A METHOD FOR PREDICTING THE DRYING TIMES FOR DOUGLAS FIR HEARTWOOD

by

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A METHOD FOR PREDICTING THE DRYING TIMES FOR DOUGLAS FIR HEARTWOOD

INTRODUCTION

The need for some method by which the drying times of lumber under varying sets of conditions can be predetermined has long been felt by dry kiln operators. A great handicap would be taken from their shoulders if there were some means by which they could tell with a fair degree of accuracy the time it would take to dry lumber under various conditions and just how much time could be saved by varying these conditions.

Drying of lumber artificially is not new, in its broad sense, but as to reaching a state of perfection there are vast improvements necessitating many experiments and careful study which must come into actuality before it can be considered on a scientific basis. Much experimentation and planning has been done in regard to the mechanical aspects until these have reached a relatively high state of perfection and efficiency.

The shortcoming lies in the drying itself. Given an efficient kiln, how can it be operated so as to give the best results? Here is the field of experimentation and research.

In working out a method by which the drying rates can be predicted, the experimenter is confronted with many perplexing and intricate problems. In the first place he is working with something which is variable. No two pieces of lumber are identical and consequently drying for the two will not be the same. Just how does lumber dry? The most accepted belief today is that it is a process of transfusion and diffusion. The moisture in a green board is quite uniformly distributed through the piece. However, after drying starts this is no longer true. The outer portion becomes dryer and the moisture tends to diffuse from the wetter interior to the drier exterior and then to the surface where it is evaporated. Is this drying rate constant throughout the drying process or does the rate of drying change? Is there any means, mathematical, graphical, or otherwise by which this can be represented so it will be of practical value?

Pertinent experimentation in this field has been limited. The use of the Fourier heat-conduction equations in the analysis of wood drying was suggested in 1925 by Tuttle (7). He carried on experiments drying slabs of Sitka spruce. Later Sherwood (4) performed similar experiments with poplar slabs and found his results to compare closely with Tuttle's data on spruce. Newman (3) further elaborated on Sherwood's mathematics but published no results of experiments.

Sherwood (4,5) derived two principal equations, which were used in carrying out the work herein described. In their present state they are too complicated to be of value to the ordinary operator.

In this problem the writer had as his objective the working out of some method by which the operator would be able to tell approximately the conditions under which he should operate the kiln to dry the stock within a certain period of time. Two important factors must be true of such a method; first, it must be simple enough so the ordinary operator can understand it, and second, it must give results of practical accuracy. From the experiments performed on the basis of Sherwood's results, the writer has attempted to devise a method of such character.

MODERN METHODS OF KILN DRYING

Artificial lumber seasoning is today being carried on under conditions over which the operator has direct control. This makes possible, not only more rapid and efficient drying, but also a better final product.

Drying conditions are varied according to the average moisture content of the stock in order to prevent casehardening, checking, warping, and other similar defects resulting from improper drying. In general, the drying period starts with a low temperature and high humidity. As drying progresses the temperature is raised and the humidity lowered. In each stage of drying the temperature and humidity remain constant. However, for certain purposes both may be kept constant throughout the entire drying period, as in the drying of common boards and dimension.

Humidities are chosen on the basis of equilibrium moisture contents, since most drying defects are due to too steep moisture gradients. In other words, the moisture gradient must be controlled.

Circulation in the modern kiln is produced by motor driven fans which are a great improvement over the old natural draught kiln. Here again the operator has control over the circulation rate. The fans may be of variable speed and reversible so the air can be circulated in either direction at various rates. The tendency is toward a faster circulation rate in order to reduce the temperature drop across the load. The faster the circulation rate the shorter will be the time necessary for the leaving-air side of the load to reach the same temperature as the entering-air side. Consequently, the shorter this period, the more even will be the drying.

