SECTIONS OF WOOD AT HIGH TEMPERATURES

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1953

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CONTENTS

ILLUSTRATIONS

CONTENTS

TABLES

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DRYING RATES OF THIN SECTIONS OF WOOD AT HIGH TEMPERATURES

INTRODUCTION

PAST research in drying wood has established the practical limits of temperature and relative humidity that apply to lumber drying. In connection with lumber drying it was early recognized that drying at elevated temperatures results in a reduction in strength and a softening of the wood (*35*)[1] that, combined with drying stresses, placed a practical limit on the temperatures that might be used.

In some cases, green wood is cut into large, relatively thin sheets before drying. Practical experience has shown that these thin sections, often from 1/32- to 1/8-inch thick, may generally be dried at temperatures above the boiling point of water without apparent harm such as may result in drying lumber at these temperatures. One reason for the success of this method of drying is that the thin sections dry so rapidly that the wood need not be exposed for long periods to the high temperatures. Furthermore, it was thought that there might exist a limit in thickness below which stresses resulting from a moisture gradient during drying would not develop to such an extent as to cause defects.

Detailed fundamental information is lacking about the drying of wood in thin sections and the effects of high temperatures commonly used in drying such material. This study was intended to investigate the drying of small, thin wood sections at high temperatures, with particular emphasis on the drying rates. Factors other than temperature that might affect such rates, namely air velocity and atmospheric humidity, were also included as variables in the study. The drying data were critically examined to see whether they followed the trends predicted by the commonly used diffusion equations. The specimens were also analyzed for shrinkage and examined for the development of drying defects.

CHARACTERISTICS OF DRYING RATE CURVES

Based on experiments with sand, soap, silica gel, wool, paper, wood, and other materials, typical drying phenomena have been analyzed and defined

[1] Italic numbers in parentheses refer to references cited at the end of this paper.

by periods, depending on the mechanism that is thought to be controlling the drying at any particular time. A "typical" drying rate curve is composed of three major drying periods.

Before the start of the first period a relatively short period of adjustment may be observable. If present, it is an unstable state, during which the drying conditions within the substance adjust themselves to the steady state represented by Period I.

Period I is the early stage of drying during which the drying rate remains relatively constant (29). It continues as long as free water is supplied to the drying surface as quickly as it can be evaporated. In this period the moisture content distribution curve through the thickness of the drying specimen gradually becomes parabolic. The period ends when the surface moisture content has dropped to the fiber saturation point while the interior is still at a higher moisture content *(10).* During the constant rate period it is supposed that the surface temperature of the drying slab remains at the wet-bulb temperature of the drying medium (29). Surface evaporation and diffusion of water vapor away from the surface are therefore limiting factors. The transfer of water to the surface may be by capillary action, surface tension being effective in causing it to move through the wood (11).

The constant-rate period is generally succeeded by two falling-rate periods (29). In the first of these (Period II), the rate falls more or less linearly with the continued decrease in water content. The period is characterized by a spot-wise recession of the evaporating surface area actually wetted. The wetted surfaces from which evaporation occurs, in this case, are the surfaces of the menisci within the capillaries, which are constantly receding. In this period, as in the constant rate period, the resistance to the diffusion of water to the evaporating surface is small as compared to the resistance to the escape of water vapor from the surface.

Period III, the second falling-rate period, is not always clearly distinguishable from Period II. The drying rate may fall progressively with decreasing water content, so as to form a curve that is concave upward (29). It is assumed that internal diffusion is generally the controlling factor during this period, and that the moisture distribution at the start of the period is parabolic through the thickness of the piece, the surface moisture content being at equilibrium with the atmosphere, while the interior is at a higher moisture content. The rate of diffusion at any point is assumed to be proportional to the moisture content gradient *(30).* This phase may also be characterized by subsurface evaporation from a continuously receding surface, and by the necessity for the heat required for evaporation to penetrate increasing thicknesses of partially dried stock. In this case the controlling factor is the resistance to movement of moisture through the interior of the body, which is great compared to the resistance to the escape of water vapor at the surface. Drying in Period III continues until the rate becomes 0, which occurs when the moisture content throughout the material reaches the equilibrium condition.

Calculation of Drying Rates During the Falling-rate Period

Diffusion laws were first applied to the drying of wood by Loughborough and Tuttle (*38*). It was assumed that the diffusion of water would follow the same laws as those governing the transfer of heat, which had been studied in greater detail.

Fourier's law for the conduction of heat (*22*) states that the instantaneous rate of heat flow $dQ/d\theta$ is equal to the product of three factors: the area A of the section, taken at right angles to the direction of heat flow; the temperature gradient $-dt/dx$, which is the rate of change of temperature t with respect to the length of the path x; and the proportionality factor k, known as thermal conductivity. Fourier's law is expressed mathematically as follows:

$$\frac{dQ}{d\theta} = -kA\frac{dt}{dx}$$

where dQ is the amount of heat flowing in differential time $d\theta$.

Tuttle's tests permitted him to write a similar equation for unidirectional flow of moisture through wood, substituting the total evaporable moisture, that is, the moisture above that present when equilibrium conditions have been reached, for heat to be transferred and the moisture gradient for the temperature gradient. The constant, "k," was termed transfusivity, and has later been referred to by other investigators as the diffusion coefficient, the diffusion constant, the drying coefficient, or simply as the k-factor.

Stillwell (*34*) studied the shape of the moisture gradient curve when diffusion to the drying surface occurred in each of the three principal directions of the wood. Measurements of the rate of flow of moisture through wood plugs were made under steady flow conditions below the fiber saturation point. The tests indicated that the resulting flow along the wood substance was proportional to the vapor pressure fall or the moisture content gradient.

Martley (*20*) showed that under steady flow conditions the moisture, q, flowing through a unit cross section of the test piece in unit time, at any point where the moisture gradient was du/dx, was

$$q = k\ du/dx$$

This equation is similar to the basic equation for thermal conduction in the steady state (*22*). Martley found that the constant, k, was dependent upon the drying temperature, the direction of flow (relative to the wood structure), the species, the specific weight of wood, and the moisture content of the wood.

Sherwood further developed (*28*) the theoretical equation for drying when internal diffusion is controlling, following the analysis developed by Tuttle. Unlike Tuttle, Sherwood did not use moisture gradient data in his application of the Fourier heat transfer law, but worked primarily with average moisture changes during drying. By constructing special plotting paper, Sherwood was able to plot the theoretical drying equation data as a straight line, and from this he determined the k-value rather simply.

For an approximate analysis to be used for both falling-rate periods (Periods II and III), Sherwood assumes (*29*) that the rate of drying is a linear function of the water content of the material. In place of the true moisture gradient through the thickness of the piece, the gradient used, called E, is equal to:

$$\frac{\text{the free water content at any given time}}{\text{the free water content at the start of the period}}$$

Sherwood demonstrated mathematically that a plot of E′ over θ', the time after the start of the falling-rate period, gave a straight line on semilogarithmic paper. With a given value of k, Sherwood illustrated that the drying data for the falling-rate period of whiting slabs of several thicknesses could be represented fairly well by the equation

$$\log E' = -k\frac{\theta'}{R}$$

where R is one-half the thickness of the slab.

Newman (*23*) applied Sherwood's mathematical analyses to the drying of specimens having various fixed shapes, including the slab. Based on the relationship between E, the fraction of the evaporable water remaining in the specimen at any time, θ, and $k8/a^2$, where k is the diffusion constant, θ is time, and a is one-half the thickness, Newman calculated various numerical values of $k8/a^2$ for corresponding values of E, for various shapes of drying bodies. The relationship expressed in Newman's tables may also be shown graphically on special plotting paper, substituting the values of E for the scale used by Sherwood in his graphical approximation mentioned above. When plotted on this paper, the drying rate values for a slab having a given value of k, and of a given thickness, will plot as a straight line as long as the diffusion conditions assumed, namely, the falling-rate period with diffusion controlling, apply. It is this relationship that is most commonly used in connection with drying rate calculations.

Newman (23) further modified earlier theories by pointing out that the entire drying process might be divided into only two periods instead of three. The two falling-rate periods may be considered as one, in which the drying will be influenced by surface conditions as well as by internal diffusion. At any instant, however, the surface condition controls the rate of evaporation. What the rate will be at a subsequent instant depends on the internal diffusion during the elapsed time. The effect of Newman's so-called "surface emissivity" is observed when drying similar materials at uniform temperature conditions, under which the diffusion coefficient presumably would be constant, but at varying air velocities. At low velocities the rate of drying is retarded because of high surface resistance to the escape of moisture. Newman also pointed out that surface resistance presumably would be the major controlling factor in the drying of a thin sheet.

The importance of air circulation in the drying of wood is stressed by Mathewson *(2I)*, for under practical air-drying conditions it is the prime factor in supplying the heat necessary for evaporation and also in removing the evaporated moisture.

In 1931 Hawley *(II)* pointed out that the apparent success of the application of the diffusion equations by Tuttle and Sherwood proved only that the probably complicated mechanism actually in operation happened to have a resultant the same as that of the assumed simple mechanism. In view of the dependence of the diffusion rate on the moisture content of the wood at any period, Stamm (32), Egner (6), and others have pointed out that the Fourier law is not properly applicable over the complete moisture content range in the falling-rate periods when used in connection with rate-of-drying data rather than moisture-distribution data. Egner found it impossible to derive the assumed moisture distribution curves mathematically, in accordance with the diffusion theory, but his empirical data on moisture gradients nevertheless indicated that the diffusion laws applied.

Hougen, McCauley, and :Marshall *(14)*, after a study of drying phenomena in various materials, concluded that diffusion equations have been applied without due regard to the applicability or the limitations of such equations. They point out that other forces that may be active in drying are capillarity, specific gravity, external pressure, convection, and sequences of vaporizations and condensations due to temperature differences. From a study of the movement of moisture below the fiber-saturation point in the longitudinal, radial, and tangential directions of the wood, Buckman and Rees (3) concluded that in coniferous wood this movement was predominantly by bound liquid diffusion through the cell walls and by vapor diffusion across the cell cavities. This conclusion was based chiefly on the determination that the rate of moisture movement in the longitudinal direction was about 5 times the rate in the two transverse directions.

Bateman, Hohf, and Stamm *(I)* have shown that the movement of bound water takes place by diffusion through the cell walls, the diffusivity being much greater in the direction of the fiber lengths than across the cell walls. The movement of free water, however, is influenced by capillarity and specific gravity, and is restricted by the small openings and cell wall pits connecting the cell cavities. Therefore, diffusion may assume importance even in the movement of free water, nearly all the water escaping during drying being moved finally by diffusion. They showed that diffusion equations can be applied for calculating moisture distribution below the fiber-saturation point, provided values of diffusivity are employed that vary with temperature, pressure, moisture content, density, and direction of flow. For drying completely water-filled wood (Sitka spruce) the moisture distribution curves were extremely complex, and diffusion equations were found to be applicable only below the fiber-saturation point.

The major work of Stamm on the movement of liquids, vapors, and dissolved materials through softwoods, as affected by capillary-structure considerations (32), served to bring together and explain many of the isolated findings and conclusions of previous investigators. Stamm found that the movement of liquids through wood was chiefly through the wood fibers. In wood liquids can move not only through the cell cavities, in series with pit chambers and pit membranes, but also through the capillary structure within the cell wall that exists because of the swelling action of such liquids as water upon the cell wall structure. These so-called "transient cell-wall capillaries" can also function in parallel with the many pit chambers and membranes in the cell walls.

Using the analogy of electric current flow, Stamm (32) calculated the longitudinal and the transverse diffusion of water through wood, taking into account the diffusion constant of the solute, the diffusion of the solute through the system of cavities, and the continuous diffusion through the cell walls. The rate of longitudinal diffusion through softwoods was found to be 14.5 times that of transverse diffusion. In the case of transverse diffusion, the resistance to movement attributable to the pit system and to the cell wall cavities was about twice that attributable to the fiber cavities. As a result of these resistances, the transverse diffusion was reduced to 0.0448 times the diffusion constant.

If drying were controlled by simple diffusion, the diffusion constant should be independent of moisture content. That this is not the case (20) is, according to Stamm (32), an indication of the complex nature of the capillary structure of wood, and the great variation in the dimensions of the structural units through which diffusion occurs. Three driving forces may be effective in the movement of water in drying: (1) liquid movement due to capillary forces, (2) vapor flow due to a relative vapor-pressure gradient, and (3) bound water movement due to a moisture content gradient. At moisture contents above the fiber-saturation point, the force causing movement of capillary water and water vapor may be furnished by a slight depression of vapor pressure. Below the fiber-saturation point, the movement of bound water and water vapor should be controlled by diffusion. In this case, two driving forces may be at work: the vapor-pressure gradient, and the moisture content gradient. By the application of standard diffusion equations, Stamm showed theoretically that the diffusion constant in drying was controlled chiefly by bound-water diffusion at the higher moisture contents and by water-vapor diffusion at the lower moisture contents. Vapor diffusion predominates in wood of low specific gravity, and hence the diffusion coefficient varies more with moisture content for such woods than for woods of high specific gravities. As drying temperatures increase, vapor diffusion becomes the predominant factor. Average diffusion values increase appreciably with an increase in temperature.

Comparison of the theoretical values obtained by Stamm (32) using calculated diffusion constants for the transverse drying of wood with constants obtained by other methods showed excellent agreement and indicated that this type of approach to the diffusion problem was a valid one. Stamm's data indicated that the use of average values of the diffusion constant results in a degree of accuracy that is adequate for purposes of calculating approximate drying rates.

It is evident that moisture diffusion theories as applied to the drying of wood have had a long and varied history. In spite of the controversial nature of some of the theory involved, the method of estimating drying rates on the basis of diffusion calculations has survived all criticism. That the method applies to the drying of thin wood specimens, dried under the high temperature conditions represented in the present study, has, however, not been demonstrated to date.

EXPERIMENTAL PROCEDURE

THE DRYING APPARATUS

THE drying apparatus used for these tests is shown in Plate 1. The apparatus is shown before insulation was applied to its surfaces, in order that the various parts may be more clearly seen.

Air to be used for drying was conditioned in a dry kiln, the door of which is seen at the extreme left *(A)*. In this kiln the wet and dry bulb temperatures were controlled by means of automatic control equipment. Air was drawn from the kiln through the pipe B and entered a pump, C, capable of being operated at high temperatures. Air leaving the pump at the bottom might pass either to the right to the dryer, or be returned to the kiln to the left. The pump motor is shown at D. Condensate developed during the warming period could be drained off below the pump. The volume of air passing into the dryer was controlled by means of a valve, E, and by by-passing a portion of the air back to the kiln.

Air passing through the heating tube F was heated by means of electrical resistance heaters, the sockets and switches for which are seen on the tube. A rheostat G shown below the heating tube was used to control the temperature of the air leaving the heating tube, but this was later replaced by a thermostatically operated switch that provided closer temperature control than could be maintained manually. From the heating tube the air entered the plenum chamber H, having a circular observation window at its front. Thermometer openings permitted thermometers to be inserted at several points within the plenum chamber for setting and checking the accuracy of operation of the thermostat. Because of the eccentric position of the air inlet duct, the air circled about the outer walls of the chamber, gradually rising to its top.

Near the top of the chamber the air was free to enter the top of the drying tube, J, a rectangular enclosure having inside dimensions of 1 by 4 inches, with a rectangular glass front; it can be seen through the larger circular window in the chamber H. The drying test specimen, which can also be seen hanging in the drying tube, was held loosely between two sets of rigid wires to keep it from approaching either wall of the tube. After passing downward over the specimen, the air continued through a circular duct K and was exhausted to the atmosphere.

At the end (not shown) of the exhaust duct K, the tube was provided with a flange to which plates having various orifice diameters could be fastened. Several inches back from the flange was a pressure tap leading to a manometer L for measuring the back pressure built up at the orifice. This provided the means for estimating the air velocity over the drying specimen.

The wood specimen to be dried, 3 by 6 inches in size, hung on a spring weighing apparatus, M, capable of weighing roughly to 1/2 of 1 percent of the oven-dry weight of the specimen. The weighing springs used were the type intended for use in a Jolly balance and were of several different capacities to cover the range in weights represented by specimens of different thickness. The specimen was held on a swivel hook by a thin, flexible cable. It was dropped into the drying tube through the hinged opening in the drying chamber cover, N. The spring weighing apparatus hung on pulleys and was counterweighted so that it was readily adjustable vertically, so that the test specimen hung at the proper height in the tube. As the specimen dried and rose in the tube because of the decreased spring tension, the weighing scale was moved down to keep the specimen at the proper height.

When weighing a specimen, it was necessary to eliminate the flow of air over it. To do this, a lever, O, was pushed down, which closed a damper in the exhaust tube K and opened a damper in outlet P, venting the plenum chamber to the outside and eliminating the downflow of air over the specimen. After some practice in operating the equipment, it was found that the time elapsed at one weighing, during which the air flow over the specimen was stopped, usually amounted to 3 to 5 seconds.

The entire system operated under a pressure slightly higher than atmospheric so that any leakage in the ductwork was toward the outside. This prevented the entrance of unconditioned air into the drying system. The exhaust duct was made airtight so that no leakage could occur between the drying specimen and the exhaust orifice, which might affect the accuracy of the air velocity measurements. Thermometer openings were also provided in the exhaust duct for checking temperatures.

DRYING CONDITIONS

The range of drying conditions chosen for use in this study included those that might be considered relatively severe from the standpoint of lumber drying, particularly with respect to temperature. Since most lumber is dried at temperatures below 212° F., high drying temperatures might be considered those above this temperature and upward, approaching the ignition point of wood. The high temperatures chosen for these tests were

250° and 350° F. For comparison with more moderate temperatures, a temperature of 150° F. was also included.

Several humidity conditions were used, representing the lower and the upper range of relative humidities that can be readily controlled in non-pressurized drying equipment. Because of the wide range of temperature conditions included in the study, humidity was expressed in absolute terms. For the low absolute humidity condition the saturation temperature of the air used was 88° F. and the atmosphere contained 0.029 pound of water per pound of dry air (39). At 150° F. the relative humidity of this mixture was about 17 1/2 percent. When this same mixture was raised in temperature to 250° and 350° F., the relative humidity values[2] were 2.2 and 0.5 percent respectively.

For the high humidity condition it was convenient to use a value of about 100 times that used for the low humidity condition, or 2.9 pounds of water per pound of dry air. This mixture has a saturation temperature of 202° F. The calculated relative humidity of this mixture, when heated to 250° F., was 41 percent, and at 350° F. was 9 percent. Naturally this mixture could not be used at the control temperature of 150° F. because of condensation problems in the drying apparatus. The highest humidity that could be consistently maintained with a dry bulb of 150° F. was a relative humidity of 68 percent (wet bulb depression of 14°). The absolute humidity in this case was 0.144 pound of water per pound of dry air.

The flow of air over the drying specimens was maintained at three levels: 200, 600, and 1,000 feet per minute.

EQUILIBRIUM MOISTURE CONTENT OF WOOD UNDER TEST CONDITIONS

The equilibrium moisture content of wood at various temperatures and relative humidities below 212° F. is given by Hawley *(II)*. For the 150° F., low absolute humidity condition, when the relative humidity was 17 1/2 percent, the equilibrium moisture content was 2 1/2 percent; at the high absolute humidity condition (68 percent relative humidity), it was 10 percent. At temperatures above 212° F. the equilibrium moisture content of wood normally is assumed to be zero. From extrapolation of

[2] The relative humidity above 212° F. was calculated from the formula: Percent relative humidity=p/P. x 100, where p is the pressure at saturation of the mixture and P. is the saturation pressure at the temperature used. The psychrometric data used in these and other calculations are those of Zimmerman and Lavine (39).

the curves shown by Hawley, Norris (24) concluded that the equilibrium moisture content of wood at temperatures somewhat above 212° F. and at high relative humidities was considerably above zero. The validity of Norris's extrapolation was established by Keylwerth *(IS)*, who demonstrated in tests on beech and pine, held in saturated steam at temperatures above 212° and up to 248° F., that the experimentally determined values fell close to the extrapolated curve for a 100 percent humidity. In superheated steam at 248° F., Keylwerth found that the equilibrium moisture content of wood was about 4 percent, or approximately as predicted. Upon extrapolation of the 100 percent humidity curve to a temperature of 350° F., an equilibrium moisture content well below 1 percent would be indicated.

In the present series of tests at the high humidity condition, the relative humidity at 250° F. was 41 percent, indicating that an equilibrium moisture content of between 1 and 2 percent might be expected. At other conditions above 212° F., the equilibrium condition would be so close to zero that the moisture remaining in the wood in this condition would not be determinable by ordinary oven-drying methods.

CONTROL AND MEASUREMENT OF DRYING CONDITIONS

The temperature of the air entering the drying tube was controlled by a thermostat that maintained it to within about ±2° F. of the desired temperature. Tests made to explore the temperature variation through the various portions of the dryer showed that the air temperature was highest at the point where the air entered the plenum chamber. Because of the relatively large size of this chamber, the air rose spirally and rather slowly to its upper part. In some cases the drop in temperature from the lower to the upper part of the chamber was as much as 10° F. The drying tube, centrally located within the chamber, was affected by this temperature difference, so that the temperature of the air as it passed downward through the drying tube actually rose.

With a drying specimen in place, the temperature conditions within the tube were somewhat different. In spite of the small size of the specimen, the air passing over it during the early part of the drying cycle was cooled considerably because of evaporation of water. Temperature measurements were made during the drying cycle with the aid of thermocouples placed 1/4 inch above and below a 1/8-inch specimen, dried at 250° F., 600 feet per minute, low humidity. In this case it was found that the temperature of the air at the top, where it first contacted the specimen, remained at

250^{0} F. at the start of the drying. The temperature of the air leaving the specimen was 205^{0} F. at the start of the drying. It rose constantly as the specimen dried and reached 250^{0} F. near the end of the cycle. After the specimen was almost dry and evaporation was greatly retarded, the temperature of the air rose to 255^{0} F. because of heat transfer through and radiation from the walls of the heating tube, which were at a higher temperature in the lower part of the tube.

The great drop in temperature of the air passing over the specimen during the early part of the drying period is an indication of the extreme rapidity with which water may evaporate under the high temperature conditions prevailing in these tests. In this study the drying temperature referred to is the temperature of the air as it entered the drying tube, rather than the average temperature over the area of the specimen at anyone time.

The control of humidity, as mentioned above, was effected in a dry kiln. Before each series of drying tests, the apparatus was first thoroughly heated so that no condensation occurred in the apparatus during the tests. The accuracy of the absolute humidity depended on the control of kiln conditions, which was effected by a wet- and dry-bulb temperature controller with air-operated valves on the kiln coils and spray pipe. Wet- and dry-bulb temperatures were held to approximately $\pm 2^{0}$ F.