For efficient dry kiln operation, it is becoming a common practice to segregate heartwood and sapwood pieces, and also flat and vertical grained heartwood rather than sending the straight mill run through the kiln. The reason for this is that the drying rates are not the same. Also, conditions which will satisfactorily dry one kind would damage another.

THE PROBLEM

The problem for solution was the devising of some method by which the minimum drying times for one-inch, rough Douglas fir could be predicted for various drying conditions commonly met in the lumber industry. The minimum times were selected because of the great variations in equipment and methods found in commercial use. These minumum times could be used to measure the efficiency of individual installations and could answer the perpetual question, "How fast can the lumber be dried?"

HOW THE DRYING WAS CARRIED ON

Drying for this work was carried on under practically the same conditions as those found in a modern commercial kiln with possibly two exceptions. The work was on a smaller scale and conditions were so fixed that the theoretical maximum drying rate was closely approached.

Since the drying of lumber depends on temperature, humidity and circulation, it was necessary that these be properly controlled at all times if drying was to be successful. To secure satisfactory drying, circulation must always be active, and the drying rate must be controlled and regulated by temperature and humidity. The average circulation rate was 550 feet per minute at a temperature of 140 degrees and 38 per cent relative humidity. This rate was kept constant and in one direction for all runs. The ideal aimed at was to get a circulation rate high enough so that there would be as small a temperature loss from the air as possible as it traveled through the load. The purpose of this was to have a uniform drying rate in all parts of the load.

Constant dry bulb temperatures of 190, 170, 150, and 130 degrees Fahrenheit were used. The humidity was kept constant for each drying stage. At the desired time it was lowered by dropping the wet bulb temperature.

All the runs were based on the equilibrium moisture content principle. Badger and McCabe (1) explain this as follows:

> "In general, a given material, if brought into contact with air of definite temperature and humidity, will reach a definite moisture content that will be unchanged by further exposure to this same air. This is known as the equilibrium moisture content of the material under the specified conditions. If the material contains more moisture than the equilibrium value it will dry until its moisture content reaches the equilibrium value. On the other hand, if the material is dryer than the equilibrium value and is brought into contact with air of the stated temperature and humidity, it will absorb water until it reaches this same equilibrium point."

Conditions were so regulated that most of the loads were subjected to three equilibrium moisture contents (10.8%, 7%, and 4.1%) as the drying progressed. The times when these changes were made were determined by the moisture content of the lumber. Samples were taken at the beginning to determine the moisture content of the stock. This gave a fairly close figure for the average moisture content of the load and was used for estimating when the changes should be made.

Each load was started at an equilibrium moisture content of 10.8% with a wet bulb depression of 12 degrees. When the lumber reached a moisture content of approximately 25%, the wet bulb was lowered to a depression of 23 degrees giving an equilibrium moisture content of 7%. Likewise, when drying had progressed to a moisture content of approximately 15%, the wet bulb was again lowered to a depression of 40 degrees giving an equilibrium moisture content of 4.1%. The lumber was then kept under these conditions until the kiln was shut down.

Since the dry bulb temperature was held constant, lowering of the equilibrium moisture content was brought about by the lowering of the relative humidity. Whether the dry bulb temperature be 190 degrees or 150 degrees, the wet bulb will, in both cases, be lowered the same amount to secure the desired equilibrium moisture content within the range of temperatures used. This is quite significant and simplifies matters for the operator, since it means that the equilibrium moisture content is governed by the wet bulb depression, i.e. the difference between the wet and dry bulb readings. Torgeson (6) has shown this in his discussion in regard to drying schedules which are equivalent in the sense that they produce the same moisture gradients in the drying lumber, even though the temperatures and relative humidities vary over quite a range.

EQUIPMENT

A great deal of criticism is many times directed at experimental work, the basis for such criticism being the fact that it is not applicable to practical situations. True, in a large portion of experimental work the equipment used is of a miniature nature or is in some manner quite different from that used in actual practice. The writer considers himself fortunate that he had standard dry kiln equipment at his disposal. This, supplemented with other needed instruments, made it an experimental as well as a practical piece of work.