Under the conditions applying in these tests, the most accurate measurement of air flow rates appeared to be obtainable by use of sharp-edged orifice plates located at the end of the air exhaust duct (K in Plate I). Pressure developed at a tap located a few inches behind the orifice was measured with an inclined-scale manometer (L in Plate I). By use of orifices having different diameters of 5/8 inch, 1 inch, and 1 1/2 inches, depending on the air velocity required, it was possible to cover the range of air velocities desired without exceeding a pressure of 1 inch of water. This method of air velocity measurement reportedly is capable of measuring with an accuracy of 1 percent, especially at low air velocities (26).[3]

[3] Calculation of air velocities was based on the use of the formula *(Z9)*:

$$Q = 1096.5\, C A_2 f \sqrt{p/r}$$

where Q = discharge, cu. ft. air per min.; A_2 = area of orifice, sq. ft.; p = pressure in pipe (static plus /low), in. water; r = weight of air, lb. per cu. ft.; and f = velocity of approach factor. C, the coefficient of discharge, is 0.601 when A_2/A_1 is less than 0.1 (A_1 the cross-sectional area of the pipe, was 0.0873 sq. ft.). In this case f, the velocity of approach factor, drops from the formula, for a plenum chamber effect exists. When A_2/A_1 is greater than 0.1, as it was when the 1 1/2-inch orifice was used, f must be taken into account. In this case A_2/A_1 was 0.14, and, from standard tables *(Z9)*, C becomes 0.604 and f, 1.004, and the combined effect $C \times f = 0.606$.

Calculations were made to take into account the variable weight of the drying atmosphere with temperature and absolute humidity changes. The values obtained were adjusted to give the desired rate of flow through the 1- x 4-inch duct in which the drying specimen hung, taking into account the reduction in cross-sectional area because of the space occupied by wood specimens of various thicknesses. Account was also taken of the drop in temperature and the corresponding decrease in volume of the air from the drying chamber to the end of the exhaust duct, where the air flow was measured. The various values of air and water vapor weights and volumes required for these calculations were obtained from Zimmerman and Lavine (39).

Finally, the data were transferred to alinement charts that made it possible to determine quickly what setting was required on the manometer to obtain any desired rate of air flow over the specimen.

SELECTION AND PREPARATION OF TEST MATERIAL

Yellow-poplar *(Liriodendron tulipifera* L.) was used for the major series of drying tests. Two old-growth logs having diameters of 23 and 28 inches were obtained from the vicinity of Pickens, South Carolina. They were green and straight grained. A 14-inch-long portion was taken from log No. 1, and a 38-inch-long portion from log No. 2.

The test specimens were prepared by sawing and planing, rather than by cutting with a knife, in order that they might be free of checks. The green bolts were split radially into segments of triangular outline, each segment large enough so that a rectangular block somewhat wider than 3 inches in the tangential dimension could be hewed from it. The sapwood was split away, as was also the inner part containing heart defects. This roughing-out was done by splitting, so that the finished squares would have the grain parallel to the surfaces. There remained 11 pieces from log No. 1 and 16 pieces from log No. 2, somewhat over 3 inches in the smallest tangential dimension and from 3 to 5 inches in the radial dimension, all coming from a relatively narrow circular portion within the outer heartwood portion of each log. These squares were wrapped in moist cloth and stored in a refrigerated room for further processing.

Tests on portions of the blocks showed that the specific gravity of wood in the samples from log No. 1 was 0.32 to 0.37, based on green volume and oven-dry weight. The moisture content, based on oven-dry weight, was 65 to 100 percent and the growth rate was 35 to 55 rings per inch. In samples from log No. 2, the specific gravity was 0.43 to 0.45, the moisture content was generally between 140 and 160 percent, and the growth rate was 15 to 30 rings to the inch. The specimens used were free from mineral stain often found in yellow-poplar heartwood.

To prepare the drying specimens, blocks from each log were randomly designated for cutting into sheets of designated thickness, namely, 1/32, 1/16, 1/8, and 1/4 inch. Each block was then planed on its two radial surfaces to 3 inches (-1-0.02) in width. The blocks were cut tangentially on a saw into sheets that were somewhat thicker than the desired finished thickness. Before each sheet was cut, the previously sawed surface was jointed to get a smooth surface. The saw-cut surface of the strip was then planed to the finished thickness. Specimens not meeting a final thickness tolerance of ±0.002 inch, as well as those that showed other defects in processing, were discarded. The thin strips were then cut on a smooth-cutting saw to a length of 6 inches -1-0.02. During processing the surfaces of the specimens were kept wet, and whenever possible the pieces were kept in a solid pile under a moist cloth.

Log No. 1 yielded enough pieces for one complete set of tests. Log No. 2 yielded a greater supply of material than required, because of its greater length. Hence, the complete series of tests was made on strips obtained only from four adjacent segments of the sixteen segments split out of the log, each segment yielding test pieces of a single thickness. All test pieces were numbered in such a way as to provide identification as to exact origin in each log. Individual test pieces were randomly selected for drying at a specific combination of temperature, air velocity, and absolute humidity.

The specimens were measured for width and length to 0.01 inch and for thickness to 0.001 inch. They were then end-coated with a rubber-base end-sealing material that had been found to be tough and resistant under the temperatures used in these tests. A small hole was punched near one end of the specimen and this was lined with a metal eyelet, through which a fine wire was attached for hanging the specimen during drying.

In addition to the specimens prepared for the drying-rate tests, additional pieces for temperature tests were prepared from log No. 2 to provide for one test at each of the various combinations of thickness, temperature, and air velocity, using only the low humidity condition. These pieces were not chosen at random, but were individually chosen from positions longitudinally adjacent to those of pieces that had been used for corresponding drying-rate tests. Thus, for each condition represented, closely matched pieces were used for the drying-rate and temperature tests.

After completion of the major series of tests on yellow-poplar, additional check tests were made on sweetgum *(Liquidambar styraci/lua* L.) and redwood *(Sequoia sempervirens* (D. Don) End!.). The sweetgum specimens were taken from the outer heartwood of an old-growth tree, at a diameter of approximately 24 inches. In this area the growth rate was 35 rings per inch, the specific gravity was 0.40, and the moisture content was 108 percent. The redwood specimens were also of heartwood, from an old-growth log having a diameter of about 40 inches. The specimens came from a diameter of about 27 inches within the log. The growth rate was 30 rings to the inch, the specific gravity was 0.39, and the moisture content was 106 percent. Test specimens were prepared in the same manner and in the same four thicknesses as the yellow-poplar specimens.

MANNER OF MAKING THE DRYING-RATE TESTS

At the beginning of each day's tests, specimens for the day's work were removed from storage in a refrigerated room and permitted to come to room temperature. Specimens were kept in metal foil waterproof containers, except for the period required for weighing, measuring, and end-coating. The weighing scales used in the dryer had been previously adjusted to take into account the average weight of the dry end-coating and of the metal eyelet in the specimen, as well as the other weighing accessories, so that the weight of the specimen could be read directly. The change in weight of the end-coating during drying, due to evaporation of solvent, was negligible.

During the drying test, time was measured with a stop watch, beginning when the specimen was placed in the dryer. Weights were taken at intervals, from 1/4 minute to 1/2 hour (or in a few cases even longer), depending on the rate at which the specimen lost weight. The specimen remained in the dryer until its weight began to approach a previously calculated equilibrium weight, which was often the oven-dry weight.

After completion of the drying test, specimens were placed in a drying oven at a temperature of 220° F. for 1 day, after which they were weighed and measured. Curves showing the moisture content during drying in percent, based on oven-dry weight, plotted against time, were then prepared for each specimen.

EXPERIMENTAL PROCEDURE

MANNER OF OBTAINING TEMPERATURES OF THE DRYING SPECIMENS

Temperature data were obtained on one set of 36 specimens only. On specimens 1/8- and I/4-inch thick, holes 0.020-inch in diameter were drilled from the edges of the specimens to their centers. These holes were drilled perpendicular to the edges of the specimens, I 1/2 inches deep, so that, as far as could be determined, they reached the exact centers of the samples. Copper-constantan thermocouples of No. 30 wire were sealed in the holes with the same rubber-base cement used as an end-coating.

Surface temperatures were obtained on all specimens with the aid of temperature-indicating waxes having predetermined melting points.[4] These waxes are reported to be accurate to within plus or minus I percent of the designated temperature. In order to provide a visible mark on the wet wood surface, it was found necessary to pulverize the wax so that it could be applied as a small dust spot. When this dust reached its melting temperature, it visibly fused to make a grease spot on the wood. It is thought that this procedure did not seriously interfere with evaporation of moisture, at least until the measured temperature was attained, since the dust did not form a continuous coating on the wood surface. The waxes used for these tests had melting temperatures of 125°, 150°, 163°, 175°, 200°, 225o, 250°, 300°, and 350° F.

In order to get a series of surface-temperature readings on one specimen, a number of dust spots were made on its surface. These spots were randomly and compactly arranged at the middle of one face of the specimen. As the specimen dried they were observed through the glass windows of the drier. The time required to reach each designated temperature was measured from the beginning of the drying cycle with a stop watch.

To check the accuracy of the temperature readings obtained by this method, several specimens were prepared in the usual manner, after which a thermocouple was embedded in the wood surface in the area of the temperature measurements. The temperature rise curve obtained from thermocouple readings, during the drying cycle, was similar to that obtained by use of the wax indicators. However, the levels of the two curves were not identical, for one regularly fell either above or below the other. The variability appeared to be due to variation in the depth to which the thermocouple was embedded, and it appeared that the indicating waX method of surface temperature measurement was the more consistent of the two.

• "Tempilstiks," made by Tempi! Corp., 132 W. 22nd St., New York, N.Y.

STUDY OF SHRINKAGE AND DRYING STRESSES

Since the initial examination of some of the dried specimens indicated the presence of drying defects that appeared to be attributable to stresses developed in drying, special tests were made on some specimens to determine the nature of the stresses present in the dry material. The specimens chosen for this study were similar to and closely matched with specimens used in the drying-rate tests. They were dried for periods determined from previous tests to be of the proper length to bring the final moisture content very close to the equilibrium condition. Drying temperatures used were again 150°, 250°, and 350° F. Only the low absolute humidity condition and an air velocity of 600 feet per minute were used. The specimens were 1/4- and 1/8-inch thick. Two specimens of yellow-poplar from log No. 2 and two of sweetgum were used for each combination of thickness and temperature.

After drying, these specimens were not placed in a drying oven, but were conditioned at a constant relative humidity of 30 percent and at a temperature of 80° F. for a period of 10 days, so that they attained a moisture content of 5 to 6 percent. Strips 1/2 inch in the dimension parallel to the grain were sawed from the middle part of each specimen. These were set on edge and split open through the middle with a knife. The amount of bowing occurring in the two halves was a measure of the residual stress in the wood. Portions of these specimens were also examined under the microscope.

THE STATISTICAL DESIGN

Tests made in the drying of yellow-poplar specimens were set up for analysis according to the factorial design, as described by Cochran and Cox (4). This design was considered particularly appropriate in this case because the study included a large number of factors, all varying simultaneously. The method provides the advantage that each treatment or interaction effect is measured by the results gained from all combinations of factors. The analysis tests the main effects of varying each of the factors, the effects of the interactions of the various factors, and the linearity of the effects for those factors that are represented in more than two levels.

In the drying-rate tests, specimens from each of the yellow-poplar logs were represented in all possible combinations of the following factors:

Thickness: 1/32, 1/16, 1/8, and 1/4 inch

Temperature:	150°, 250°, and 350° F.
Air velocity:	200, 600, and 1,000 feet per minute
Absolute humidity:	high and low.

In preparation for the analysis of variance (31) the effects of each factor at its several levels, and of each interaction, were separated. A table was prepared listing all combinations of factors. With the aid of the appropriate orthogonal coefficients (31) the gross and net sums of squares for each factor or interaction were obtained. For factors represented in three levels, the linear and the quadratic effects were obtained separately. First order interactions were included in the initial analysis, and, since most of the interactions of a higher level were found to be non-significant, they were generally included in the error term. The significance of each factor or interaction was determined by means of the F-test (31).

RESULTS

The Drying-rate Data

THE results of the drying-rate tests were obtained in the form of weights of specimens at various intervals during the drying cycle. The percentage moisture content of the wood at intervals during drying was calculated on the basis of the oven-dry weight of each specimen. A group of representative curves for yellow-poplar specimens, showing moisture content in percent during the drying cycle, is shown in Figure 1.

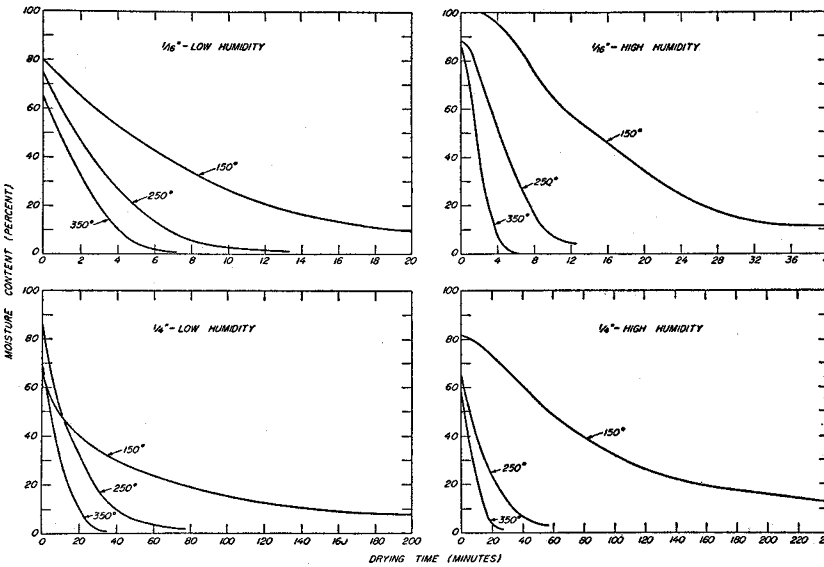

FIGURE 1. Representative drying curves (moisture content vs. time) for yellow-poplar heartwood specimens, 1/16- and 1/4-inch thick, from log No. 1, dried at an air velocity of 600 feet per minute and at indicated temperature and absolute humidity conditions.

In analyzing the drying data, it was found useful to deal with drying rates expressed in terms of weight of water evaporated per unit of time, rather than in terms of moisture content percentages. Because of the relatively small weights and short drying times involved, rates of evaporation were expressed in grams per minute and drying periods in minutes.

RESULTS

When analyzed graphically, it was found that the specimens could be classified into three general groups. In the first group, the rate-time relationship was curvilinear, as shown in A, Figure 2. This group was composed chiefly of the 1/4-inch specimens of all species, especially those dried at 150° and at 250° F. The 1/8-inch specimens of all species dried at 150° F. also tended to be slightly curvilinear, as did also the sweetgum 1/32- and 1/16-inch specimens dried at 150° F.

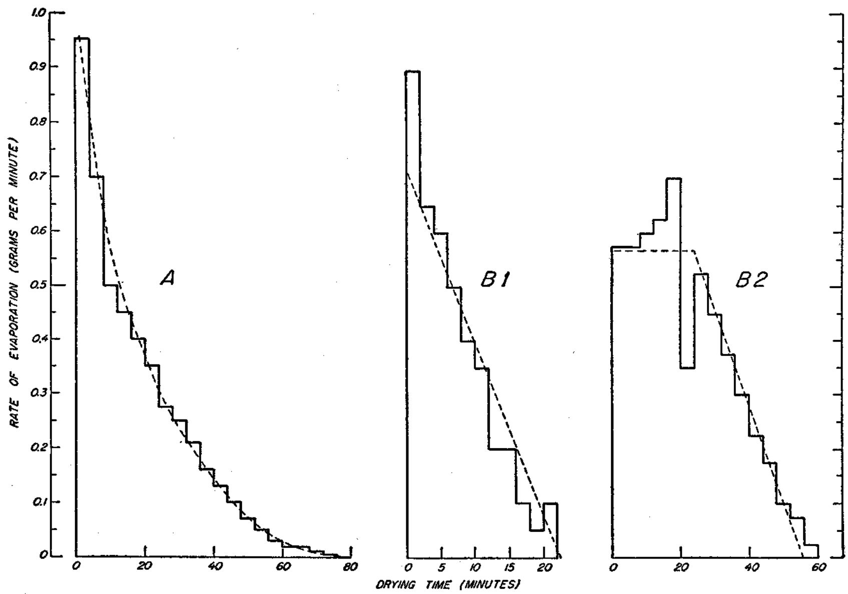

FIGURE 2. Types of drying-rate curves encountered when plotting drying rates against time. A: Yellow-poplar log No. 1, 1/4-inch thick, dried at 250° F., air velocity of 600 feet per minute, low absolute humidity; B1: Yellow-poplar log No. 1, 1/8-inch thick, dried at 350° F., velocity of 600 feet, high absolute humidity; B2: Yellow-poplar log No. 2, 1/8-inch thick, dried at 250° F., velocity 600 feet, high absolute humidity.

The second group was characterized by a more or less rectilinear rate-time relationship, as illustrated in B1, Figure 2. This pattern was common among the 1/32-, the 1/16-, and most of the 1/8-inch specimens. The 1/4-inch yellow-poplar specimens dried at 350° F. also tended to be of this type, whereas the 1/4-inch sweetgum and redwood specimens were definitely of type A.

The third type is represented by B2 in Figure 2, in which the latter part of the drying curve was similar to the rectilinear type of B1. During the early part of the drying of such specimens, the rate of evaporation generally rose but was somewhat irregular. It could sometimes be represented by a straight, horizontal line, resembling "constant rate" lumber drying conditions. This pattern of drying occurred chiefly in specimens from yellow-poplar log NO.2, dried at high absolute humidity. In yellow-poplar specimens other than those from log NO.2, dried at high humidity, the initial irregularity was most frequently perceptible in specimens dried at an air velocity of 200 feet per minute, and was generally not detectable at higher air velocities. The specimen represented by B2 in Figure 2 is one of the most extreme of those that differed from the B1 pattern. In most cases the discrepancy was not so great, and for this reason the initial irregularity was overlooked, and in the first analysis the specimens were grouped together with the other *1/32*-, 1/16-, and 1/8-inch specimens.

At the end of the drying cycle, usually when the specimen came within 1 to 2 percent of the equilibrium moisture content, the drying rate was often greatly retarded.

In the subsequent analysis and discussion the drying data are examined first in the light of the commonly accepted diffusion theories to determine the applicability of diffusion formulas. For thin specimens that were found to depart from the trends predicted by the diffusion calculations, a method of dealing with drying rates on the basis of heat transfer theories is developed.

TEMPERATURE DATA, SHRINKAGE, AND STRESSES

Temperature data were obtained on a set of yellow-poplar specimens during drying over the range of conditions represented in the drying-rate tests, except that only one log and the low absolute humidity condition were included. The specimens were closely matched with corresponding specimens used for the drying-rate tests, so that direct comparisons of moisture contents and temperatures at specified times during the drying cycle could be made. The temperature data are graphically summarized in Figure 3.

Values for the shrinkage of specimens in thickness (radially) were found to be somewhat variable, depending on the thickness being measured. This

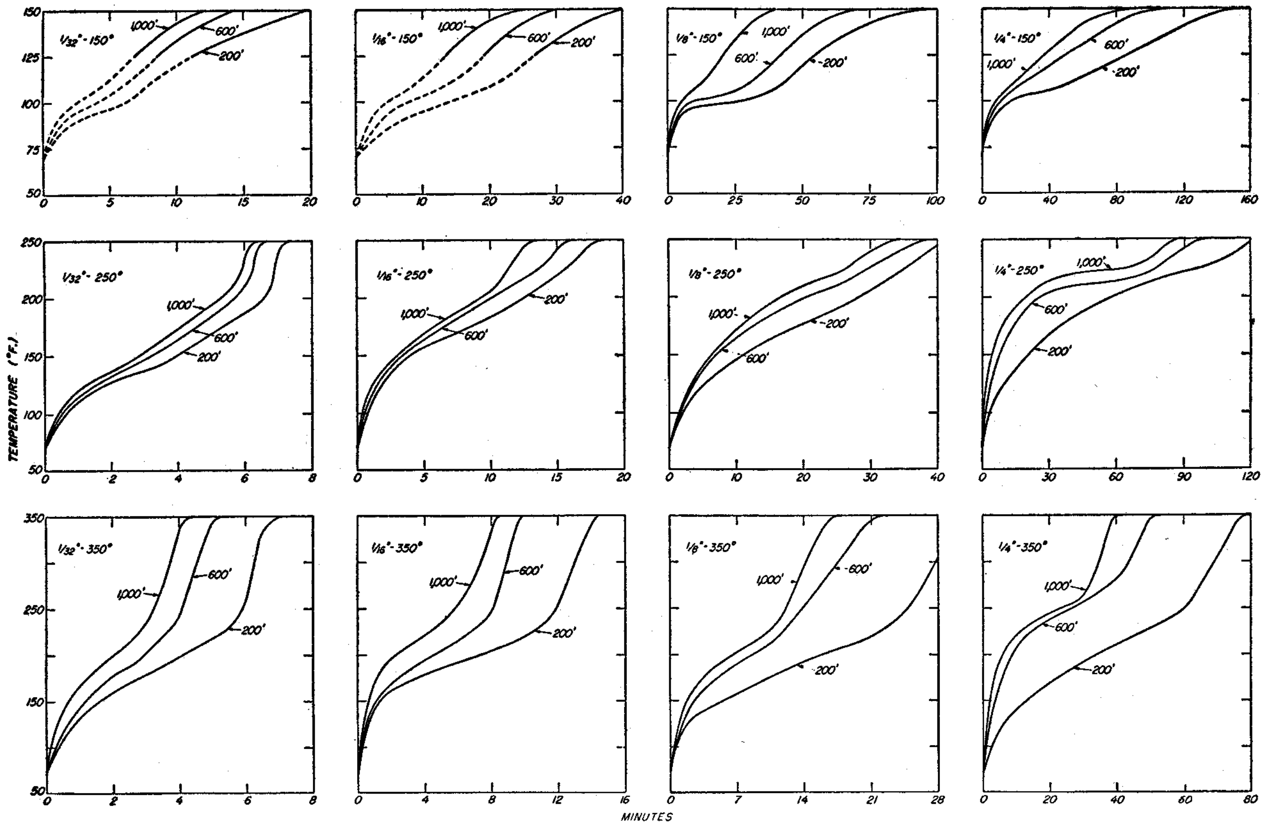

FIGURE 3. Temperatures during drying of yellow-poplar specimens of four thicknesses from log No. 2, dried at the low absolute humidity condition and at indicated temperatures and air velocities. Temperatures shown for 1/8- and 1/4-inch specimens are averages based on surface and interior measurements; those for thinner specimens are surface temperatures.

occurred because of insufficient refinement in the measurement of the thinnest specimens. On 1/32-inch specimens that had a green thickness of 0.032 inch, shrinkage in thickness was often less than 0.001 inch, which was the unit of measurement. Widthwise or tangential shrinkage, measurements of which appeared to be more reliable, was therefore used in the further analysis. The results of the widthwise shrinkage measurements are given in Table 1.

The results of the tests for residual stress in the dry pieces of yellow-poplar and sweetgum may be seen in Plates II and III, respectively.

TABLE I. TANGENTIAL SHRINKAGE OF YELLOW-POPLAR SPECIMENS UNDER VARIOUS DRYING CONDITIONS

Drying conditions			Tangential shrinkage[1]							
			Specimens from log No. 1				Specimens from log No. 2			
Absolute humidity	Temperature	Air velocity	1/32-inch thick	1/16-inch thick	1/8-inch thick	1/4-inch thick	1/32-inch thick	1/16-inch thick	1/8-inch thick	1/4-inch thick
	°F.	Ft. per min.	Percent	Percent	Percent	Percent	Percent	Percent	Percent	Percent
Low	150	200	6.64	7.31	6.64	8.97	6.62	7.64	7.67	6.33
	150	600	7.64	6.31	5.98	7.64	7.64	7.00	7.67	6.98
	150	1,000	6.00	5.98	6.98	6.98	7.33	7.64	7.62	6.33
	250	200	7.64	7.31	6.64	7.64	6.31	5.65	7.00	6.31
	250	600	7.64	5.98	5.65	4.32	7.64	5.65	6.98	5.33
	250	1,000	6.31	6.31	5.00	5.65	6.00	6.33	6.64	5.00
	350	200	6.31	7.31	6.31	5.65	6.31	7.00	6.00	5.98
	350	600	6.31	5.65	4.65	3.65	6.31	5.98	5.98	5.65
	350	1,000	7.31	4.65	5.65	4.65	6.64	6.33	6.67	5.33
High	150	200	6.64	5.67	8.31	4.67	6.29	7.33	8.33	7.33
	150	600	7.31	5.33	6.98	6.67	6.67	7.95	8.33	7.33
	150	1,000	5.32	6.00	7.00	7.67	5.67	6.31	8.33	6.67
	250	200	6.31	6.31	7.14	5.15	7.67	6.67	7.67	6.62
	250	600	8.31	6.98	4.98	4.32	6.67	6.67	7.67	6.00
	250	1,000	5.98	4.98	5.32	5.65	7.28	6.62	7.33	5.67
	350	200	6.31	5.32	4.33	4.32	8.64	5.67	6.67	6.00
	350	600	6.64	5.65	4.32	3.32	6.00	6.00	6.67	5.63
	350	1,000	6.98	5.32	3.99	3.65	8.00	6.00	6.67	5.00

[1] Shrinkage in percent is based on green width. Dry dimensions were taken after oven drying the specimens.

ANALYSIS AND DISCUSSION OF DIFFUSION PHENOMENA

THE APPLICATION OF CONVENTIONAL DRYING-RATE THEORIES

THE conventional concepts used in connection with the calculation of drying rates of lumber have already been discussed, and it has been shown that the so-called k-value, a constant representing the rate of diffusion of moisture through wood during the falling-rate portion of the drying cycle, may be used to obtain approximate drying curves throughout most of the cycle.

For purposes of checking the range over which a constant k-value will accurately apply in the drying of a lumber specimen, it is convenient to use a graphic method based on Newman's (*23*) relationship for the slab between E, the fraction of evaporable water remaining in the specimen at any given time θ, and $k\theta/a^2$, where k is the diffusion constant, and a is one-half the thickness of the drying specimen. The units of measurement are immaterial for purposes of this test.

Numerical values for the term E, which varies during the drying cycle, may be calculated from the relationship:

$$E=\frac{w-c_1}{c_0-c_1} \tag{1}$$

where w is the moisture content of the specimen at any time θ, c_1 is the equilibrium moisture content of wood under the drying conditions used, and c_0 is the original moisture content of the wood.

The plotting paper used in making the check is developed by laying off the abscissa scale in uniform units of $k\theta/a^2$, then plotting Newman's tabular values of E as the ordinate at such intervals that the tabular values corresponding to various values of $k\theta/a^2$ will plot as a straight line. The resulting plotting paper resembles semilogarithmic paper closely, except for a certain amount of distortion in the upper range of the E-scale.

When using the paper, it may be assumed that k remains constant during the drying of a specimen. Shrinkage is neglected and the thickness, 2a, is also considered constant. The values k and a therefore drop out of the equation and E may be plotted directly against θ.

For any portion of the resulting curve that plots as a straight line on the E-θ paper, a constant k-value may be calculated from the relationship between E and $k\theta/a^2$. When a straight line is not formed throughout any portion of the drying cycle, the k-value is not constant and a single value cannot adequately represent any portion of the drying curve. Some curves representing the drying of 1/4-inch specimens from yellow-poplar log No.2, dried at 600 feet per minute and at low absolute humidity, are shown in Figure 4.

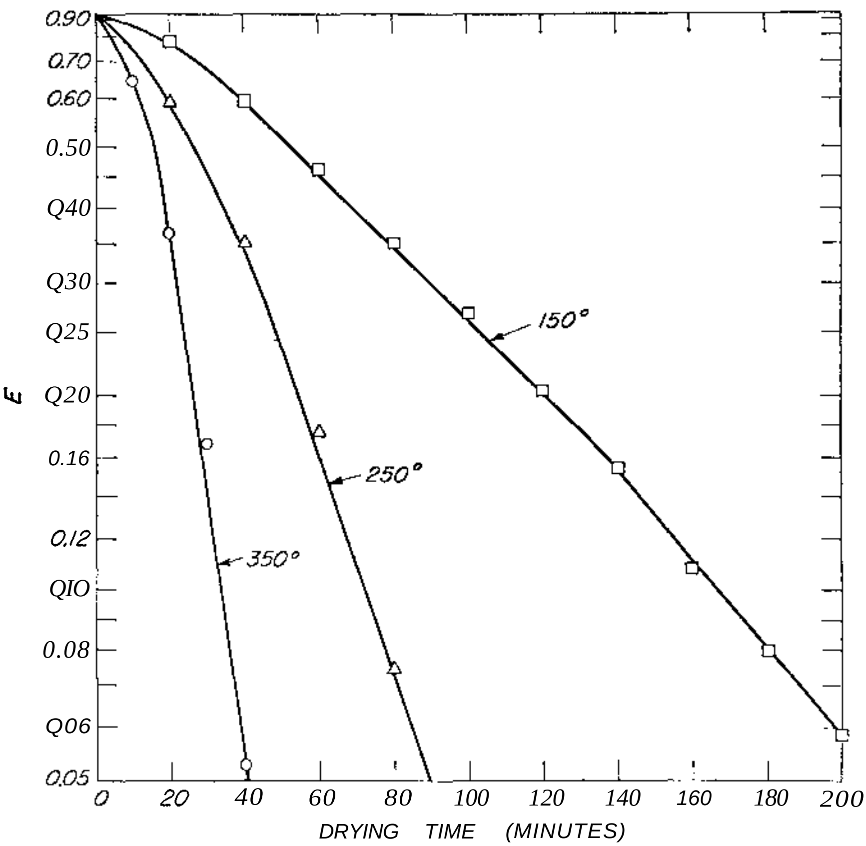

FIGURE 4. Typical curves on E-θ paper for 1/4-inch specimens. Specimens were from yellow-poplar log No.2, and were dried at low absolute humidity, 600 feet per minute air velocity, and at indicated temperatures.

Data representing the 1/4-inch specimens typically plotted as straight lines over a large part of the drying cycle. In the early part of the drying period they curved, convex upward, approaching an E-value of I at zero time. Such an initial curvature is usually encountered and may represent the constant rate period or a period of initial adjustment. The diffusion constant is usually calculated for and applies only to the straight-line portion of the curve. Yellow-poplar specimens dried at 350° F. sometimes could equally well be represented by curves, convex upward, throughout the drying period. Those dried at 150° F. often could be represented best by two straight lines, and the break between the two often occurred approximately at a moisture content of 30 percent. This would indicate a change in the diffusion coefficient approximately at the fiber-saturation point of the wood.

Data for the thinner specimens typically plotted as curves, convex upward, on the special E-θ paper. Curves for a group of 1/I6-inch yellow-poplar specimens, dried under conditions identical with those used in drying the 1/4-inch specimens plotted in Figure 4, are shown in Figure 5. The constantly changing E-θ relationship indicates either that the diffusion coefficient is constantly changing or that diffusion is not a controlling factor in the drying of these specimens. Of those specimens 1/16- and 1/8-inch thick, the least curvature and the nearest approach to a straight line on E-θ paper occurred with the sweetgum specimens dried at 150° F. Curves for the thin redwood specimens dried at 150° F. were intermediate between those of the sweetgum specimens and those of the yellow-poplar specimens.

The tendency for thin wood specimens to depart from the typically straight E-θ relationship during the falling-rate periods of drying is reported by Ogura (25). He dried small specimens of beech, approximately 1/I6-inch thick, at a temperature of 122° F. and at various relative humidities from 15 to 80 percent, in still air. He reported that the diffusion factor, k, constantly changed during the drying of some specimens. He found that this tendency was greatest at the highest relative humidities, whereas at a relative humidity of 15 percent a constant k-value applied. Plots on E-θ paper of his data for high-humidity drying showed curves that resembled closely those shown in Figure 5. Ogura's tests on thicker material (lumber) resulted in curves similar to those shown in Figure 4.

If the curvilinear E-θ relationship is characteristic of thin wood sections, it may be assumed that it might also be observable, perhaps in more extreme fashion, in the air drying of paper. Higgins (12) presents data on the rate

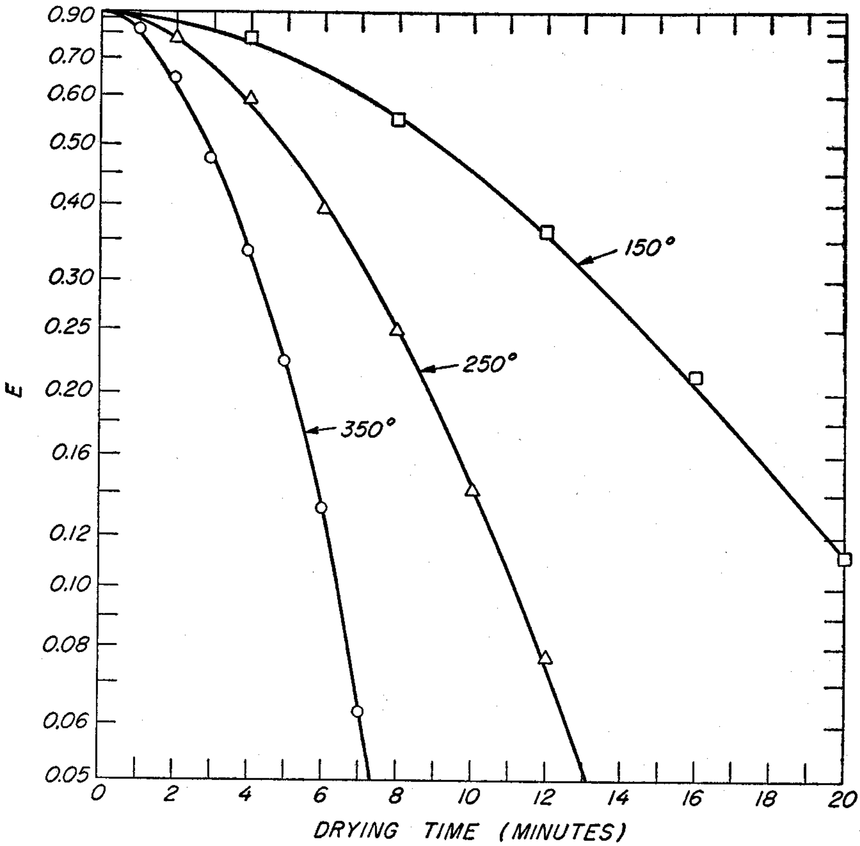

FIGURE 5. Typical curves on E-θ paper for specimens thinner than 1/4 inch. Specimens shown were 1/16-inch thick, from yellow-poplar log No. 2, and were dried at low absolute humidity, 600 feet per minute air velocity, and at indicated temperatures.

of drying of paper 0.010-inch thick in air, at a temperature of 110° F., with a wet bulb temperature of 92° F. and an air velocity of 310 feet per minute. When plotted in terms of rate of drying against moisture content, his data indicated a constant rate period followed by a second period in which the drying rate fell in a pronounced curve, convex upward. Such a curve denotes a similar type of curve on E-θ paper (Figure 5).

Figure 6 shows the plot of a hypothetical specimen whose drying rate falls in a perfectly straight line when plotted over time on conventional plotting paper, as illustrated by the dotted line, B1, Figure 2. On the special paper the drying of this hypothetical specimen was represented by a curve, A, that appeared to be a parabola except where the E-scale deviated from the conventional logarithmic scale in its upper range. Curves shown in Figure 5 for thin specimens were similar to this parabolic curve. A specimen that dried throughout its range in accordance with diffusion calculations would be represented by a straight line, B, in Figure 6.

It appears, therefore, that the rectilinear E-θ relationship that forms the basis for the usual method of computing drying rates by use of diffusion equations frequently does not hold for wood specimens approximately 1/8-inch thick or thinner. A division strictly on the basis of thickness is apparently not justified, however, for the temperature and species factors also appear to have an effect. At 150° F. the rectilinear relationship held fairly well for the 1/8-inch thickness and even for thinner specimens of sweetgum; whereas at 350° F. a curvilinear relationship was indicated even on 1/4-inch specimens.

It may be expected that all degrees of curvature between the two shown in Figure 6 may occur in the borderline zone between the two typical curves. However, even a moderate degree of curvilinearity in the E-θ relationship makes it impossible to use a single diffusion constant in predicting drying rates, for it will result in a progressively greater error as the line is extrapolated beyond the relatively narrow range where it might be considered to fit. The usual diffusion equations should therefore not be used in calculating drying rates for wood sections 1/8-inch thick and thinner.

The Calculation of k-values for 1/4-inch Specimens

Numerical values of k, the diffusion coefficient, were calculated for the 1/4-inch specimens of the three species tested. As a first step in the calculation, a value of E was determined on the basis of the remaining evaporable moisture in the specimen after it had reached a fairly low moisture content approximately equal to the fiber-saturation point. This low range of moisture content was used in order that the temperature of the specimen might be fairly close to the temperature of the drying atmosphere (Figure 3).

In applying formula (1), the moisture, w, remaining in the specimen at any time, was chosen as a value 10 percent higher than the equilibrium

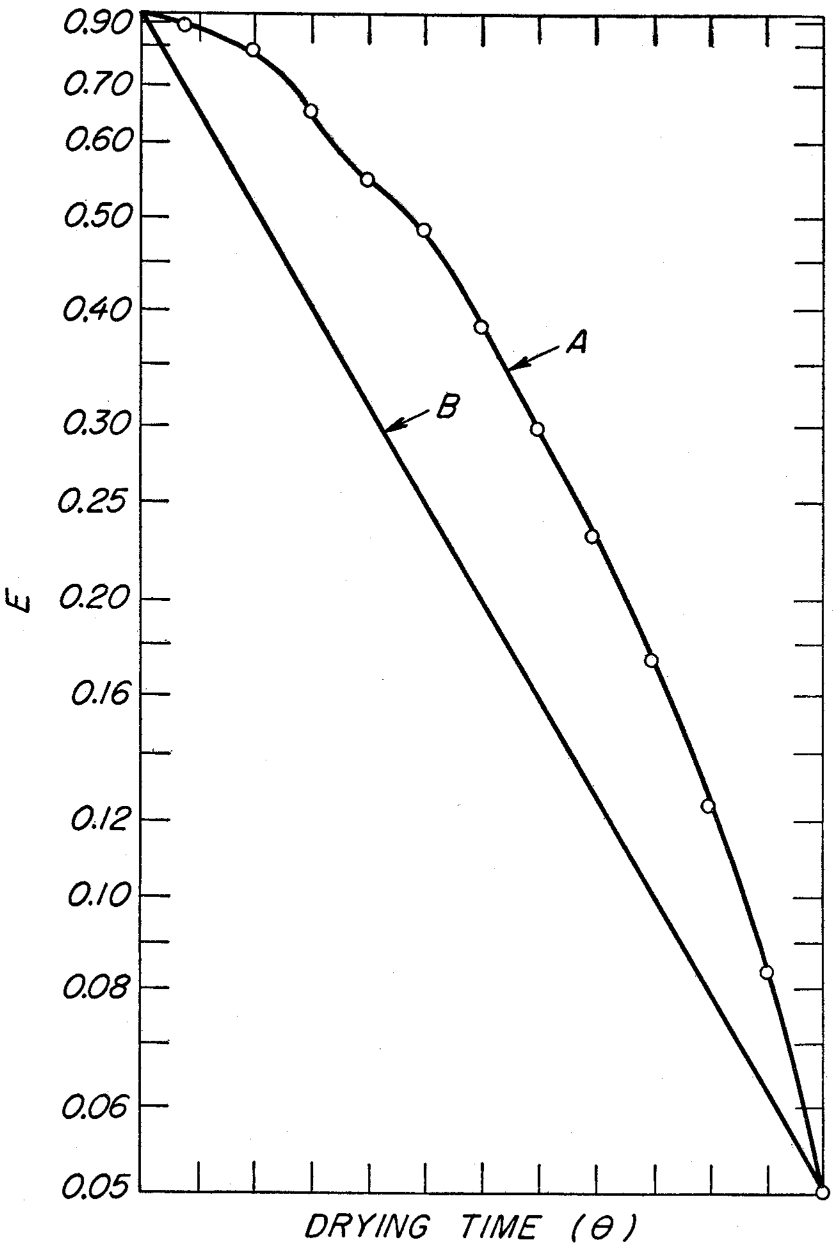

FIGURE 6. Plots of hypothetical drying specimens on E-θ paper. A: A specimen whose drying rate fell in a straight line when plotted against time on conventional coordinates; B: A specimen that dried with a constant k-value throughout the drying cycle.

moisture content under the drying conditions used, represented by c_1. A value of c_0, the moisture content at the start of the period under consideration, was chosen as 20 percent higher than the value of w. For specimens dried at high temperature and low absolute humidity, where $c_1 = 0$, w would therefore be 10 percent and c_0 would be 30 percent. Therefore,

$$E = \frac{10-0}{30-0} = 0.333$$

and from Newman's tables (*23*):

$$k\theta/a^2 = 0.355$$

To solve for k, values must be inserted for θ, the time to dry from 30 to 10 percent moisture content, in hours, and for a, one-half the thickness in inches.

For a 1/4-inch specimen having a value of θ of 16 minutes,

$$\frac{k\ (16/60)}{(0.125)^2} = 0.355$$

$$k = \frac{0.355 \cdot 0.015625}{0.266} = 0.0208$$

These calculations apply to a slab of infinite width and length. When dealing with slabs of moderate size, having end surfaces sealed to prevent evaporation, the results may be adjusted to fit the width-thickness ratio of the specimen on the basis of an equivalent squares calculation. For specimens 1/4 x 3 inches in cross section, the appropriate calculation indicates that a reduction of the above k-value, in the ratio of 64:64.44 is required. For the example given here, therefore,

$$k = 0.0208\ \frac{64}{64.44} = 0.02064$$

The k-values obtained in this fashion for yellow-poplar, based on moisture content in percent, thickness in inches, and time in hours, are given in Table 2. Those for sweetgum and redwood are given in Table 3.

TABLE 2. K-VALUES FOR 1/4-INCH YELLOW-POPLAR HEARTWOOD SPECIMENS UNDER VARIOUS DRYING CONDITIONS

Drying conditions		*k-values for log No. 1*		*k-values for log No. 2*		
Temperature	*Air velocity*	*Low absolute humidity*	*High absolute humidity*	*Low absolute humidity*	*High absolute humidity*	*Average k-value*
°*F.*	*Ft. per min.*					
150	200	0.0031	0.0046	0.0034	0.0018	0.0032
150	600	.0041	.0045	.0023	.0025	.0033
150	1,000	.0041	.0049	.0034	.0028	.0038
250	200	.0085	.0135	.0073	.0075	.0092
250	600	.0174	.0178	.0132	.0100	.0146
250	1,000	.0174	.0174	.0157	.0122	.0157
350	200	.0206	.0348	.0236	.0275	.0266
350	600	.0348	.0389	.0300	.0448	.0371
350	1,000	.0413	.0446	.0413	.0300	.0393

TABLE 3. K-VALUES FOR SWEETGUM AND REDWOOD HEARTWOOD SPECIMENS, 1/4-INCH THICK, DRIED AT AN AIR VELOCITY OF 600 FEET PER MINUTE AND AT LOW HUMIDITY

Drying temperature	*k-values*	
	Sweetgum	*Redwood*
°*F.*		
150	0.0011	0.0010
250	.0075	.0107
350	.0300	.0330

THE SIGNIFICANCE OF FACTORS AFFECTING THE K-VALUES

A statistical analysis of k-values for the 1/4-inch yellow-poplar specimens was made to establish the significance of the temperature effect, varying in three levels, the air velocity effect in three levels, and the absolute humidity effect in two levels. Possible significant differences between the two logs were also examined. The results of the analysis of variance are given in Table 4.

TABLE 4. ANALYSIS OF VARIANCE OF K-VALUES FOR 1/4-INCH YELLOW-POPLAR SPECIMENS

Main effects and first order interactions

Source	*Component parts*[2]	*Degrees of freedom*	*F*	*Significance*[1]
Total	——	35	——	——
Temperature	T_1	1	457.59	V. S.
	T_2	1	21.02	"
Air velocity	V_1	1	20.69	"
	V_2	1	2.71	N. S.
Absolute humidity	H_1	1	1.80	"
Logs	L_1	1	6.19	S.
Temperature X velocity	$T_1 V_1$	1	11.70	V. S.
	$T_1 V_2$	1	1.98	N. S.
	$T_2 V_1$	1	0	"
	$T_2 V_2$	1	0	"
Temperature X humidity	$T_1 H_1$	1	2.69	"
	$T_2 H_1$	1	1.12	"
Velocity X humidity	$V_1 H_1$	1	3.98	"
	$V_2 H_1$	1	.51	"
Logs X temperature	$L_1 T_1$	1	.26	"
	$L_1 T_2$	1	.70	"
Logs X velocity	$L_1 V_1$	1	.36	"
	$L_1 V_2$	1	.09	"
Logs X humidity	$L_1 H_1$	1	2.13	"
Error[3]	——	16	——	——

[1] Establishment of significance is based on 1 degree of freedom for the effect and 16 for error. Significance at the 5 percent level requires an F ratio of 4.49; and at the 1 percent level of 8.53. V. S. = significant at the 1 percent level; S. = significant at the 5 percent level; N. S. = not significant at the 5 percent level.