The kiln used in this work is of the internal fan, reversible, cross-circulation type. It is full size in every detail with the exception of the length. The drying chamber has an inside dimension of 11 by 12 by 22 feet. This is exclusive of the lower part which houses the heating coils, spray line and fans. This lower part has a depth of about six feet. The drying chamber is of tile and concrete construction and is covered on the inside with a moisture and heat resisting paint. The open end of the kiln is closed by patented fire-proof double hinged doors.

The operating room is adjacent to the closed end of the kiln and contains the instruments and apparatus necessary to carry on the work. This apparatus includes the recording and controlling thermometers, air compressor, boiler, fan drive, scale dial and steam valves. Additional equipment for making moisture content determinations consist of a triple beam balance, an electric oven, and a small electric band saw.

Temperature and humidity are automatically controlled by means of a Foxboro controller-recorder. Its operation depends on two bulbs, one which measures temperature while the other is completely covered with a wick which is kept wet by being suspended in a water box receiving water from the operating room by means of a small copper tube. These two bulbs are located on the wall in the drying chamber equidistant from either end. By noting the difference between the temperatures of these two thermometers, the relative humidity may be determined.

This instrument can be set for any desired temperature and humidity and it is so constructed that its mechanism causes compressed air to operate diaphragm valves on the steam and spray lines. Air entering these valves causes them to open, and when the conditions reach the desired point they are closed by means of springs as the air pressure is released.

Another thermometer known as a Bristol recording thermometer was used to record the temperature drop across the load at the beginning of the run. The bulb of this instrument was placed on the side of the load opposite the controller bulbs. The loss in temperature of the air after it had traveled across the load was thus recorded.

Loss in weight, as the lumber progressed in drying, was read from the scale dial in the operating room. The loaded kiln trucks were run onto a scale platform which hung freely in the drying chamber by means of four iron rods. Through a system of levers on the roof of the kiln the pointer on the scale dial in the operating room gave the load weight. The dial was graduated in 25-pound divisions up to 37,000 pounds. The weight of the kiln trucks, baffles, and stickers were offset on the adjusting scale beam in the operating room, so that the scale dial indicated the weight of the lumber only.

Circulation was maintained in the kiln by means of three 38-inch, twelve-bladed, disc fans having variable speed control and a reversible motor making possible circulation in either direction. The fan speed could be varied from 325 to 605 revolutions per minute.

Steam for the heating coils was supplied by the college heating plant during the day and by the boiler at the kiln during the night. The heating coils were of the return bend header type and were in two banks, one on each side of the kiln just below the level of the track.

The vapor line, located underneath one set of steam coils, consisted of a single pipe with steam jets distributed evenly throughout its length.

CHECKING THE INSTRUMENTS

As an assurance that the instruments were in proper adjustment they were calibrated twice during the year on a rising temperature. For this calibration a thermometer having a United States Bureau of Standards certificate was used. In addition to this, the conditions inside the drying chamber were checked at least once during each run with a hygrometer (an instrument consisting of a wet and a dry bulb thermometer) to see if the existing conditions under which the lumber was drying were as indicated by the controller-recorder in the operating room.

RECORDING THE DATA

A complete record was kept of each kiln charge. A regular form was made, one of which was used for each run. All data which had any bearing whatsoever on the work were recorded thereon. Drying times, weights and corresponding moisture contents, temperatures, humidities, equilibrium moisture contents, kind of material, and conditions of the lumber after drying were some of the more important recordings.

MATERIAL

Lumber for this work was secured from the Corvallis Lumber Company. Douglas fir (Pseudotsuga taxifolia (LaMarck) Britton) heartwood only was used, sapwood not being attainable. It was ungraded, clear, one inch in thickness and ranged from three to six inches in width. Most of the material was either four or six inches wide. The material was sorted into vertical and flat grained loads at the mill. Such a segregation was necessary since the drying rates for vertical and flat grain lumber were thought to be different. Care was also taken to get lumber green from the saw.

PREPARATION OF LOADS

The lumber was piled horizontally on the kiln trucks, edge to edge with no space in between. Difficulty was experienced due to random lengths, but an attempt was made to "splice" the ends together so the load would be as nearly 20 feet in length throughout as possible with no open spaces within the load. In order to secure an even distribution of air, a full 20-foot face was maintained on the entering-air side of the load.

The loads were four feet wide or only one-half the width capacity. This reduced width lessened the temperature drop across the loads at the beginning of the runs. Also, this width was advantageous since it reduced the quantity of lumber required.

Each load was built nine layers or "courses" high and contained approximately 650 to 750 board feet. Between each layer, five stickers surfaced to one and one-third inches square and four feet long were placed at intervals of four feet across the load at right angles to the length. Care was taken to place the stickers directly over the steel bunks of the kiln trucks and each succeeding sticker directly over the preceding one. This prevented warping and twisting of the stock during seasoning.

Since such small loads were dried it was necessary to employ the use of temporary baffles. These consisted of pieces of sheet iron, one about three feet wide and 20 feet long supplemented by two smaller pieces about five feet long. These shorter pieces were used at the ends. These baffles were supported by stickers laid on top of the load and extending to the wall of the kiln. Since circulation was in this direction this baffling effect compelled all the air to go through the load. When the baffles were in place and the thermometer bulbs located as desired the doors were tightly shut and the load weight read in the operating room. As was previously stated this weight is that of the lumber alone, the weight of the trucks, stickers and baffles being offset before loading.

OPERATING THE KILN

The operation of the dry kiln during the work on the problem, with the exception of recording data, was very similar to that of an ordinary commercial operation. Greater care and attention were, no doubt, exercised than would be the case in the regular operation.

After the load was in place in the drying chamber and the doors tightly closed, the kiln was ready to be started. Before starting, a complete oiling of all the necessary parts was made. The load weight was also read and recorded. The charts were placed on the recording-controlling and recording instruments and the pens set for the desired temperature and humidity. The fans were then started and steam turned into the heating coils and spray lines. After the desired drying conditions were reached, they were automatically maintained at this point by the recording-controlling thermometer until further changes were made. Both wet and dry bulb temperatures were graphically recorded on the charts throughout the entire run. During the first hour or hour and a half the load weights were read at fifteen minute intervals in order that the behavior of the lumber in the earliest stages of drying might be observed.

By noting the chart on page 17, it will be seen that the load increases in weight at the beginning of the run. This "pick up" is due to the cold air in the kiln and the cold lumber condensing the steam used for humidifying the air, the condensate thus collecting on the lumber and increasing the weight. It usually requires about one hour from the time the kiln is started until the load reaches its original weight and removal of water from the wood actually starts. From this time until the kiln was shut down, the load weights were taken at three or four-hour intervals except during the night when the last reading was taken at mid-night.

Once each day a complete oiling and inspection of the mechanical parts were made to insure proper operation and the avoidance of serious break downs.

MOISTURE CONTENT DETERMINATION

In cutting samples for the determination of moisture content certain things had to be observed if correct results were to be obtained. The samples were cut at least two feet from the ends of the boards. Samples taken at the very ends would not give accurate results because they would usually be dryer than the bulk of the