[2] Each factor at the first level (e.g.: T_1) yields the significance of the linear effect; at the second level (e.g.: T_2) it yields the significance of the quadratic effect.

[3] Interactions other than first order interactions were included in the error term. The value of the error mean square was 0.0000125.

The F-test (*31*) applied to the sums of the k-values for the two logs showed a high significance for the temperature effect on the linear as well as the quadratic level. The relation between k-values and temperature therefore is a curvilinear one when plotted on arithmetic coordinates. The fact that diffusion rates vary significantly with temperature has already been pointed out in a discussion of the literature on the subject. However, no reference was found to tests that covered so wide a range of temperature as is represented in this study. From a study of drying lumber at temperatures up to 230° F., Egner (*7*) concluded that there was no discontinuity in the drying behavior of wood when the boiling point of water was passed.

This indicates that when k-values are plotted against temperature, smooth curves may be drawn to connect values obtained above and below the boiling temperature. Trial plots made in several different ways indicated that k-values plotted against drying temperatures approached a straight line on logarithmic cross-section paper (Figures 7 and 8).

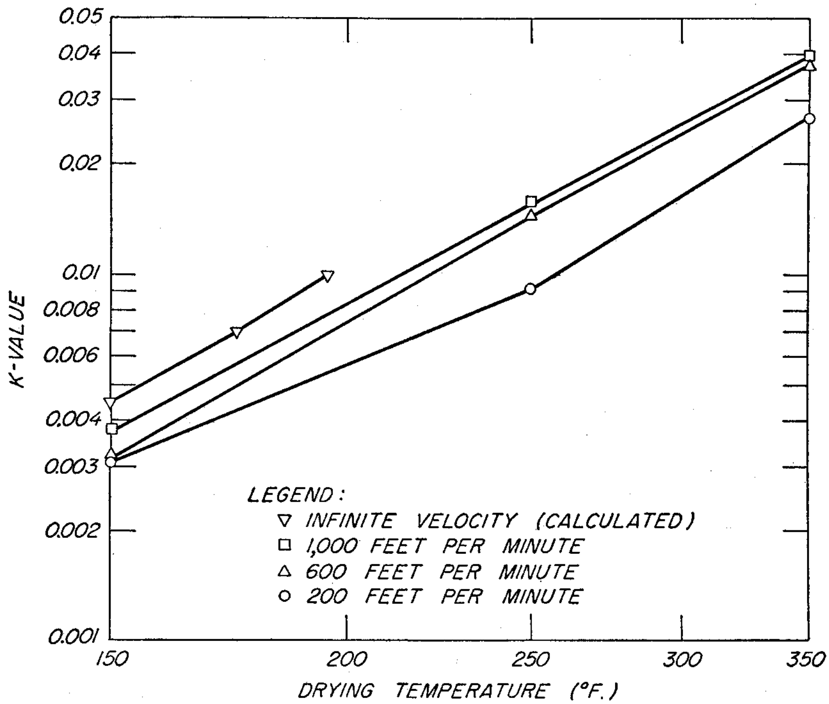

FIGURE 7. Average k-values for 1/4-inch yellow-poplar heartwood, showing variation due to drying temperature and air velocity, compared with k-values calculated from capillary structure considerations for wood having a specific gravity of 0.4, drying at infinite air velocity.

The air velocity factor was found to have a highly significant linear effect on the experimentally determined k-values. Since the quadratic effect was not significant, it appeared that the effect of velocity on k-values within the range used in these tests might be adequately represented as a straight-line relationship. Newman (*23*) and other investigators have shown that

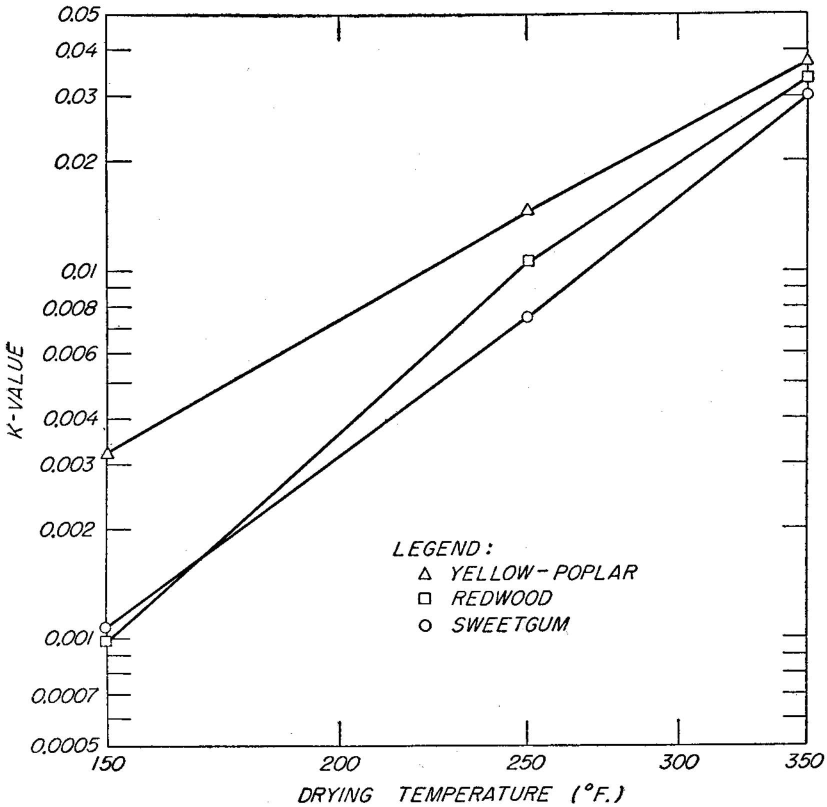

FIGURE 8. Experimentally determined k-values for three species dried at an air velocity of 600 feet per minute.

the effect of air velocity on drying is a surface effect only, and that diffusion coefficients are properly determined only at high air velocities where surface emissivity no longer affects the drying rates. The k-values determined in these tests therefore are somewhat below the true values, except perhaps for those determined at the highest velocity used.

The analysis further indicated that humidity had no significant effect on k-values, nor were there any significant interaction effects between the various factors, except for the significant temperature-air velocity interaction at the linear level. This indicated a changing effect of air velocity as the drying temperature varied.

The F-test applied to differences between k-values obtained for the two yellow-poplar logs showed a significant effect. The reason for this probably is that the specific gravity of one log was 0.32 to 0.37, while that of the other log was 0.43 to 0.45. Average diffusion rates for wood of both logs would therefore apply to yellow-poplar wood having an average specific gravity of about 0.40. As a result of this analysis, it appeared that the k-values obtained for the two logs at the two humidity levels could be combined into a single average value. Such averages are shown in the last column of Table 2 and have been plotted in Figure 7.

Figure 7, in its lower temperature range, also shows k-values calculated for an infinite air velocity from the capillary structure data of Stamm (32) for a wood having a specific gravity of 0.40. The experimentally determined values at an air velocity of 1,000 feet per minute are slightly lower than the theoretical values. For a true comparison, the empirical data should be adjusted to the true average temperature of the wood during the period for which the k-values were determined. The empirical k-values for a drying temperature of 150^{0} F. are really based on an average wood temperature of about 1400 F. or less (d. Figure 3), and the true empirical value for a wood temperature of 150^{0} F. and an air velocity of 1,000 feet per minute apparently lies only slightly below the point indicated by capillary structure considerations for an infinite air velocity.

In Figure 8 the k-values obtained for sweetgum and redwood are compared with those of yellow-poplar. All specimens represented in this graph were dried under an air velocity of 600 feet per minute. The very limited number of tests included here indicates that the diffusion coefficient for redwood is considerably lower than that for yellow-poplar, and that for sweetgum is lower than the other two. The differences between the species appear to become less pronounced as the drying temperature increases.

DRYING RATES OF THIN SPECIMENS

Consideration of Temperature Data

SINCE the drying tests indicated that diffusion calculations could not be used in the analysis of drying rates of thin specimens up to 1/8-inch thick, the attempt was made to develop an alternate method of dealing with these thicknesses. The temperature data shown in Figure 3 were examined with this in mind.

For purposes of clarity in presentation and for later use in calculations, the surface and interior temperature readings obtained in yellow-poplar specimens 1/8-inch and 1/4-inch thick are not shown separately in summary Figure 3. The figure presents only average temperatures for each specimen, calculated on the assumption that the heat distribution, at any moment, would be parabolic through the thickness of the piece, with the highest temperature at the surface and the lowest temperature at the middle plane.

It has been proposed that the temperature of the wood during drying would remain at the wet-bulb temperature of the drying atmosphere during most of the drying cycle (*17*). There is no evidence of such constancy of temperature in the curves shown in Figure 3. These curves differ in this respect from those obtained by Keylwerth (*16*), who measured temperatures at the midplane of veneer 2 millimeters thick, during drying at temperatures above 212° F. Rates of air circulation over the specimen are not given, but apparently were relatively low. He found that the temperature rose rapidly to the wet-bulb temperature of the drying air, then remained there unchanged throughout much of the cycle, until the moisture content of the specimen had dropped to 5 percent or less, then rose rapidly to the dry-bulb temperature.

The data obtained in the current study on rates of evaporation indicated a continually decreasing rate during the drying cycle, instead of a constant rate during any part of the cycle. Under these conditions it would not be likely that wood temperatures would remain constant. Only if there were a prolonged period of evaporation at a constant rate, such as prevails when water evaporates freely from the wick surrounding the wet bulb of a thermometer, would the temperature be likely to remain at a constant, wet-bulb level.

Figure 9 gives more detail about the temperature distribution in the 1/8- and 1/4-inch specimens from log No. 2, dried at temperatures of 150°, 250°, and 350° F., at low humidity, and with an air velocity of 600

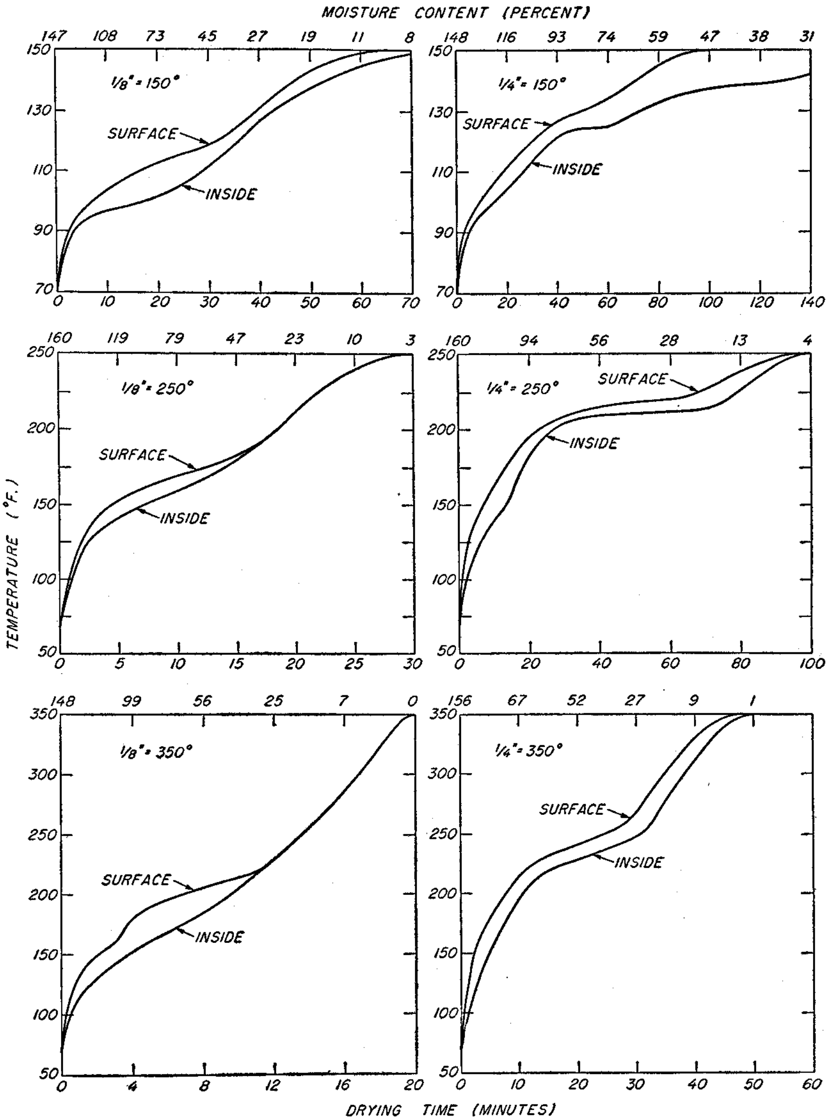

FIGURE 9. Surface and interior temperatures of drying specimens, and average moisture contents during drying. Specimens were 1/8- and 1/4-inch thick, from yellow-poplar log No. 2, and were dried at low absolute humidity, 600 feet per minute air velocity, and at the indicated temperatures.

feet per minute. Data obtained at other air velocities were similar to those presented here.

In the 1/4-inch specimens a definite temperature gradient was apparent throughout the drying cycle. The curves typically rose rapidly, then tended to flatten out usually in the vicinity of the wet-bulb temperature of 99° F. when the drying temperature was 150° F., or of 212° F. when the drying temperature was 250° and 350° F., then rose rapidly again to the temperature of the drying medium. They generally did not remain constant at the wet-bulb temperature for any appreciable period.

In the 1/8-inch specimens dried at 150° F., the temperature rise was similar to that occurring in 1/4-inch wood. For the 250° and 350° F. drying temperatures, however, a measurable temperature gradient occurred only at the start, approximately before the surface reached the wet-bulb temperature of 212° F. Beyond that point the surface and interior temperatures were not measurably different. This effect at temperatures above 212° F. occurs because the vapor pressures developed are well above atmospheric pressure, apparently causing an equalization of vapor pressure as well as of temperature through the cross section. Under these conditions the moisture gradient would be negligible and moisture would be evaporated as fast as heat could be supplied to vaporize it and as fast as it could be carried away from the surface.

The temperature differences observed here correspond to the two types of drying behavior observed earlier (Figure 2). Where the data indicated the existence of a temperature gradient throughout the drying cycle, a relatively constant diffusion coefficient was indicated. In those 1/8-inch specimens in which no temperature gradient was apparent during the latter part of the drying, and apparently also for most of the thinner specimens, a constant diffusion coefficient did not exist.

The correlation of moisture content with temperature is also shown in Figure 9, where average moisture contents at various temperature stages are indicated on the upper scale. Since the moisture content determinations were not made on the same specimens as those used for the temperature tests, but on closely matched specimens, the correlation can only be considered an approximation. When drying 1/8-inch specimens at 250° and 350° F., an average moisture content of 30 percent appeared to be attained at about the time that the surface and interior temperatures had merged to form a single curve and had begun to rise appreciably above the wet-bulb temperature. In 1/4-inch specimens and in 1/8-inch specimens dried at 150° F.

a moisture content of 30 percent generally corresponded roughly to the point on the two curves where the retardation in the neighborhood of the wet-bulb temperature had been overcome, and the curves had begun to rise more rapidly again.

The attainment of an average moisture content of 30 percent indicates that free water evaporation has ceased to occur not only at the surface but within the interior also. This condition is thought by Sherwood (29) to occur at some point within the first falling-rate period. On thin specimens dried at high temperatures, however, the absence of a temperature and presumably of a moisture content gradient is an indication that diffusion does not assume a controlling role in drying, but that the rate at which heat is supplied controls the rate at which water is evaporated even after low moisture contents are reached.

THE HEAT TRANSFER CONCEPT IN DRYING

A mathematical approach to drying rates, based on heat transfer, has not been overlooked by investigators. Sherwood (29) calculated drying rates in the constant rate period by equating the rate of vapor diffusion from the surface of the drying material to the air stream against the rate of heat transfer to the drying material. The equation was developed for steady state temperature conditions where the surface temperature is assumed to remain constant at the wet-bulb temperature.

In this connection, Sherwood (29) calculated an over-all coefficient of heat transfer from the air to the solid in drying whiting paste slabs. He found that its value remained constant during the constant rate period and during the early part of the falling-rate period, or as long as evaporation occurred at the solid surface. During the latter part of the falling-rate period, when evaporation was assumed to be occurring at points within the interior of the drying body, the heat transfer coefficient dropped off rapidly in a straight line when plotted over moisture content in percent.

In Germany recent developments in drying wood in superheated steam have stimulated consideration of the theoretical aspects of drying wood at temperatures above 212° F. Recognizing the importance of heat transfer at these high temperatures, Kiefer (17) used a relationship similar to that which Sherwood applied to drying at lower temperatures to the constant rate period. Kiefer's formula equates the rate of heat transfer to the rate of vaporization from the drying surface. In setting up this relationship, Kiefer assumes that the surface temperature of the drying specimen rapidly comes to a wet-bulb temperature of 212° F. and remains there during the greatest part of the drying cycle. If this situation actually prevails, then steady-state heat transfer conditions may exist, and the calculation either of heat transfer or of moisture diffusion, following conventional formulae, may be valid.

In thin specimens, in which the temperature of the drying wood is not constant through the greatest part of the drying cycle, the heat flow process is referred to as heat conduction in the unsteady state (*22*). This type of heat flow can generally be determined only empirically, since data are lacking regarding many of the factors that may enter into the computations.

In the heating of an extremely thin slab of material, where the temperature is substantially uniform throughout the thickness, the simplest case of unsteady heat conduction applies (*22*). At any time θ from the start of the heating, the quantity of heat dQ transferred in time $d\theta$ depends on the surface area of the slab, A, the difference in temperature between the air, t′, and that of the slab, t, and a factor h, the surface coefficient of heat transfer:

$$dQ/d\Theta = h\ A\ (t' - t) \qquad (2)$$

In applying equation (2), let it be assumed that a thin specimen of oven-dry wood being at temperature t were to be heated to a specified temperature t′, equal to that of the heating medium. A plot of the heating rate, $dQ/d\theta$, over time, θ, would then result in a parabolic curve similar to A in Figure 10. The area under the curve, representing the total amount of heat transferred, would be proportional to the specific heat of the dry wood. A second specimen may now be assumed, being in the wet condition and being heated, hypothetically, in such a way as to permit no water to escape from it. Studies by J. D. MacLean (*18*) indicate that the surface resistance to heat transmission between wood and air is lower under moist conditions than under dry conditions. A higher surface coefficient of heat transfer therefore exists for the wet specimen that also has a higher over-all density and specific heat. Consequently, a heat transfer curve similar to B, Figure 10, would result. The area under curve B would be larger than that under A in proportion to the heat capacity of the water contained in the second specimen.

In drying any wood specimen, the hypothetical conditions postulated above for either A or B do not prevail. The specimen enters the drying cycle with a high moisture content and consequently with a high value

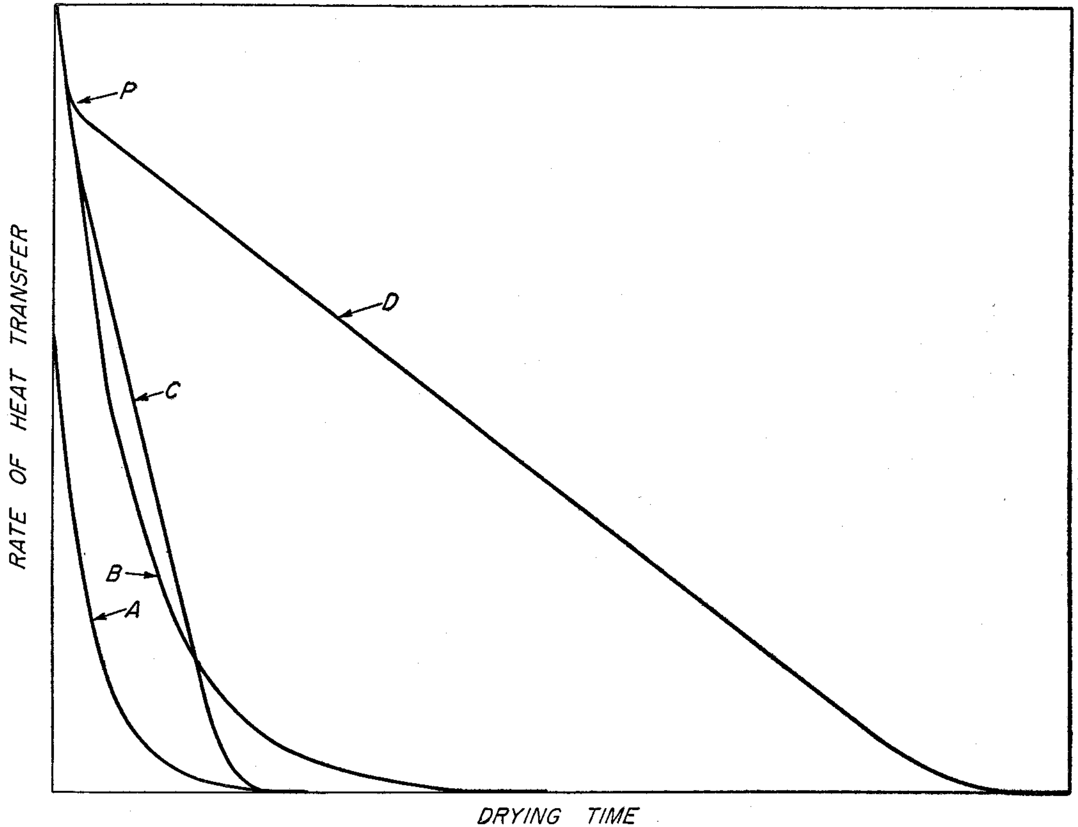

FIGURE 10. Hypothetical heat transfer curves for (A) a dry specimen, (B) a wet specimen being heated without evaporation of water, (C) a wet specimen affected by evaporation, and (D) a drying specimen.

of h. As it dries, the value of h drops until, when the specimen is dry, the h-value is that of specimen A. The resulting heat transfer curve must therefore be a hybrid of A and B.