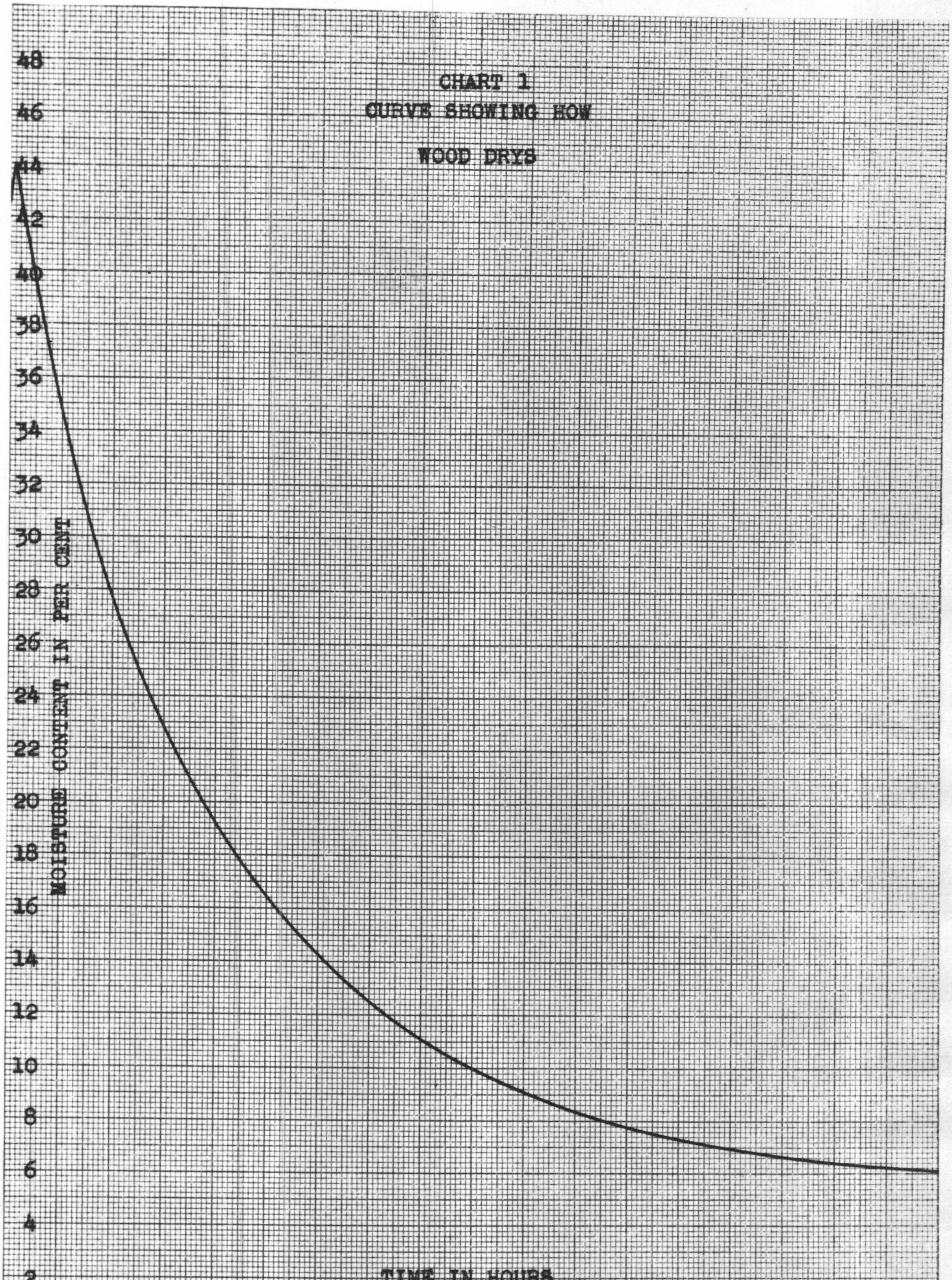


CHART 1
CURVE SHOWING HOW
WOOD DRYS
MOISTURE CONTENT IN PER CENT
48
46
44
42
40
38
36
34
32
30
28
26
24
22
20
18
16
14
12
10
8
6
4
2
TIME IN HOURS
5 10 15 20 25 30 35 40 45 50 55 60 65 70 75 80 85

lumber since evaporation is faster from the ends. Sample cuts were not made through any abnormalities in which the moisture content would not be typical. By the use of the small band saw, cross-section wafers about one-half inch thick were cut. These samples were selected from every other layer on both sides of the load and their positions recorded. In addition to a sample for the moisture content of the whole piece, a second sample was so sawed as to have the shell of the sample and the core separate in order to note the uniformity of drying in the final product.