During the drying, however, other changes also occur. In the lower ranges of moisture content, the specimen begins to shrink, with the result that the surface area available for heat transfer becomes smaller. By far the most important factor, however, is the evaporation of water throughout the operation, which draws off large quantities of heat and tends to keep the wood surface cooler than it would normally be without evaporation. The temperature difference $(t' - t)$ during the early part of the heating is kept at a higher level than it would be if evaporation were not going on, so that the heat transfer rate would actually drop more slowly during the first part of the cycle than the rate represented by curve B. Such a condition is represented by curve C, Figure ro. The illustration shows that the heat transfer conditions peculiar to a specimen from which evaporation may go on freely during heating would cause the typically parabolic heat transfer curve to approach a straight line in shape. If, on the other hand, evaporation were retarded because of a limited rate of diffusion of moisture to the surface, then the temperature of the specimen would rise at a faster rate, the temperature difference $(t' - t)$ would decrease, and the straight line would again tend to drop closer to the parabolic shape indicated by B.

Curve C (Figure ro) does not, however, represent the final curve applying to a drying specimen. Because of the large quantity of heat consumed in vaporizing water, as compared to that required merely to raise the temperature of the specimen, the area under hypothetical curve C must be many times the area shown. Curve C must therefore be swung out on the time scale so as to cover a much larger area. Pivoting curve C about a point at which evaporation begins (P), the surface temperature of the specimen having surpassed the saturation temperature of the drying atmosphere, a heat transfer curve, D, is obtained for a drying specimen, under conditions where diffusion is not the governing factor. The heat transfer data to be presented in the next two sections will serve to confirm this graphic derivation of the curve representing heat transfer during drying.

METHOD OF CALCULATING HEAT TRANSFER TO THE TEST SPECIMENS

Heat transferred to a drying specimen may be used in several ways: (a) to heat the wood substance, (b) to heat the water in the wood, (c) to vaporize water, and (d) to supply the energy necessary to overcome the greater attractive force of wood for water than of water for itself, below the fiber-saturation point. The last of these is equivalent to the "heat of swelling" of wood in water (33).

The calculation of heat transferred during any given period of drying becomes merely a summation of the calories of heat consumed in the various ways outlined above, divided by the length of the period in some suitable units of time, in this case, minutes. To relate the heat transfer to a unit of surface area, the value must also be divided by the square feet of surface area of the green specimen. In this case the end surfaces were included in calculating the total surface area of the specimen. Even though the ends were coated to prevent evaporation, heat transfer was still possible. In an analogous case, Sherwood (29) found that when a part of a wetted surface was covered with a thin impervious membrane, so as to decrease the wetted surface, but offering negligible resistance to the transfer of heat, the rate of evaporation was not decreased in proportion to the wetted surface area exposed.

Since the specific heat of water within the temperature range used is approximately 1, the calories of heat required for heating the water during any given period are equal to the average moisture content during the period, in grams, times the temperature change during the period in degrees C.

For heating the wood, the calories consumed for any given period are equal to the oven-dry weight of the wood, times the temperature change in degrees C., times the specific heat of the wood at the average temperature during the period. The specific heat, H, is calculated from the formula (5) :

$$H=0.266+0.00116\,t$$

where t is the temperature of the wood in degrees C.

The heat of swelling needs to be taken into consideration only at moisture contents below the fiber-saturation point of wood. The calories required for any period are equal to the total grams of water evaporated during the period times the heat of swelling at the average moisture content during the period. Values for the heat of swelling have been determined by Stamm and Loughborough (33).

For any given period during the drying of a specimen, the average heat transfer, in calories per minute per square foot of surface area, may be determined from the formula:

$$H_m = \frac{\left[\left(\frac{M_1+M_2}{2}\right)(T_1-T_2)\right]+\left[DH_a(T_1-T_2)\right]+V(M_1-M_2)+S_a(M_1-M_2)}{\theta A}$$

where:

H_m = Heat transfer per minute per square foot of surface area, calories.
M_1 = Moisture content of specimen at start of the period, grams.
M_2 = Moisture content of specimen at end of the period, grams.
T_1 = Temperature of the specimen at the start of the period, °C.
T_2 = Temperature of the specimen at the end of the period, °C.
D = Oven-dry weight of the specimen, grams.
H_a = Specific heat of the wood at the average temperature during the period.
V = Heat of vaporization of water at the average temperature during the period (*13*).
S_a = Heat of swelling at the average moisture content during the period.
θ = Length of period used in calculations, minutes.
A = Surface area of the specimen, square feet.

Characteristic Heat Transfer Curves

By use of this equation, the heat transfer was calculated for each of the yellow-poplar specimens for which temperature data were available. Curves obtained for the 1/8- and 1/4-inch thicknesses are reproduced in Figure 11. The curves in this case are not on the basis of 1 square foot of surface area, but represent total values for the respective specimens. The 1/16- and 1/32-inch curves are not shown since they were similar to the curves for the 1/8-inch thickness. In most cases the curves for specimens of these thicknesses could be approximated fairly well by straight lines. This straight-line relationship also held for most of the thin specimens dried at a temperature of 150° F., even though many of these specimens may have resembled the 1/4-inch specimens with respect to the temperature gradient. In general, most of the 1/4-inch specimens assumed a curve throughout, unlike the straight lines obtained for the thinner specimens. It is assumed that this curvature results from the effect of diffusion that retards the drying of the thicker specimens. The curvature was least pronounced at the highest temperature used.

Figure 12 shows one of the heat transfer curves in greater detail, this one representing data obtained on the 1/8-inch specimen from log No. 2, dried

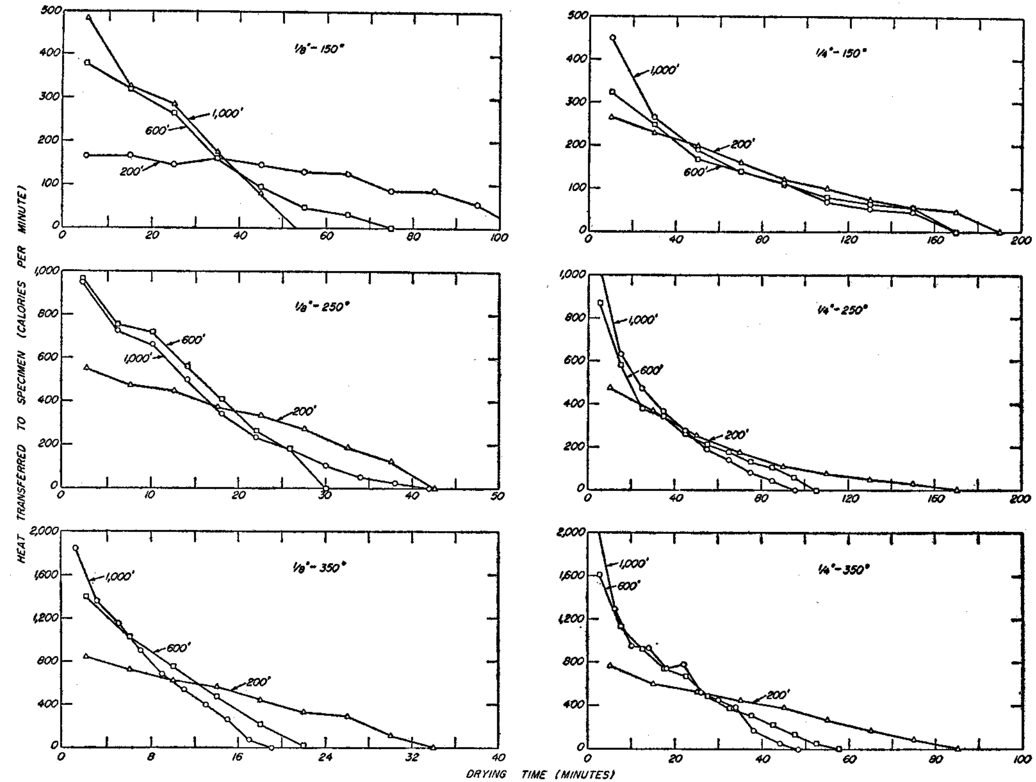

FIGURE 11. Typical curves showing heat transfer rates plotted against time during drying. Specimens were from yellow-poplar log No. 2, and were dried at low absolute humidity. Thicknesses, drying temperatures, and air velocities are indicated.

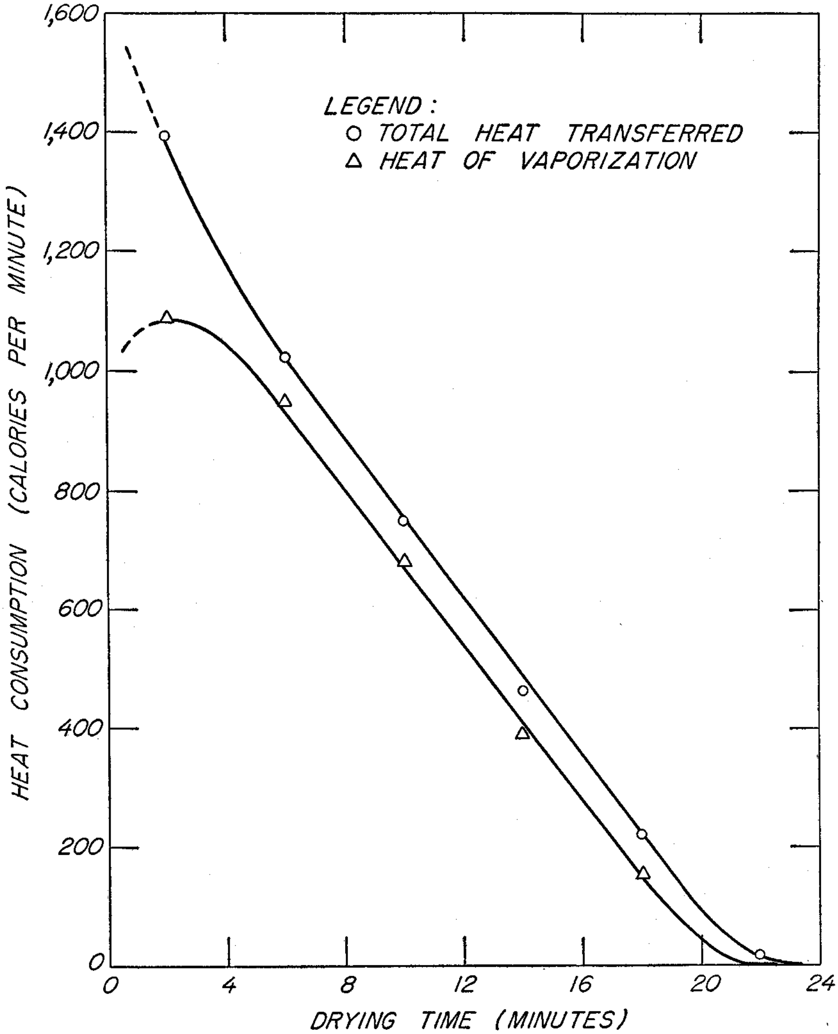

FIGURE 12. Curves showing total heat transfer and heat consumed in evaporating water during the drying of a 1/8-inch yellow-poplar specimen from log No. 2, at an air velocity of 600 feet per minute, low absolute humidity, and a temperature of 350° F.

at 350° F., low humidity, with an air velocity of 600 feet per minute. The resemblance to curve D, Figure 10, is unmistakable. Below the heat transfer curve is another curve representing only the heat consumed in vaporizing water. The quantity of heat consumed in vaporizing water (including the heat of swelling) is represented by the area below this curve, while the quantity of heat consumed in heating the specimen together with the water in it is represented by the area between the two curves.

Figure 13 shows a different form of the data shown in Figure 12, this time in terms of the surface coefficient of heat transfer, plotted on a logarithmic scale, against the moisture content of the specimen during drying,

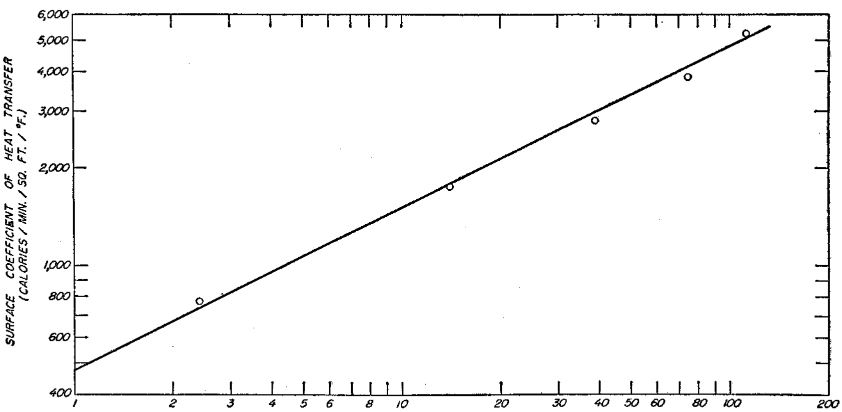

FIGURE 13. The relation between the surface coefficient of heat transfer and moisture content during drying, for the same specimen shown in Figure 12.

also on a logarithmic scale. In this graph the drying progresses from right to left, unlike the plots in other related curves shown in the report. Again the data fell approximately in a straight line when plotted in this fashion.

The formula for the line shown in Figure 13 is of the type:

$$y = a\, x^b,$$

where y is the surface coefficient of heat transfer and x is the moisture content of the specimen during drying. This represents the straight-line relationship when values both of y and of x form a geometric series (*27*). The slope of the line, b, is approximately 0.5, so that the equation becomes:

$$y = a\ x^{\frac{1}{2}}$$

or

$$y^2 = a^2\ x,$$

which is the equation of a parabola. The value a is determined by the intercept of the line with the y axis and, in this case, equals 475. The equation for this line therefore is:

$$y^2 = 475^2\ x,$$

or

$$y = 475\ \sqrt{x}$$

For the drying conditions represented here, it appears therefore that the rate of heat transfer and consequently also the drying rate decrease geometrically in proportion to the decrease in moisture content of the drying specimen. The relationship between rate of heat transfer and moisture content appears to be a parabolic one; between rate of heat transfer and time, as shown in Figure 12, it is a straight line.

Sherwood's (*29*) experience in drying a slab of whiting paste has already been mentioned. He found that during the latter part of the falling-rate period, when diffusion was assumed to control the drying, the coefficient of heat transfer decreased in a straight line when plotted against moisture content in percent. Sherwood ascribed this to the increasing resistance to heat flow that developed as the plane of evaporation withdrew into the interior of the drying material. Sherwood's straight line relationship between heat transfer and moisture content, as compared to the parabolic relationship indicated in Figure 13, is merely another manifestation of the characteristic difference between the drying of thick material, with diffusion controlling, and the drying of thin material where diffusion is of no importance.

Mathematical Treatment of the Test Data

Figure 12 shows that by far the largest proportion of the heat transferred to a drying specimen was used in evaporating water. At the start of the period, most of the heat was used to bring the specimen to the saturation temperature of the drying atmosphere, for evaporation cannot begin until this temperature is attained. After reaching this point, the rate of evaporation soon attained its highest level. From here on the curves representing the two rates dropped approximately as straight lines with time, until the specimen was almost completely dry and was near the temperature of the drying medium.

For purposes of estimating drying rates, the slope of the heat-of-vaporization curve may be considered identical with that of the curve representing the rate of evaporation. A rough conversion from heat of vaporization (in calories) to grams of water evaporated may be made by dividing the former by 539, the number of calories required to evaporate 1 gram of water.

From this relationship between total heat transfer, heat of vaporization, and water evaporated, it follows that the constantly changing drying rate, in weight per unit of time, should also plot as a straight line over time (Figure 2, B1). For specimens 1/32-, 1/16-, and 1/8-inch thick plots were made of drying rates in terms of grams evaporated per minute, over time in minutes. Excluding the two extremes, the slope of the straight line became a measure of the speed of drying of the specimen.

In Figure 14 this constantly changing drying rate is represented by the line s. This line has been extrapolated so as to intercept the vertical and the horizontal axes at points R_o and θ_e. Once the slope of the line s has been determined for any specimen, the remaining moisture to be dried at any time θ within the straight-line portion may be determined by integration, for it is equal to the area below line s, between θ and θ_e.

For given values of R and θ,

$$R = R_o - s\Theta$$

When $R = 0$, and the specimen has reached the equilibrium condition,

$$\Theta_e = R_o/s$$

Therefore, the water remaining above the equilibrium moisture content at any time θ, termed w, is derived by integrating the area under s from θ to R_o/s:

$$w = \int_{\Theta}^{R_o/s} R \, d\Theta$$

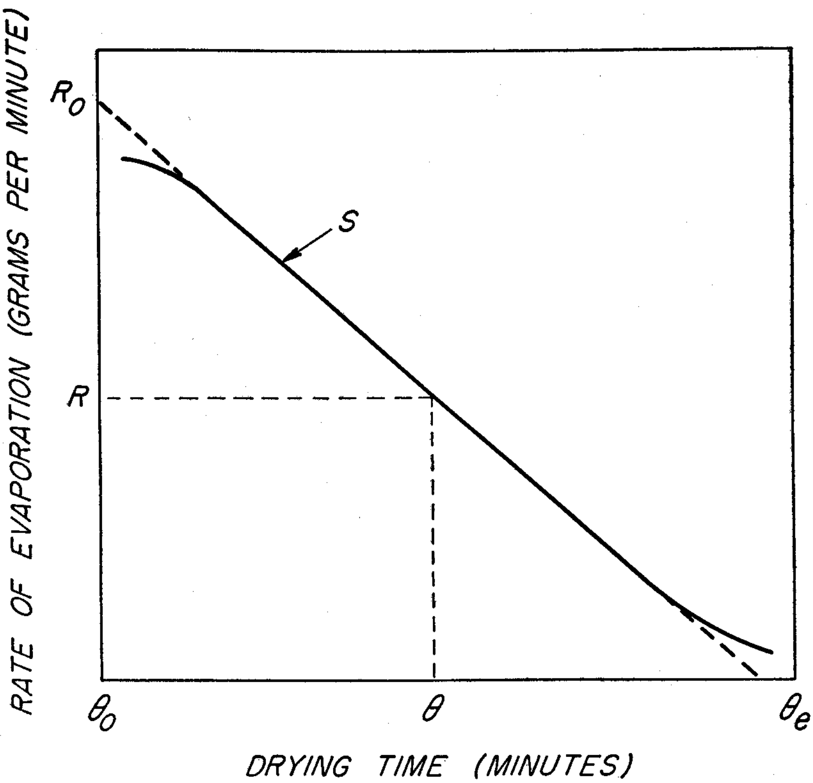

FIGURE 14. Plot of "s," representing a constantly changing rate of evaporation during drying, over drying time.

$$w = \int_{\Theta}^{R_o/s} (-s\Theta + R_o)\, d\Theta$$

$$w = \left[-\frac{s\Theta^2}{2} + R_o\Theta \right]_{\Theta}^{R_o/s}$$

$$w = -\frac{R_o^2}{2s} + \frac{R_o^2}{s} + \frac{s\Theta^2}{2} - R_o\,\Theta$$

$$w = \frac{R_o^2}{2s} + \frac{s\Theta^2}{2} - R_o\Theta$$

The area under s from θ_o to θ_e represents the total amount of water to be evaporated in drying, and may be termed w_e. Then

$$w_e = \frac{R_o\ (R_o/s)}{2}$$

$$w_e = \frac{R_o^2}{2s} \tag{3}$$

Therefore

$$w = w_e + \frac{s\Theta^2}{2} - R_o\Theta \tag{4}$$

To determine the total amount of water remaining in the specimen at any time, it is necessary to include w_d, the water remaining after the specimen has been dried to equilibrium with the drying conditions. Therefore, the initial total water content of the specimen, W_t, equals the water to be removed plus that below the equilibrium condition:

$$W_t = w_e + w_d$$

The water content at time θ, termed W, is obtained by adding w_d to both sides of equation (4) to obtain:

$$W = W_t + \frac{s\Theta^2}{2} - R_o\Theta \tag{5}$$

From equation (3) above,

$$R_o = \sqrt{2\ s\ w_e}$$

This relationship may be used to eliminate R_o from equation (5), thus making the calculation of moisture content dependent on the single constant factor s:

$$W = W_t + \frac{s\Theta^2}{2} - \Theta\sqrt{2\ s\ w_e} \tag{6}$$

The value of W obtained in this way represents the weight of water present at any time θ. To obtain moisture content in percent, termed M. C., it is necessary to divide by the oven-dry weight of the wood divided by 100:

$$\text{M. C.} = \frac{W_t + \frac{s\Theta^2}{2} - \Theta\sqrt{2\,s\,w_e}}{(\text{o.d.}/100)} \tag{7}$$

Equations (6) and (7) are comparable to the simple expression:

$$Y = A - B\,X + C\,X^2$$

in which $Y = W$ or M. C. and $X = \theta$. It represents a parabola when Y is plotted against X (*27*). Such plots of empirical data are shown in Figure 1 for 1/16-inch yellow-poplar specimens.

Determining S-values from the Experimental Data

The slope of the line, s, may be readily approximated for most specimens by fitting a line to the test data plotted in a form similar to B1, Figure 2. In this case the position of the line should be adjusted by trial and error until the area beneath it, $R_0\theta_e/2$ (see Figure 14), is equal to the weight of water evaporated in drying to the equilibrium condition. For most purposes it is desirable to locate the line so as to get the most favorable fit in the lower portion of the line, since this will result in the greatest accuracy in the lower ranges of moisture contents, to which the wood is usually to be dried.

For purposes of this study it was decided to calculate the slope s mechanically rather than to fit it by trial and error, thus eliminating the need for human judgment. Since the experimentally determined values of R (Figure 14) tended to depart from the straight line and become asymptotic to the horizontal axis, it was necessary to calculate a value of θ_e, making the line fall so as to fit the data at some higher level of moisture content. A moisture content of 30 percent was arbitrarily chosen as the point to which the line was to be fitted. In cases where the drying curve flattened out at a point somewhat higher than the predicted equilibrium moisture content, the experimentally determined level was used as the equilibrium condition in the calculations. For this lowest level of moisture content, usually within

1 or 2 percent of the equilibrium condition, but never more than 5 percent above it, the fitted moisture content curve no longer held. With the above restrictions, the values for W and θ in equations (5) and (6) became W_{30} and θ_{30}.

From Figure 14 it may be shown that $s = R_o/\theta_e$ and that $R_o = 2\ w_e/\theta_e$. Substituting these values in equation (5):

$$W_{30} = W_t - \frac{2\ w_e\ \Theta_{30}}{\Theta_e} + \left(\frac{2\ w_e}{\Theta_e}\right)\left(\frac{\Theta_{30}{}^2}{2}\right)$$

$$0 = (W_t - W_{30}) - \frac{2\ w_e\ \Theta_{30}}{\Theta_e} + \frac{w_e\ \Theta_{30}{}^2}{\Theta_e{}^2}$$

In the solution of this quadratic equation, two values of θ_e were obtained, of which the larger value satisfied the restrictions set up above:

$$\Theta_e = \frac{2\ w_e\ \Theta_{30} + \sqrt{(2\ w_e\ \Theta_{30})^2 - 4\ (W_t - W_{30})\ (w_e\ \Theta_{30}{}^2)}}{2\ (W_t - W_{30})} \qquad (8)$$

As an example of the solution of this equation, data for the 1/8-inch yellow-poplar specimen from log No. 2, dried at 350° F., at low humidity, with an air velocity of 600 feet per minute will be used. This specimen is referred to in Figures 12 and 13.

The test data were as follows:

Initial weight: 41.0 grams

Weight when specimen approached equilibrium: 16.5 grams

Oven-dry weight: 16.5 grams

Calculated weight at 30 percent: 21.45 grams

Drying time to reach 30 percent: 11.25 minutes

From these data, the values to be used in equation (8) were:

$W_t = 41.0 - 16.5 = 24.5$

$w_e = 41.0 - 16.5 = 24.5$

$W_{30} = 0.30 \times 16.5 = 4.95$

$\Theta_{30} = 11.25$

Substituting in equation (8):

$$\Theta_e = \frac{(2 \cdot 24.5 \cdot 11.25) + \sqrt{(2 \cdot 24.5 \cdot 11.25)^2 - 4(24.5 - 4.95)\ (24.5 \cdot 11.25^2)}}{2(24.5 - 4.95)}$$

$\Theta_e = 20.44$

Since $s = 2\ w_e/\Theta_e^2$,

$$s = \frac{2 \cdot 24.5}{20.44^2} = 0.1173$$

This value of s is based on a green surface area of 38.25 square inches. It is converted to a unit surface area basis of 1 square foot as follows:

$$S = 0.1173 \times \frac{144}{38.25} = 0.4415$$

The value S represents the slope of the constantly changing drying rate, in grams per minute per square foot of green surface area. S-values for all yellow-poplar specimens except those 1/4-inch thick are given in Table 5. Similar values for sweetgum and redwood are given in Table 6.

TABLE 5. S-VALUES REPRESENTING DRYING RATES OF YELLOW-POPLAR HEARTWOOD SPECIMENS UNDER VARIOUS DRYING CONDITIONS

Drying conditions			*S-values for log No. 1 specimens*			*S-values for log No. 2 specimens*		
Absolute humidity	*Temperature*	*Air Velocity*	*1/32-inch thick*	*1/16-inch thick*	*1/8-inch thick*	*1/32-inch thick*	*1/16-inch thick*	*1/8-inch thick*
	°F.	*Ft. per min.*						
Low	150	200	0.0790	0.0376	0.0228	0.0505	0.0262	0.0104
	150	600	.1571	.0878	.0260	.2234	.0996	.0437
	150	1,000	.2895	.1300	.0407	.3602	.1446	.0524
	250	200	.3684	.1485	.0763	.4230	.1603	.0702
	250	600	1.2211	.4199	.1925	1.0141	.3732	.1844
	250	1,000	2.6496	.6243	.1490	1.4003	.5318	.1640
	350	200	.8760	.5904	.1250	.6094	.3777	.1521
	350	600	3.0584	.7852	.4686	2.7998	1.0467	.4415
	350	1,000	5.8311	1.8832	.5348	4.0921	1.3878	.5930
High	150	200	.0144	.0137	.0077	.0059	.0036	.0017
	150	600	.0362	.0306	.0096	.0145	.0079	.0035
	150	1,000	.1010	.0283	.0154	.0111	.0060	.0049
	250	200	.5205	.2791	.1059	.0876	.0670	.0183
	250	600	.5186	.2690	.1585	.1622	.1018	.0472
	250	1,000	1.9085	.9018	.2581	.2937	.1540	.0784
	350	200	1.7855	.5890	.2861	.6567	.3296	.1509
	350	600	4.0036	1.2409	.5695	1.3439	.6239	.2867
	350	1,000	3.6247	2.6424	.6947	2.0228	.9439	.4087

TABLE 6. S-VALUES FOR SWEETGUM AND REDWOOD DRIED AT AN AIR VELOCITY OF 600 FEET PER MINUTE AND AT LOW ABSOLUTE HUMIDITY

Thickness of specimen	Drying temperature	S-values	
		Sweetgum	Redwood
In.	*of.*		
1/32	IS°	0.°712	0.1421
1/32	25°	.6292	1.2745
1/32	35°	2.3358	1.9881
1/16	15°	.°°78	.0614
1/16	25°	.2022	.264°
1/16	35°	.7170	1.6010
1/8	15°	.0014	.°°74
1/8	25°	.0502	.°927
1/8	35°	·3°10	.7208

These values may be substituted in equation (7) to calculate the parabolic curve of moisture content in percent against drying time. The fit of the curve for the specimen described above, having an s-value of 0.1173, is compared with the original drying data in Figure IS. The exactness with which the fitted curve conformed to the test data was not peculiar to this specimen, but was common to practically all specimens dried at 350° F. At lower temperatures, and particularly at 150° F., the fit was only slightly less exact. In every case the computed curve fitted the test data at the start of the drying cycle, and again when a moisture content of 30 percent was reached, since these points had been used in the computations. At other points a slight departure from the test data sometimes occurred. If for some reason it were desired to get a better fit in the lower ranges of moisture content, a lower moisture content level could be used to determine Wand () in equation (8).

STATISTICAL ANALYSIS OF S-VALUES FOR YELLOW-POPLAR

Preliminary examination of the S-values for yellow-poplar indicated that logarithmic relationships apparently existed between the values and the most important variable factors included in the study. For example, when plotting S-values over thickness, ,which varied geometrically, a straight-line relationship appeared to exist on logarithmic cross-section paper. Similarly, for the temperature effect, the linearity of the data was improved by

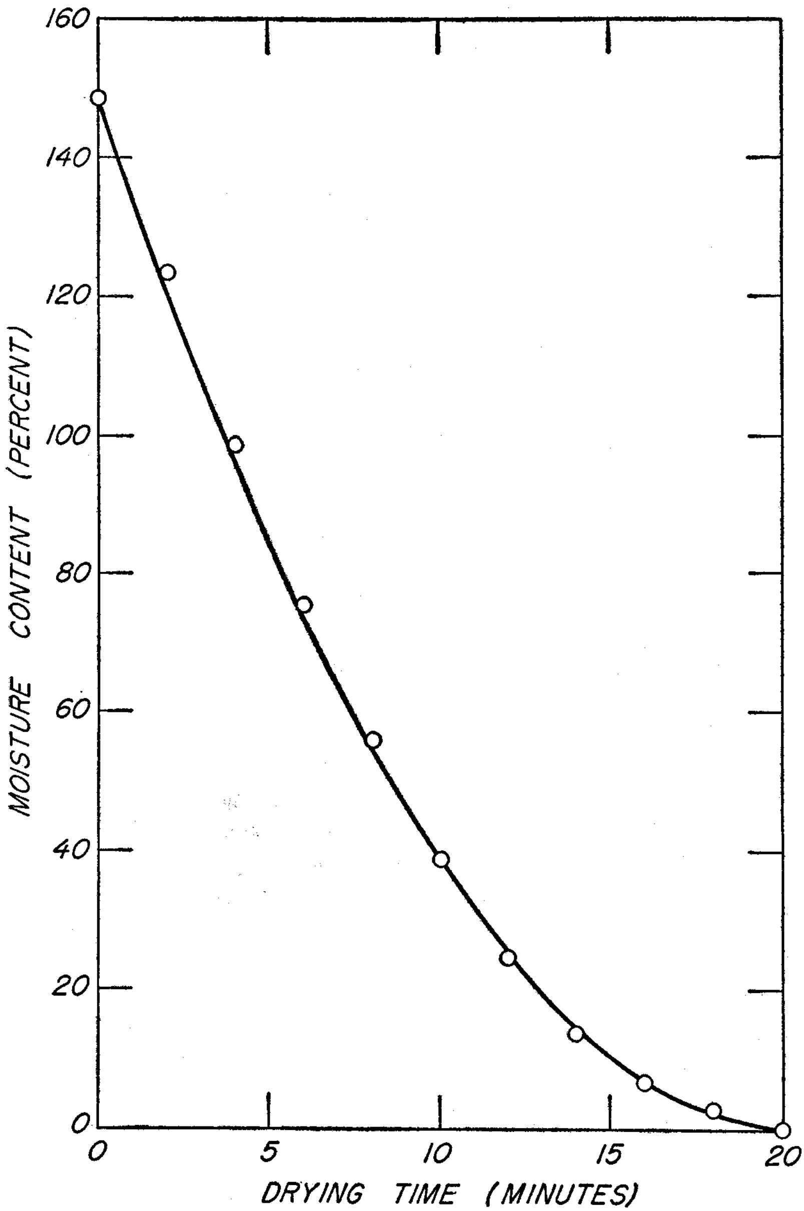

FIGURE 15. Comparison of a curve showing moisture content during drying, calculated from the s-value, with original test data, shown by points. The specimen was of yellow-poplar, 1/8-inch thick, from log No. 2, and was dried at low absolute humidity with an air velocity of 600 feet per minute and a temperature of 350° F.

plotting S-values on a logarithmic scale. For use in the statistical analysis the S-values were therefore first converted to logarithms.

The analysis of variance (31) is summarized in Table 7. The F-test showed that logarithmic values of S were very significantly affected on the linear level by thickness (varying geometrically) and absolute humidity. The temperature and air velocity effects were highly significant at the quadratic level, indicating curvilinear relationships. Specimens from the two yellow-poplar logs were very significantly different. Very significant interactions occurred between temperature and humidity, logs and humidity, thickness and velocity, thickness and humidity, and velocity and humidity. The significance of the first two of these interactions was many times greater than that of the other interactions. Significant interactions occurred between thickness and temperature, logs and velocity, and logs and temperature.

The great variety of significant interactions made the interpretation of the results very difficult. However, further examination of the S-values led to the conclusion that most of the interactions might be eliminated if the analysis were made to cover a narrower range of conditions. Specifically, two groups of data did not appear to be in harmony with the major part of the data: (a) those tests made on specimens from log No. 2 at high humidity, regardless of the dry-bulb temperature, and (b) those tests made at a temperature of 150° F. To determine whether the remaining data could be treated as a homogeneous group, two supplementary analyses were made to determine (a) the significance of differences in results obtained for the two logs, this time at low humidity only, and (b) the significance of the humidity effect in log No. 1 only, at temperatures of 250° and 350° F. These analyses are summarized in Tables 8 and 9. The analyses indicated that, within the limits fixed here, the main effects of logs and humidity were not significant. All interactions were nonsignificant, except for the interaction between thickness and velocity in Table 8, which was significant at the 5 percent level.

The supplementary analyses provided justification for developing an estimating equation for S-values, using all values obtained in tests at 250° and 350° F. for log No. 1, and those specimens from log NO.2 that were dried at these same temperatures, at low absolute humidity only. The significant independent variables in this case were temperature, thickness, and air velocity. The effect of each of the factors was linear when both

TABLE 7. ANALYSIS OF VARIANCE OF LOGARITHMS OF S-VALUES FOR YELLOW-POPLAR SPECIMENS 1/32-, 1/16-, AND 1/8-INCH THICK

Main eifects and first order interactions

Source	*Component parts*[2]	*Degrees oj jreedom*	*F*	*Significance*[1]
Total		1°7		
Thickness	DI	I	814.80	V. S.
	D2	I	1.39	N.S.
Velocity	VI	I	432.08	V. S.
	V2	I	16.80	"
Temperature	TI	1	3,492.86	
	T2	I	97.19	
Absolute humidity	HI	I	317.92	
Logs	LI	I	174·39	
Thickness X temperature	DI TI	I	5,47	S.
	D2 TI		.13	N.S.
	DI T2		.91	"
	D2 T2		°	
Thickness X velocity	DI VI		7.51	V. S.
	DI V2		·30	N. S.
	D2 VI		.41	
	D2 V2		.60	
Thickness X humidity	DI HI		11.94	V. S.
	D2 HI		·47	N.S.
Temperature X humidity	TI HI		248.73	V. S.
	T2 HI	I	9.89	
Temperature X velocity	TI VI	I	.67	N.S.
	TI V2	I	.°3	"
	T2 VI	1	.10	
	T2 V2	I	2·59	
Velocity X humidity	VI HI	I	8·59	V. S.
	V2 HI	I	5·50	S.
Logs X thickness	LI DI	I	2.66	N.S.
	LI D2	I	'°4	"
Logs X velocity	LI VI	I	.°4	
	LI V2	1	6.07	S.
Logs X temperature	LI TI	I	3·75	N.S.
	LI T2	1	5.30	S.
Logs X humidity	LI HI	I	136.24	V. S.
Error[3]		74		

[1] Establishment of significance is based on I degree of freedom for the effect and 74 for error. Significance at the 5 percent level requires an F-ratio of 3.97, and at the I percent level of 6.99. V. S. = significant at the I percent level; S. = significant at the 5 percent level; N. S. = not significant at the 5 percent level.

[2] Each factor at the first level (e.g., D,) yields the significance of the linear effect; at the second level (e.g., D.) it yields the significance of the quadratic effect.

[3] Interactions other than the first order interactions were included in the error term. The value of the error mean square was 0.01145.

TABLE 8. SUPPLEMENTARY ANALYSIS OF VARIANCE OF LOGARITHMS OF S-VALUES FOR LOGS NOS. 1 AND 2, AT LOW HUMIDITY ONLY

Source	*Degrees of freedom*	*F*	*Significance*[1]
Total	53	——	——
Thickness	2	340.01	V. S.
Temperature	2	638.22	"
Air velocity	2	200.54	"
Logs	1	1.56	N. S.
Thickness X temperature	4	1.06	"
Thickness X velocity	4	3.62	S.
Thickness X logs	2	.76	N. S.
Temperature X velocity	4	.78	"
Temperature X logs	2	.38	"
Velocity X logs	2	2.49	"
Error[2]	28	——	——

[1] Establishment of significance is based on 28 degrees of freedom for error. Significance at the 1 percent and 5 percent levels requires F ratios as follows: for 1 degree of freedom for effect, 7.64 and 4.20; for 2 degrees of freedom for effect, 5.45 and 3.34; for 4 degrees of freedom for effect, 4.07 and 2.71. V. S. = significant at the 1 percent level; S. = significant at the 5 percent level; N. S. = not significant at the 5 percent level.

[2] Interactions other than first order interactions were included in the error term. The value of the error mean square was 0.00863.

the effects and the S-values were expressed in logarithms. The estimating equation, therefore, was of the following type:

$$\log S = a + b\,(\log X) + c\,(\log Y) + d\,(\log Z)$$

where X, Y, and Z were temperature, air velocity, and thickness, respectively.

By applying the method of least squares to the S-values for specimens dried at 250° and 350° F., from log No. 1 (both low and high humidity) and from log No. 2 (low humidity only) the following equation was developed for estimating S-values of yellow-poplar for any given combination of factors within the range covered:

$$\log S = 2.984\,(\log T) + 0.784\,(\log V) - 1.344\,(\log D) - 11.336 \qquad (9)$$

TABLE 9. SUPPLEMENTARY ANALYSIS OF VARIANCE OF LOGARITHMS OF S-VALUES TO DETERMINE SIGNIFICANCE OF DIFFERENCES BETWEEN HIGH AND LOW HUMIDITY FOR SPECIMENS FROM LOG NO. 1 ONLY, DRIED AT TEMPERATURES OF 250° AND 350° F.

Source	*Degrees of freedom*	*F*	*Significance*[1]
Total	35	——	——
Thickness	2	146.05	V. S.
Temperature	1	134.30	"
Air velocity	2	64.46	"
Absolute humidity	1	3.35	N. S.
Temperature X velocity	2	.84	"
Temperature X thickness	2	.12	"
Temperature X humidity	1	1.81	"
Velocity X thickness	4	1.99	"
Velocity X humidity	2	3.36	"
Thickness X humidity	2	1.60	"
Error[2]	16	——	——

[1] Establishment of significance is based on 16 degrees of freedom for error. Significance at the 1 percent and 5 percent levels requires F ratios as follows: for 1 degree of freedom for effect, 8.53 and 4.49; for 2 degrees of freedom for effect, 6.23 and 3.63; for 4 degrees of freedom for effect, 4.77 and 3.01. V. S. = significant at the 1 percent level; S. = significant at the 5 percent level; N. S. = not significant at the 5 percent level.

[2] Interactions other than first order interactions were included in the error term. The value of the error mean square was 0.01390.

where T = temperature of the drying atmosphere, °F.;
V = air velocity parallel to the surface, feet per minute; and
D = thickness of the drying material, inches.

The Significance of Absolute Humidity and Its Interactions

In the first analysis (Table 7) the effect of absolute humidity on S-values was found to be very significant. The supplementary analysis, Table 9, however, showed that the humidity effect in specimens from log No. 1, dried at temperatures of 250° and 350° F., was not significant, nor were there any significant interactions.

It may be expected that the drying rate would be inversely related to atmospheric humidity when drying temperatures are below 212° F., because of the relatively limited capacity of a given atmospheric volume to hold additional moisture. At drying temperatures above 212° F., however, no such limitation exists, for water vapor in the form of superheated steam may exist in any proportion in the atmosphere.

Figure 16 illustrates the effect of humidity at the lowest temperature used in these tests, and indicates its diminishing effect as the temperature of the drying atmosphere approaches 212° F. Values plotted in Figure 16 are average values of S for log No. 1, irrespective of air velocity and thickness of specimen.

The S-values obtained for specimens from log No. 2, tested at high humidity, were all considerably lower than the corresponding values from log No. 1. They were also consistently lower than S-values obtained for either log No. 1 or log No. 2 at low humidity. This resulted in the very significant interaction between logs and humidity in Table 7. It brings to mind the earlier reference to specimens from log No. 2, dried at high humidity, to the effect that the drying rate curve followed a somewhat different pattern (Figure 2, B2) from the more general curve (Figure 2, B1). These specimens were characterized by a reluctance to reach a high level of evaporation in the early part of the cycle and a relatively long period of irregularity before the drying rate began to decrease in regular fashion.

Since log No. 2 specimens had a very high initial moisture content as compared to log No. 1 specimens, it appears that this factor may have had an important effect on the drying rate when combined with high humidity conditions. Specimens from log No. 2 initially contained two to three times as much water as those from log No. 1. Therefore, the gross specific heat of a specimen from log No. 2 was several times as great at the start of drying as that of a specimen from log No. 1. Because of the great difference in the amount of heat required to raise the temperature by an appreciable amount, the temperature rise at the start of the drying would be slower for specimens from log No. 2 than for those from log No. 1.

In order that evaporation may begin, it is necessary that the temperature of the wood be raised above the saturation temperature of the drying atmosphere. This critical temperature was only 88° F. at the low absolute humidity condition used in these tests, but at the high absolute humidity condition it was 135° F. for a drying temperature of 150° F., and 202° F. for the higher drying temperatures. Moreover, even after a portion of the specimen which first contacted the entering air stream had attained this temperature, the remainder of the specimen might still be at a lower tem-

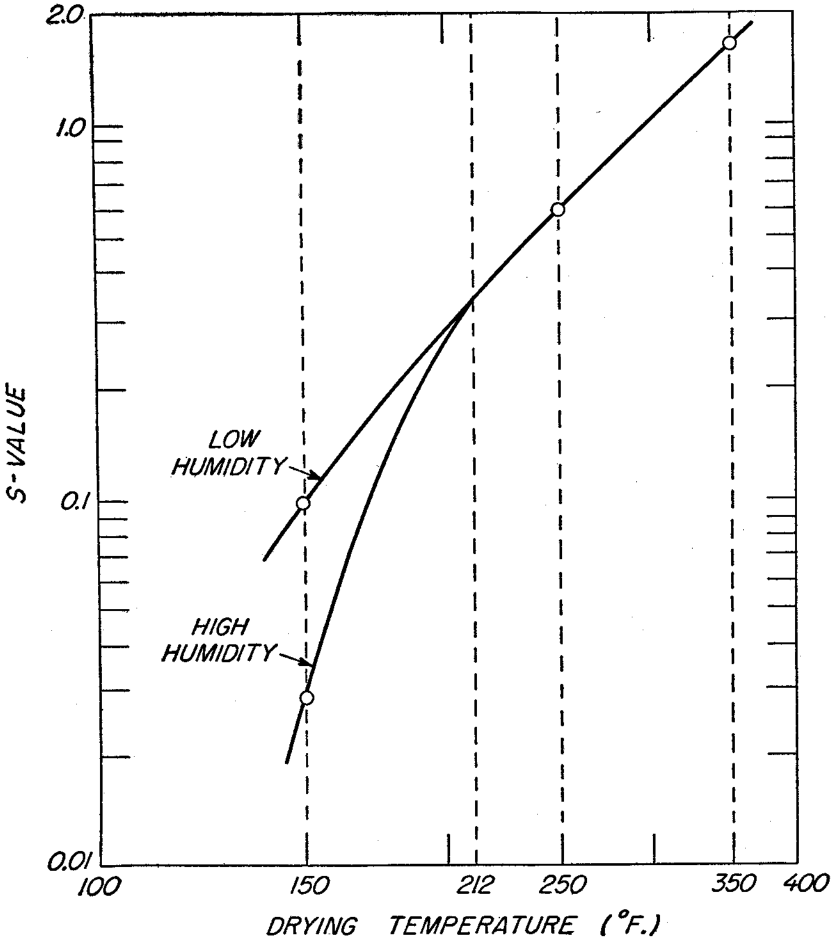

FIGURE 16. Plot of S-values for log No. 1 based on averages of 1/32-, 1/16-, and 1/8-inch thicknesses, 200, 600, and 1,000 foot air velocities, and at 250° and 350° F. for both absolute humidities, illustrating the interaction of temperature and humidity and the curvilinear temperature effect at the lower temperatures.

perature, and be surrounded by air that had lost part of its heat and attained a higher humidity by taking up evaporated moisture. A pronounced drop in the temperature of the air passing over the drying specimens during the early part of the cycle has already been described in the discussion of the control of drying conditions.

Figure 10 shows how a pronounced delay in reaching the temperature at which evaporation may begin over a part or all of the drying specimen may also have an important effect on the subsequent drying rate. In this figure the end of the warming-up period, during which the specimen comes to a temperature at which evaporation may begin, is indicated by P on curve C. If this point were to fall to a greatly lower position on curve C than that shown, then the slope of the line, D, which is approximately equivalent to the slope of the drying rate line, must necessarily be less in order that the area beneath the line, or the total quantity of heat to be transferred, may remain the same. It appears, therefore, that variations in the initial warming-up period that significantly affect the point, P, will have a significant effect on the slope of the drying-rate curve. This effect apparently was responsible for the significant interaction between absolute humidity and logs, and also for some other interactions, such as those involving thickness.