Immediately after cutting, the samples were weighed on the small scale and the weights recorded to the nearest hundredth of a gram. The weight of each sample was thus obtained and recorded as original weight. After all the samples had been cut and weighed in this manner, they were placed in the electric drying oven at a temperature of 212 degrees Fahrenheit and allowed to remain until they reached a constant weight. At this point the samples were again weighed and this weight recorded as oven dry weight. Moisture contents were thus calculated on the basis of oven dry weight by the formula

$$\left(\frac{\text{original weight}}{\text{dry weight}} - 1\right) 100 = \text{moisture}$$

content in per cent.

The average moisture content as indicated by these samples taken at the end of the run, was used as a basis for calculating the average original moisture content of the load and the intermediate moisture contents during the drying period.

RUN 1

FLAT GRAIN HEARTWOOD----DRY BULB TEMPERATURE 130°
WET BULB TEMPERATURES---118°, 107°, 90°.

Load Weight	Time in kiln in hours	Moisture content in per cent
2000	0	29.67
2020	.25	30.96
2040	.50	32.26
2030	.75	31.61
2020	1.00	30.96
2000	2.00	29.67
1985	3.00	28.70
1950	5.00	26.43
*1915	7.75	24.16
1890	9.50	22.54
1875	11.50	21.56
1860	12.75	20.59
1805	20.50	17.03
1795	21.75	16.38
1790	24.75	16.05
*1785	28.75	15.73
1770	31.75	14.76
1765	33.00	14.43
1745	36.75	13.13
1725	44.75	11.84
1725	49.50	11.84
1715	56.00	11.19

* Schedule change.

Average original moisture content---29.67%

Average final moisture content------11.19%

Average final moisture gradient----- 6.14%

Drying time--------------------------56.00 hours

Casehardening---------------------- none

Checking--------------------------- none

Warping---------------------------- none

RUN 2

FLAT GRAIN HEARTWOOD----DRY BULB TEMPERATURE 150°
WET BULB TEMPERATURES---138°, 127°, 110°.

Load Weight	Time in kiln in hours	Moisture content in per cent
2410	0	40.26
2425	.25	41.13
2425	.50	41.13
2410	.75	40.26
2395	1.00	39.38
2320	3.00	35.02
2290	4.00	33.27
"2250	6.50	30.94
2235	7.00	30.07
2080	15.25	21.05
"2070	16.00	20.47
2050	18.50	19.30
2030	20.75	18.14
1990	25.00	15.81
1985	27.50	15.52
1970	30.50	14.65
1930	39.00	12.32
1925	41.00	12.03

" Schedule change.

Average original moisture content----40.26%

Average final moisture content-------12.03%

Average final moisture gradient------ 7.57%

Drying time--------------------------41.00 hours

Casehardening----------------------- none

Checking---------------------------- none

Warping----------------------------- none

RUN 3

FLAT GRAIN HEARTWOOD----DRY BULB TEMPERATURE 170°
WET BULB TEMPERATURES---158°, 147°, 130°.