These significant interactions between humidity and the other factors indicated in Table 7 were eliminated in the supplementary analysis shown in Table 9, in which only log No. 1 specimens dried at 250° and 350° F. were included.

The Significance of Temperature

As expected, the temperature effect on S-values was a most significant one. Figure 16 shows the effect of temperature on S-values from log No. 1, averaged without regard for air velocity and thickness. The very significant quadratic effect of temperature (Table 7) appears to be of greatest importance in the lowest temperature range. Above 212° F. the temperature effect can apparently be represented adequately by a straight line when both temperatures and S-values are expressed in logarithms. In this range absolute humidity has no significant effect, except when combined with very high initial moisture contents in the drying specimen.

At drying temperatures of 150° F., the interaction between humidity and temperature was significant. In this low range, most likely extending to a high of 212° F., the combined effect can be represented by a series of curves in which each curve represents a given humidity condition. Two such curves are shown in Figure 16.

THE SIGNIFICANCE OF AIR VELOCITY

The air velocity factor exerted highly significant linear and quadratic effects on the S-values (Table 7). Air velocity rates varied arithmetically in the drying tests, and the fact that a significant quadratic effect is observed would indicate a changing effect on the rate of drying as the velocity changed. In plotting average S-values against rates of air velocity, it was found that a fairly straight line was formed on logarithmic cross-section paper. On such paper the interaction between air velocity and thickness (Table 8) also appeared to be eliminated.

From this it may be concluded that the relation between drying rates and air velocity is a geometric one rather than an arithmetic one. This agrees with the result obtained by Sherwood (29), who varied air velocity over a much wider range, from approximately 400 to 2,500 feet per minute, in drying pulp blocks during the constant rate period. He found that the rate of evaporation increased logarithmically with the logarithm of air velocity.

Interactions between air velocity and the other variable factors used in the study became nonsignificant when the range of conditions was limited, as represented in Tables 8 and 9.

THE SIGNIFICANCE OF INITIAL MOISTURE CONTENT

It has already been shown for the individual specimen that the rate of heat transfer and consequently the rate of evaporation at any time during drying is dependent upon the moisture content at that time (Figure 13). It follows, therefore, that if a specimen has a higher initial moisture content than another specimen but dries according to the same value of S, its drying rate during the early part of the cycle must be at a higher level in order that the area beneath the line S (Figure 10) may increase in proportion to the higher moisture content.

Specimens from log No. 1 differed greatly from specimens from log No. 2 in initial moisture content. The initial analysis, Table 7, indicated a very significant difference in S-values for logs, as well as some significant interactions with velocity, temperature, and absolute humidity. In Table 8, where the field was limited only to the higher temperatures and to a single humidity, the main effect of logs was not significant nor were there any significant interactions.

This effect is illustrated in Figure 17, where the drying of two 1/8-inch yellow-poplar specimens at 350° F., low humidity, with an air velocity of 600 feet per minute, is compared. The specimen from log No. 1 had an initial moisture content of 76.2 percent, and the slope of the line, s, was

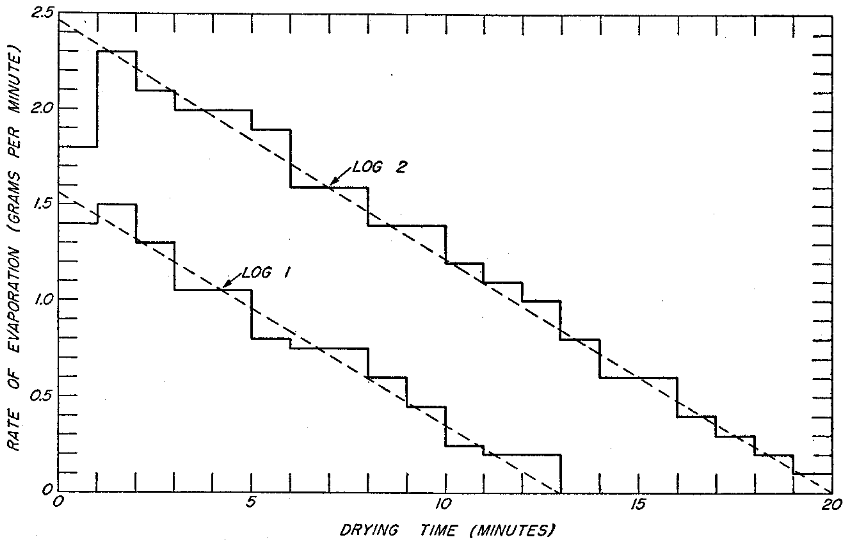

FIGURE 17. Comparison of drying rates of yellow-poplar specimens having high (log No. 2, 148.5 percent) and low (log No. 1, 76.2 percent) initial moisture contents. Specimens were 1/8-inch thick, and were dried at low absolute humidity, with an air velocity of 600 feet per minute and a temperature of 350° F. (The specimen from log No. 2 was also represented in Figures 2, 9, 11, 12, 13, and 17.)

0.120. The specimen from log No. 2 had a moisture content of 148.5 percent and the slope, s, was 0.123. The s-values are similar, and, as a result, the slopes of the lines representing the falling rate of evaporation during drying are almost parallel. Table 10 shows that the moisture contents of the two specimens at various times before the end of the drying period are comparable.

The significant interaction between initial moisture content and absolute humidity has already been discussed.

TABLE 10. COMPARISON OF MOISTURE CONTENTS AT VARIOUS TIMES DURING DRYING OF 1/8-INCH YELLOW-POPLAR SPECIMENS AT 350° F., LOW ABSOLUTE HUMIDITY, WITH AN AIR VELOCITY OF 600 FEET PER MINUTE. SPECIMENS FROM THE TWO LOGS INITIALLY WERE AT GREATLY DIFFERENT MOISTURE CONTENTS

Time from end of drying period	*Moisture content*	
	Log No. 1	*Log No. 2*
Minutes	*Percent*	*Percent*
0	0.7	0
2	2.6	2.4
4	7.8	6.7
6	17.8	13.9
8	29.4	24.8
10	45.0	38.8
12	[1]65.8	55.8
14	——	75.2
16	——	98.8
18	——	123.6
20	——	148.5

[1] The initial moisture content 13 minutes from the end of the drying period was 76.2 percent.

THE SIGNIFICANCE OF THICKNESS

If the drying rate of a specimen is entirely dependent on the rate of heat transfer, and not on diffusion of water, one might at first thought expect to find a simple inverse relationship of the first power between thickness and S-values. Doubling the thickness of a specimen has a negligible effect on the area available for heat transfer; therefore, since twice the quantity of heat is required to evaporate the water in a thick specimen as in a specimen half its thickness, the S-value for the thick specimen would presumably be halved. The estimating equation for S-values, (9), indicates that this relation does not hold. Considering only the relation between thickness and S, we find:

$$\log S = -1.344 \ (\log D)$$

or

$$S = D^{-1.344}$$

For a specimen having a thickness, D_1, twice the thickness of the first specimen, the value of S_1 would be:

$$S_1 = (2D)^{-1.344}$$

or

$$S_1 = \left(\frac{1}{2^{1.344}}\right) D^{-1.344}$$

Since $2^{1.344} = 2.539$, the equation indicates that doubling the thickness of the drying specimen does not result in a reduction of the S-value by 1/2, but by 1/2.539.

The total quantity of heat required during the drying of the second specimen, that was twice as thick as the first, and consequently contained twice the weight of water initially, was twice the quantity required by the first. For the second specimen, therefore, the area under curve D, Figure 10, would be twice the area involved in drying the first specimen. Since the slope of the line, D, has decreased by more than one-half, it is obvious that the point, P, in Figure 10, must have dropped to a lower position on curve C for the second, thicker specimen.

In this case this phenomenon, which has already been observed in connection with the interaction effect of humidity and initial moisture content, may be attributed to the increasing magnitude of the temperature gradient during the early part of the heating cycle. As thicknesses increase and temperature gradients from surface to interior temporarily become more pronounced during the early part of the heating, the difference between the surface temperature and the average temperature for the specimen becomes temporarily greater. The surface coefficient of heat transfer is affected by the temperature difference between the surface and the heating medium, $(t' - t)$ in equation (2). Because of this surface condition, the rate of heat transfer during the early part of the drying cycle is lower for a thick specimen than for a thin specimen having the same percentage moisture content. The slope of the drying-rate line, S, is affected accordingly.

THE EFFECT OF SPECIES

S-values obtained in drying tests on sweetgum and redwood are given in Table 6. The estimating equation given above for yellow-poplar was used to calculate values of S for the conditions used in drying specimens of the other two species, excluding the 150° F. temperature condition to which the equation did not apply. Calculated S-values for yellow-poplar were consistently higher than the test values for sweetgum. The values for redwood varied somewhat from the calculated values for yellow-poplar but were not consistently higher or lower. A graphic comparison of the redwood values with the calculated yellow-poplar values is shown in Figure 18.

Since only a few drying tests were made on species other than yellow-poplar, conclusions as to the variation in S-values with species are not

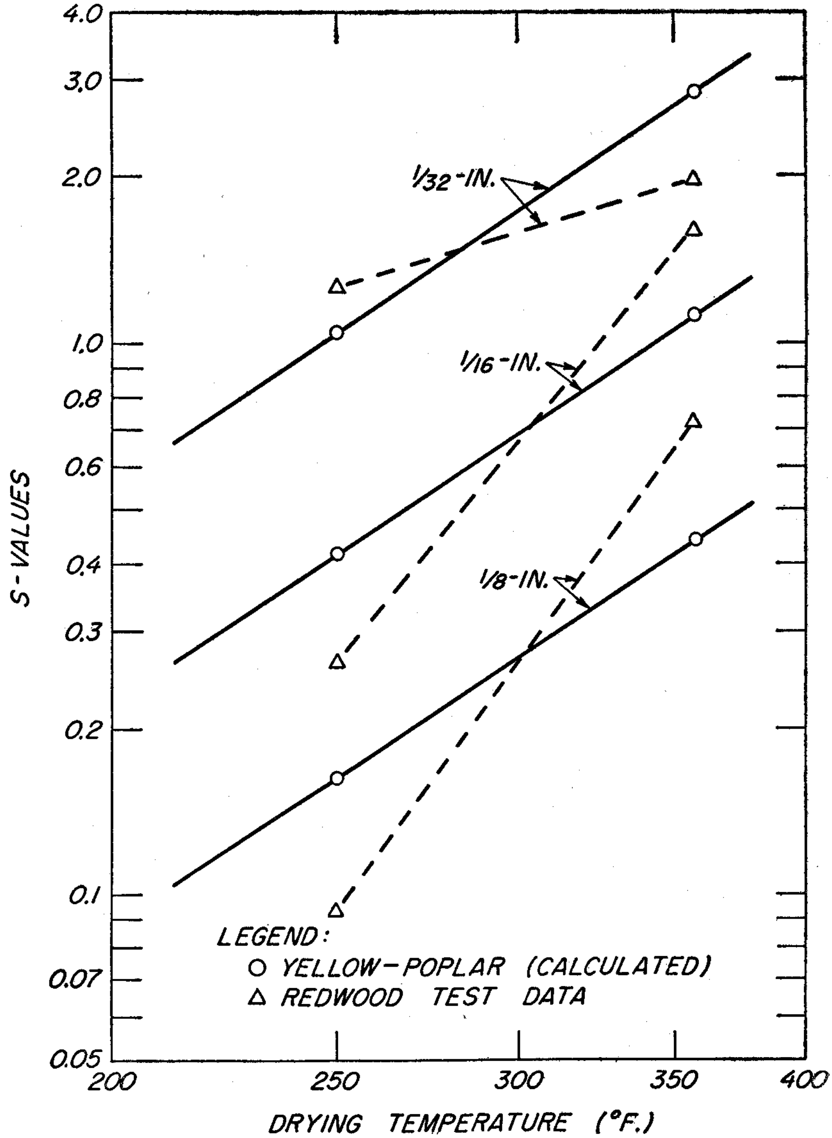

FIGURE 18. Comparison of S-values obtained in drying tests of redwood specimens with values for yellow-poplar obtained by use of the estimating equation, at an air velocity of 600 feet per minute.

justified. However, related evidence from other sources may be used to advantage. Bethel and Hader (2) present data on the drying of I/ro-inch sweetgum veneer to the effect that heartwood dries more slowly than sapwood in spite of equivalent initial moisture contents. This retardation of the drying rate of heartwood is probably brought about by the presence of heartwood-forming substances in the cells. In the heartwood of material of this species and thickness, the movement of moisture is retarded significantly, yet the constantly changing temperature and moisture conditions result in a drying curve similar to BI or B2, rather than to A, in Figure 2.

A similar effect has been observed in drying veneer in a roller-conveyor type mechanical veneer drier at the Forest Products Laboratory.[5] Water tupelo *(Nyssa aquatica* L.) veneer having an initial moisture content of approximately 140 percent in both heartwood and sapwood was dried to a moisture content of 2 to 4 percent at a temperature of 320° F. Heartwood 1/8-inch thick required 30 minutes in the drier, but sapwood of the same thickness required only 18 minutes. Veneer 1/16-inch thick, however, required only 9 minutes for heartwood and 8 minutes for sapwood. The drying rate was greatly affected in 1/8-inch heartwood material, but in 1/16-inch material the effect was slight.

It appears, therefore, that the thickness at which the free movement of moisture is significantly retarded, with a resulting effect on the drying rate, may vary with species and type of wood. The rate of heat transfer, on the other hand, presumably is affected very little by differences in density, color, wood structure, and other species characteristics. It follows, therefore, that drying rates should not vary greatly with species in very thin material, but that the species effect will become more pronounced as thicknesses Increase.

FURTHER OBSERVATIONS REGARDING A "CONSTANT-RATE PERIOD"

Bethel and Hader (2) conducted drying studies on sweetgum veneer, 1/15-, 1/8-, and 1/6-inch thick, under temperature conditions somewhat comparable to those of this study. The rate of air circulation apparently was relatively low. The drying-rate curves obtained, when transformed to the terms used in Figure 2, were similar to curve B-2. It was concluded that the drying of veneer was characterized by a rather pronounced "constant-rate period," followed by a "falling-rate period." In another

[5] Unpublished data.

study already mentioned in connection with temperature data, Keylwerth (*16*) reported temperature curves of a type that might indicate the existence of constant-rate drying conditions.

The drying behavior observed in the tests of Bethel and Hader (*2*), as well as in Keylwerth's tests (*16*), is probably typical of that occurring in many driers, for ideal conditions of temperature and heat transfer are not readily attainable. The rapid drop in temperature of the air flowing over the drying specimen, particularly during the early part of the cycle, has been described in the section on the control and measurement of drying conditions. It was also pointed out that the lowest air velocity used in this study, 200 feet per minute, was frequently accompanied by a perceptible irregularity in drying rates during the early part of the cycle, before the typically falling-rate condition developed. Air velocities lower than those used in this study presumably would result in a still greater modification of temperature conditions in the proximity of the drying specimen, and a longer period of irregularity at the start of the drying cycle. This irregularity apparently accounts for the conclusion (*2*) that a constant-rate period typically precedes the falling-rate period in veneer drying.

SHRINKAGE AND STRESS ANALYSIS

IN the previous discussion of diffusion calculations it was shown that the k-value could not be used to advantage for calculating drying rates of yellow-poplar specimens 1/8-inch thick or thinner. The question arose as to whether diffusion was a governing factor in the drying of specimens of this thickness. Consideration of heat transfer phenomena indicated that, because of the extreme thinness of the material, diffusion did not play an important role in the drying of thin specimens, especially at temperatures above 212° F.

If water diffusion were a factor influencing drying rates, this would indicate the existence of a moisture gradient during drying, which would be necessary in order that moisture might move from a point of high concentration within the piece to a point of lower concentration at the drying surface. On the other hand, if no moisture gradient through the thickness existed in the drying specimen, shrinkage in drying would be uniform throughout the cross section and no stresses would be developed to result in casehardening and other drying defects. Other factors being constant, pieces of various thicknesses would shrink equally in drying from the green to the dry condition. It appeared appropriate, therefore, to examine shrinkage and stress conditions to determine whether any evidence of a moisture gradient remained in the dry specimens.

Data on the tangential shrinkage of yellow-poplar specimens during drying are shown in Table 1. They indicate considerable variation in shrinkage, apparently corresponding to variations in thickness and in drying conditions. An analysis of variance was, therefore, made of the data. A summary of the calculations is given in Table 11. The analysis showed that the effects of temperature, thickness, and logs were highly significant, and that the effect of air velocity was significant at the 5 percent level. Absolute humidity had no significant effect on shrinkage, but the interaction between logs and humidity had a highly significant effect. In order to illustrate the relative effects of the various significant factors, the tangential shrinkage values taken from Table 1, averaged in various ways, are given in Table 12.

Variations in shrinkage during drying frequently result from the development of stresses at some period during the drying cycle, commonly causing a condition known as "casehardening" (37), in which the outer shell has dried in an expanded condition and may be under compression after drying. Table 12 indicates that a considerable reduction in shrinkage

TABLE 11. ANALYSIS OF VARIANCE OF SHRINKAGE DURING DRYING OF YELLOW-POPLAR SPECIMENS

Source	*Degrees of freedom*	*F*	*Significance*[1]
Total	143	——	——
Temperature	2	21.55	V. S.
Air velocity	2	3.72	S.
Absolute humidity	1	.56	N. S.
Thickness	3	8.75	V. S.
Logs	1	19.83	"
Logs X humidity	1	8.00	"
Error[2]	133	——	——

[1] V. S. = significant at the 1 percent level; S. = significant at the 5 percent level; N. S. = not significant at the 5 percent level.
[2] Since all interactions except logs X humidity were nonsignificant, they were included in the error term. The value of the error mean square was 0.7127.

TABLE 12. SUMMARY OF TANGENTIAL SHRINKAGE PERCENTAGES OF YELLOW-POPLAR AVERAGED ACCORDING TO THE VARIOUS SIGNIFICANT FACTORS

Factor[1] *and level*	*Number of values averaged*	*Tangential shrinkage*[2]
		Percent
Temperature 150° F.	48	6.95
Temperature 250° F.	48	6.35
Temperature 350° F.	48	5.82
Thickness 1/32 inch	36	6.82
Thickness 1/16 inch	36	6.30
Thickness 1/8 inch	36	6.54
Thickness 1/4 inch	36	5.84
Velocity 200 feet per minute	48	6.64
Velocity 600 feet per minute	48	6.30
Velocity 1,000 feet per minute	48	6.18
Log No. 1	72	6.06
Log No. 2	72	6.68
Log No. 1 X humidity 1[3]	36	6.32
Log No. 1 X humidity 2	36	5.81
Log No. 2 X humidity 1	36	6.54
Log No. 2 X humidity 2	36	6.84

[1] All factors listed were significant at the 1 percent level, except air velocity which was significant at the 5 percent level.
[2] Based on green width.
[3] Low and high absolute humidity are abbreviated "humidity 1" and "humidity 2" respectively.

occurred with increasing thickness. This could be taken to indicate an increasing effect of a moisture gradient in drying as thickness increases. The results obtained at the various temperature and air velocity levels indicated that those factors responsible for increased drying rates resulted in reductions in the over-all shrinkage. The significant difference in shrinkage between the two logs may be related to differences in density of the wood, for the log that had the highest specific gravity shrank most. The significant interaction between logs and humidity may be related to significant differences in drying rates that resulted from this same interaction (Table 7). On the basis of shrinkage observations, it therefore appears that a moisture gradient existed at least at some stage during the drying of all but the thinnest specimens.

Plates II and **III** illustrate the method used on 1/4- and I/8-inch specimens to determine the magnitude of casehardening stresses that existed in the specimens after drying. In the yellow-poplar specimens (Plate II) residual stresses were absent in specimens dried at 150° F. but became progressively more pronounced as drying temperatures rose. This observation, in agreement with the shrinkage data, indicates an increasing moisture gradient effect with increasing drying temperature.

On sweetgum, on the other hand, the results seemed to be reversed (Plate **III).** In this species severe residual stresses were present in pieces dried at the lowest temperature. At the two higher temperatures stresses were progressively less pronounced, but specimens in these groups showed considerable "honeycombing." Microscopic examination of the honeycombed cross sections shown in Plate **III** showed no evidence of collapse, for there was no abnormal distortion or obliteration of the cell cavities (]6). The defect appeared to be related to the weakening of the wood that may occur when green wood of some species is subjected to high temperatures. The absence of residual casehardening stresses in those specimens that showed the most pronounced honeycombing may be attributed to the stress relief afforded by the checking and subsequent shrinkage of the interior portions. No honeycombing was observed in any of the 1/16- and I/3z-inch sweetgum drying-rate test specimens. Again we are led to conclude, on the basis of residual stress analysis, that a moisture gradient must have existed at some stage in the drying of specimens 1/8- and I/4-inch thick.

Stresses that result in drying defects in wood may occur at a relatively high average moisture content, at a time when the surface has dried to a level below the fiber-saturation point, whereas the interior is still at a higher moisture content and has not yet begun to shrink. Thus, the evidence presented here regarding differential conditions through the cross section need not be interpreted to mean that moisture gradients existed during drying throughout the lower range of moisture contents, but indicate only that such conditions did exist at least for a short time, perhaps while the average moisture content was still above the fiber-saturation point.

In drying tests of eucalypt veneers in a dry kiln at low temperature (up to 175° F., dry bulb) Ellwood (*8*) found that buckling and splitting defects occurred before the average moisture content had dropped below 35 percent. On the other hand, he found no evidence that sets in thickness developed during the drying of veneers 1/16-inch thick (*9*). He concluded that the thinness of the samples allowed a rapid movement of moisture and thus prevented the severe moisture gradient that tends to give a set condition. He attributed differences in shrinkage and the development of defects brought about by differences in temperature and humidity conditions to differences in the degree of collapse that occurred.

On the other hand, the existence of a moisture gradient has been demonstrated even in the drying of paper as thin as 0.010 inch (*12*). In tests on air drying such paper at a dry-bulb temperature of 110° F., with a wet bulb of 92° F., and an air velocity of 220 feet per minute, Higgins showed that a moisture gradient existed in the outer layers of the paper. A layer of considerable thickness at the middle of the sheet was at a uniform moisture content higher than that at the outside. As the average moisture content decreased, the moisture decreased throughout the thickness, the gradient in the outer layers gradually became less pronounced, and the inner zone of uniform moisture content became thinner. Higgins concluded that the drying rate was controlled by heat and water transfer between the air and the paper.

To summarize, shrinkage and residual stress analysis data indicate that a considerable moisture gradient existed at one stage during the drying of the thin specimens. This moisture gradient probably existed before the average moisture content dropped below the fiber-saturation point, or approximately 30 percent. Consideration of temperature data (Figure 9) indicates that the gradient did not exist during drying below this point, in specimens 1/8-inch thick or thinner, dried at temperatures of 250° and 350° F. If diffusion were a governing factor in determining drying rates, its effect would be particularly noticeable in this period when the moisture content was low. The existence of a moisture gradient at a moisture content level above 30 percent, therefore, does not invalidate earlier observations as to the relative unimportance of diffusion in the drying of thin wood specimens.

SOME PRACTICAL APPLICATIONS OF THE DRYING DATA

THE information gained in this study may be used in many ways in connection with the drying of thin sections of wood, particularly at temperatures above 212° F. Industrially, such drying is performed primarily in the veneer-producing industry, where large mechanical driers are used that frequently operate at very high temperatures. For the proper design of a large mechanical drier it is useful to know something about the drying rates of the wood as it progresses through the machine. In the design of drying equipment it is also desirable to know the relative effects of varying the controllable factors that affect drying rates, in order that the maximum effect on drying may be attained at the minimum cost. The relative effects of the important variable factors within the range of conditions frequently used in veneer driers are indicated in this study.

To demonstrate the application of the drying-rate data to the operation of an industrial drier, an example is provided, based on actual experience with a roller-conveyor type of veneer drier of moderate size in drying a considerable quantity of Douglas-fir heartwood veneer 1/8-inch thick.[6] The wood came from several different logs, and had an average initial moisture content of 32 percent and an average specific gravity, based on green dimensions and oven-dry weight, of 0.42. At an operating temperature of 320° F. the veneer was dried for 9 minutes to an average moisture content of 3 percent.

To use such empirical information, it is necessary to establish the drying-rate curve for wood of the given species and thickness and for the particular conditions that existed in the drier. Equation (8) is first used to determine the time that would theoretically be required to dry the wood to a moisture content of zero. In order that the information may be comparable with other drying information, calculations are made for a green piece having a unit size of 6 by 12 inches, for such a piece has a surface area of approximately 1 square foot. The volume of this piece is 9 cubic inches or 147.5 cubic centimeters. Since its specific gravity is 0.42, the oven-dry weight of the piece is:

$$0.42 \times 147.5 = 62 \text{ grams}$$

An average initial moisture content of 32 percent would indicate that the piece initially contained 32 percent of 62 grams, or 19.84 grams of water. In equation (8) this is the value of W_t, the total initial water content of

[6] UDpublished data, Forest Products Laboratory.

the specimen. It is also the value of w_e, the evaporable water, since the equilibrium moisture content of wood in a drier operating at 320° F. is zero. At a moisture content of 3 percent the piece contains 1.86 grams of water. This value, termed W_3, represents the water remaining to be dried at the end of the cycle, and is substituted for W_{30} in equation (8). Similarly, the time to come to this condition, namely 9 minutes, is termed θ_3 and is substituted for θ_{30} in the equation. The term θ_e, or the time theoretically required to dry the specimen to the equilibrium moisture condition, or in this case to a moisture content of zero, can now be calculated as follows from equation (8):

$$\Theta_e = \frac{2 \cdot 19.84 \cdot 9 + \sqrt{(2 \cdot 19.84 \cdot 9)^2 - 4\ (19.84 - 1.86)\ (19.84 \cdot 9^2)}}{2\ (19.84 - 1.86)}$$

$$\Theta_e = 12.97 \text{ minutes}$$

The value of S, the slope of the drying-rate line, for a specimen having a surface area of 1 square foot, is calculated from the relation:

$$S = 2\ w_e/\Theta_e^2$$

Then:

$$S = \frac{2 \cdot 19.84}{12.97^2}$$

$$S = 0.2358$$

As a matter of interest, a value of S for the conditions used in drying this material may be calculated from the estimating equation for yellow-poplar (equation (9)). The temperature and the thickness to be used in the equation are 320° F. and 1/8 inch. The air velocity condition in the industrial-type drier used for Douglas-fir is not known exactly, but is estimated to be about 300 feet per minute at the wood surface. A proper average value is very difficult to determine because of the impedance to air flow parallel to the drying surface offered by the metal rollers that convey the veneer and the turbulence between them. These rollers may also transmit heat to the drying wood by radiation and by direct contact. However, for the stated conditions, the estimating equation (9) indicated that the S-value for yellow-poplar was 0.1968, or not greatly different from the value determined for Douglas-fir.

The S-value for Douglas-fir determined in this particular drier may be used to derive the drying-rate curve throughout the drying cycle. The curve may be extrapolated to any desired level of moisture content. For this purpose, equation (7) is used in arriving at moisture-content values at various drying times. Since the derived curve is a parabola, the drying-rate curve may also be determined more simply by use of logarithmic cross-section paper. The data will fall in a straight line on such paper, and only the two points used above in the calculation of the S-value are needed. In this case time is plotted in terms of "time required to reach the equilibrium condition," in order that w_e may be zero at zero time. Figure 19 illustrates the method.

It was determined above that Be' the time theoretically required to dry 1/8-inch Douglas-fir having an initial moisture content of 32 percent to zero moisture content was 12.9 minutes. These values determine the first point in Figure 19. After drying 9 minutes the veneer reached an average moisture content of 3 percent. Then the "time required to reach the equilibrium condition" was (12.9 minutes - 9 minutes) or 3.9 minutes. With this second point established, a straight line was drawn through the two points and the moisture content at any time during drying may be estimated from it.

The drying-rate curve may be applicable to only a single drier, for the uncontrollable·factors that affect the rate may vary greatly from drier to drier. However, such curves are easily derived and can be used to estimate changes required in drying schedules to correspond to changes in the initial or the final moisture content of the wood.

Apart from these purely practical considerations, the information presented here is helpful in arriving at the over-all picture of how thin wood dries and in determining at what level of thickness and temperature the change from diffusion to heat transfer, as the controlling factor in drying, takes place.

It is hoped that future studies in this field may develop more detailed information and may be extended to cover the effects of high temperatures often used in drying thin wood on the more important physical, chemical, and mechanical properties of the product.

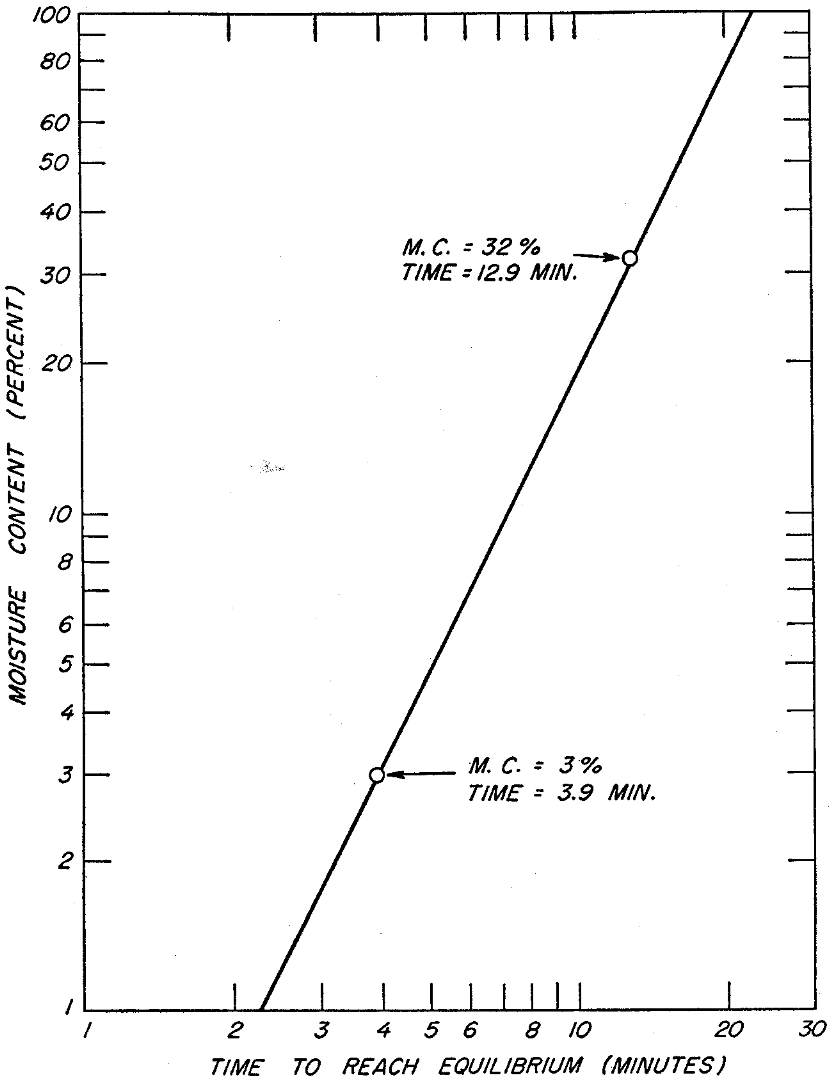

FIGURE 19. Graphic method of deriving the drying curve from two known points.

CONCLUSIONS

DRYING test on yellow-poplar wood sections *1/32*- to I/4-inch thick, performed at temperatures of 150°,250°, and 350° F., at air velocities of 200 to 1,000 feet per minute, and at widely different absolute atmospheric humidities, showed that moisture diffusion calculations based on the Fourier heat-conduction laws can be applied to predict the drying rates of specimens I/4-inch thick, but cannot be used to advantage in predicting drying rates of thinner specimens. Specimens 1/4-inch thick, when dried at the highest temperature used, 350° F., also tend to depart from the trends predicted by moisture diffusion calculations, whereas the rates of thinner specimens dried at 150° F. show some similarity to the diffusion rates. Similar conclusions were reached in drying-rate tests made on a few specimens of sweetgum and redwood. From this it is concluded that, in general, moisture diffusion is not the major controlling factor in the drying of wood I/8-inch thick or thinner. Its effect may, however, be noticeable in thinner sections when drying at low temperatures, whereas at very high temperatures it may not be important even in the I/4-inch thickness.

In specimens following the diffusion laws, a temperature gradient through the thickness of the piece exists during the entire drying cycle. Diffusion coefficients or k-values determined for the I/4-inch specimens were found to agree closely with theoretical values computed on the basis of capillary structure considerations, and varied directly in geometric proportion with temperature; they varied similarly with air velocity, apparently because the velocities used were not great enough to eliminate entirely the surface resistance to the emission of moisture.

The drying rates determined for the thinner specimens, in which moisture diffusion was not a governing factor, are dependent on the rate of heat transfer from the atmosphere to the specimen. During drying, the surface coefficient of heat transfer to the specimen falls geometrically in proportion to the decreasing moisture content. The rate of drying is closely related to the rate of heat transfer, and decreases at a logarithmic rate when plotted against moisture content, or at an arithmetic rate with time. The slope of the line representing the rate of moisture evaporation plotted against time during the drying cycle expresses the constantly changing rate of drying.

In drying thinner specimens at temperatures above 212° F., a measurable temperature gradient does not exist during the latter part of the drying period, after the wood has attained a temperature of 212° F. or the wet-bulb temperature of the drying atmosphere. This is attributable to the development of vapor pressures above atmospheric pressure that tend to bring about a rapid equalization of pressure and temperature conditions through the thin sections. In those specimens that have a very high initial moisture content and that are dried at high absolute humidity and apparently under certain unfavorable conditions, an initial period somewhat similar to the "constant-rate" period observed in lumber drying may exist. This apparently is due to the retardation of evaporation during the early part of the drying period because of the long time required for all parts of the specimen to reach the saturation temperature of the atmosphere. It may have a significant effect on the rate of drying during the remaining part of the drying cycle.

The so-called "S-value," or the slope of the line representing the rate of moisture evaporation plotted against time, may be used to predict the moisture content of the specimen at any time during drying, except when the initial period of irregularity is significantly long. Within the range of conditions usually used in drying thin sheets of wood, S-values vary directly with temperature and air velocity and inversely with thickness. At temperatures below 212° F. they also vary inversely with absolute humidity. Generally, they are not significantly affected by the initial moisture content of the wood to be dried, except as indicated above.

From data obtained in drying yellow-poplar at temperatures of 250° and 350° F., an equation was developed that may be used to estimate the S-values of this wood in thicknesses up to 1/8 inch, at all drying temperatures above 212° F., as follows:

$$\log S = 2.984 (\log T) + 0.784 (\log V) - 1.344 (\log D) - 11.336$$

where T is the temperature in degrees F., V is the air velocity in feet per minute, and D is the thickness in inches.

Sufficient data were not available for determining whether the S-values obtained for sweetgum and redwood varied significantly from the values predicted by this equation, although the variability of the redwood data was such that the values might not be significantly different.

Consideration of variations in the degree of shrinkage that occurred in drying the specimens, as well as of residual stresses in the dry pieces, indicated that a considerable moisture gradient existed at some stage during the drying. The temperature data indicated that in the thinner specimens this gradient existed only during the early part of the drying, before the average moisture content had dropped below the fiber-saturation point. The existence of this gradient did not invalidate the conclusion that the rate of drying was governed by heat transfer rather than by water diffusion.

SUMMARY

THIN sections of wood of several species were dried in air at temperatures up to 350° F. and at several levels of humidity and air velocity. Drying rates for specimens 1/4-inch thick were found to follow closely the trends predicted by water-diffusion equations based on the Fourier heat-conduction law. Thinner specimens departed from these trends, particularly when dried at temperatures above 212° F., apparently because diffusion of water did not govern the drying.

The surface coefficient of heat transfer to the drying specimen was found to vary directly, in geometric ratio, with moisture content during drying. This resulted in a simple arithmetic relationship between the drying rate and drying time, which can be integrated to determine the moisture content at any time during the drying cycle. The slope of the line representing the relationship, called "s," is a measure of the rate of drying. It was found to vary significantly, within the range of conditions normally used in drying thin wood, with temperature, air velocity, and thickness.

The existence of a temperature and moisture gradient during the early part of the drying cycle did not invalidate the conclusion that moisture diffusion was not a governing factor in determining the drying rate.

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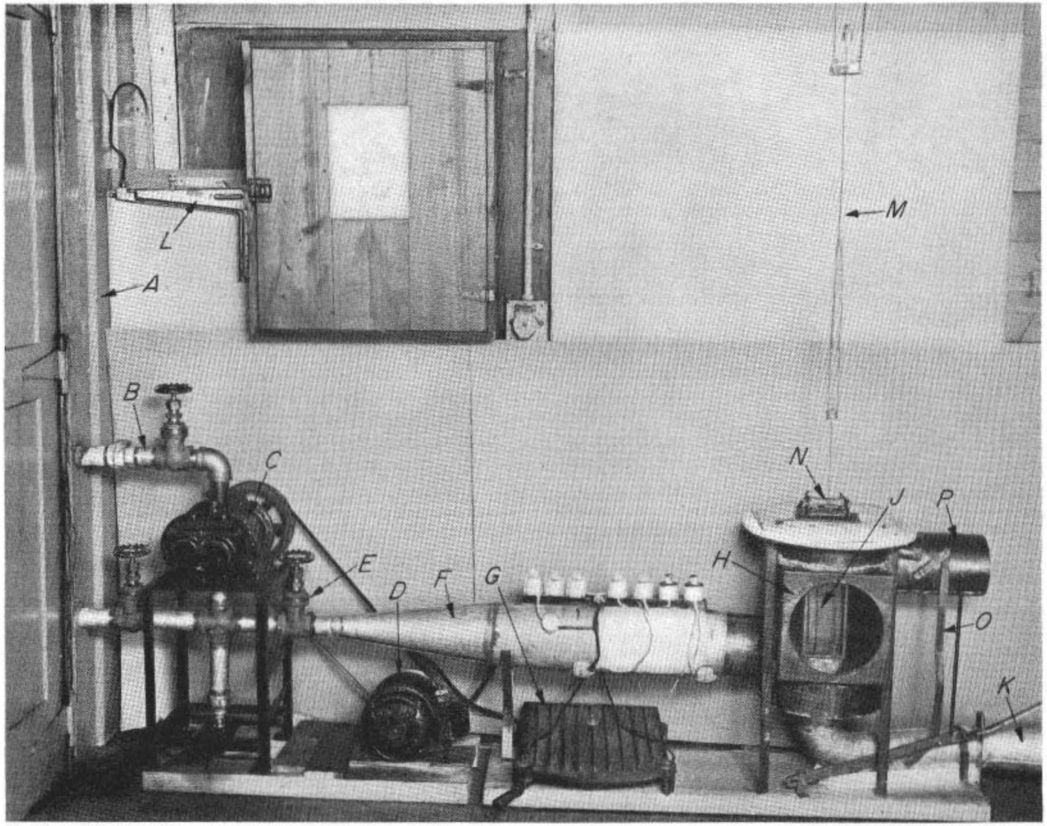
PLATE SECTION

PLATE I

The drying apparatus used in the tests before insulation was applied. See text for explanation of symbols.



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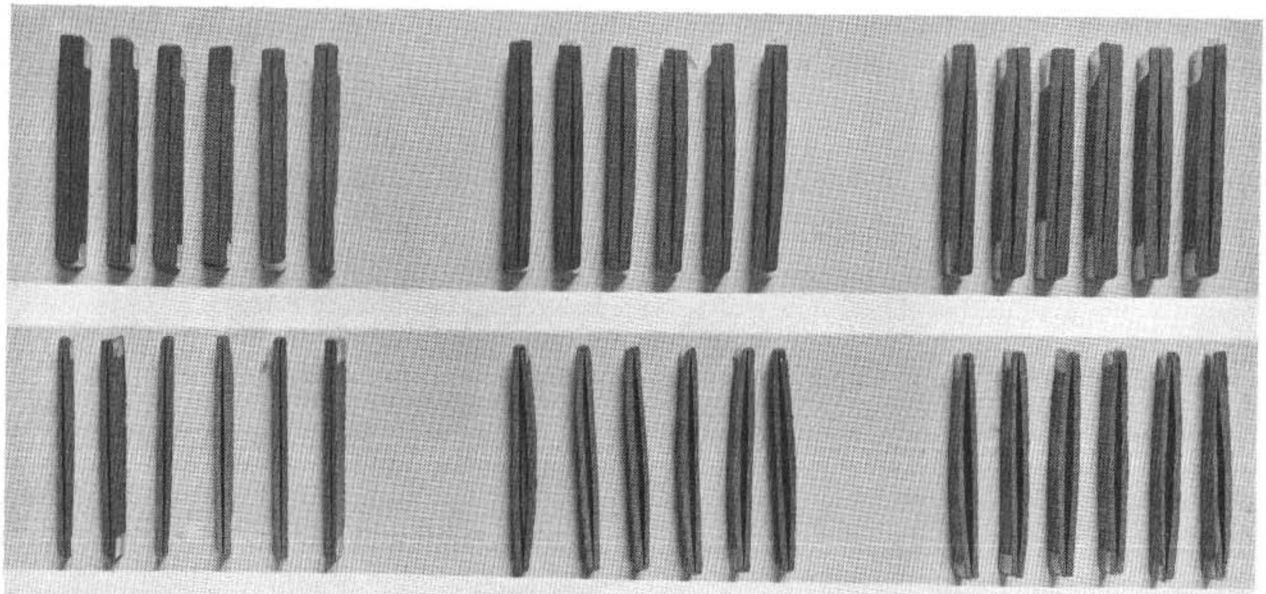
P

PLATE II

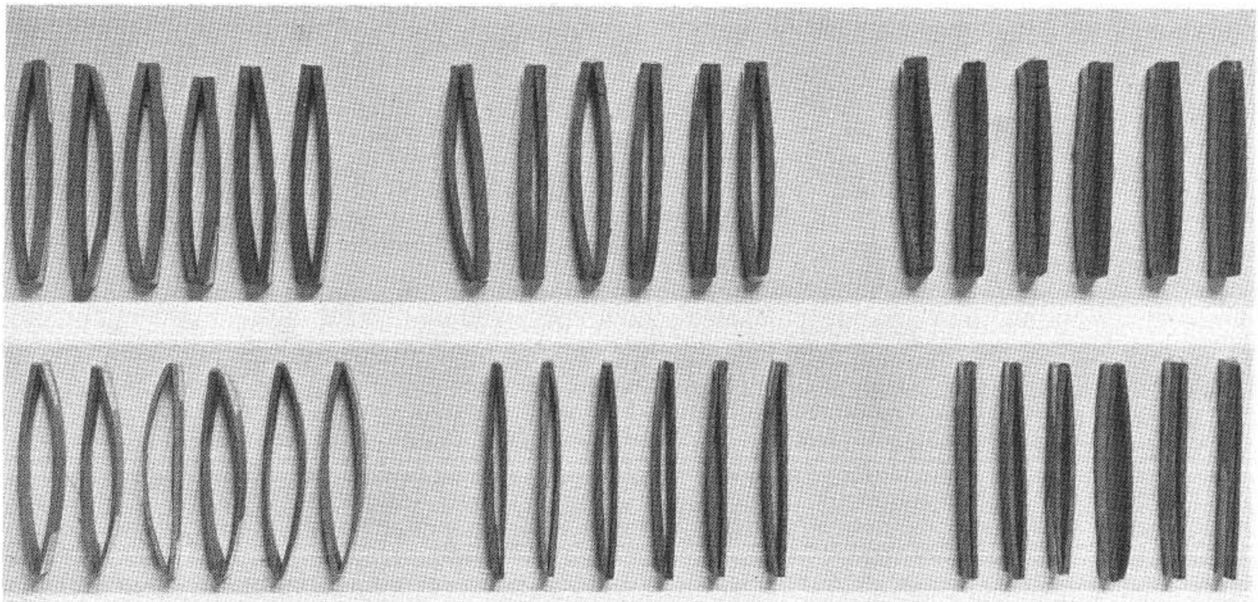
Bowing of split halves of yellow-poplar pieces from log NO.2, indicating the degree of residual stress resulting fom drying at indicated temperatures. Pieces in the upper tier were originally 1/4-inch thick and in the lower tier were 1/8-inch thiclc



Dried at 15ª ■ | Dried at 25ª ■ | Dried at 350° F

PLATE III

Bowing of split halves of sweetgum pieces, indicating the degree of residual stress and honeycombing resulting from drying at indicated temperatures. Pieces in the upper tier were originally 1/ 4-inch thick and in the lower tier were 1/ 8-inch thick.



Dried at 150° F Dried at 250 Dried at 350° F

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