Load Weight	Time in kiln in hours	Moisture Content in per cent
2310	0	42.72
2325	.25	43.64
2330	.50	43.95
2320	.75	43.33
2310	1.00	42.72
2300	1.25	42.10
2235	3.00	38.08
2210	4.00	36.54
2165	5.00	33.76
2125	7.00	31.29
2075	9.50	28.20
2060	11.00	27.27
"2050	12.00	26.65
1990	15.00	22.95
1940	19.25	19.86
1915	24.00	18.31
1890	26.25	16.77
"1865	27.75	15.22
1840	30.75	13.68
1835	31.50	13.37
1820	34.25	12.44
1810	35.50	11.83
1805	36.25	11.52
1800	38.50	11.21
1770	47.00	9.35
1765	50.00	9.05
1755	54.25	8.43
1750	56.50	8.12

" Schedule change.
Average original moisture content----42.72%
Average final moisture content------- 8.12%
Average final moisture gradient------ 3.63%
Drying time---------------------------56.50 hours
Casehardening-------------------------slight
Checking----------------------------- none
Warping------------------------------ none

RUN 4

FLAT GRAIN HEARTWOOD----DRY BULB TEMPERATURE 190°
WET BULB TEMPERATURES---178°, 167°, 150°.

Load Weight	Time in kiln in hours	Moisture content in per cent
2025	0	42.40
2050	.25	44.16
2055	.50	44.51
2040	.75	43.46
2030	1.00	42.75
1990	1.50	39.94
1935	3.00	36.07
1925	3.50	35.37
1885	5.25	32.56
1845	7.00	29.74
1820	8.50	27.97
"1790	10.50	25.88
1770	11.25	24.47
1745	12.50	22.71
1720	16.25	20.95
1690	19.50	18.84
1665	24.00	17.09
" 1640	27.00	15.33
1600	30.00	12.52
1585	33.25	11.46
1580	34.50	11.11
1570	36.00	10.41
1565	37.00	10.05
1560	39.25	9.70
1535	48.00	7.94
1525	53.00	7.24
1520	54.25	6.89

" Schedule change.
Average original moisture content-----42.40%
Average final moisture content-------- 6.89%
Average final moisture gradient------- 3.22%
Drying time----------------------------54.25 hours
Casehardening--------------------------slight
Checking-------------------------------none
Warping------------------------------- none
Lumber steamed at end of run at 100% humidity
for one-half hour to remove casehardening.

RUN 5

VERTICAL GRAIN HEARTWOOD----DRY BULB TEMPERATURE 130°
WET BULB TEMPERATURES--------118°, 107°.

Load Weight	Time in kiln in hours	Moisture content in per cent
1875	0	30.04
1895	.25	31.42
1880	.50	30.38
1875	.75	30.04
1865	1.00	29.34
1855	1.75	28.65
1825	4.00	26.57
1800	6.25	24.83
1785	7.25	23.79
1770	9.75	22.75
1760	11.00	22.06
1750	13.00	21.37
1720	22.00	19.29
1715	24.00	18.94
1700	27.75	17.90
1690	29.75	17.20
1685	31.75	16.86
1680	34.75	16.51
1670	46.50	15.82
1670	48.00	15.82
1665	50.00	15.47
*1660	54.00	15.12
1640	58.50	13.74
1630	60.50	13.04
1620	70.00	12.34
1605	76.50	11.31

* Schedule change.
Average original moisture content----30.04%
Average final moisture content--------11.31%
Average final moisture gradient------- 4.96%
Drying time---------------------------76.50 hours
Casehardening------------------------ none
Checking------------------------------ none
Warping------------------------------- none
This was the only run in which the schedule was changed but once.

RUN 6

VERTICAL GRAIN HEARTWOOD----DRY BULB TEMPERATURE 150°
WET BULB TEMPERATURE--------138°

Load Weight	Time in kiln in hours	Moisture content in per cent
1855	0	32.20
1875	.25	33.63
1880	.50	33.98
1875	.75	33.63
1865	1.00	32.92
1860	1.25	32.56
1855	1.50	32.20
1825	2.50	30.06
1785	4.50	27.21
1760	6,00	25.43
1740	8.50	24.01
1725	9.75	22.94
1700	13.25	21.16
1665	21.00	18.66
1655	23.75	17.95
1645	26.50	17.24
1620	29.50	15.45
1610	36.50	14.74
1590	45.75	13.32
1585	49.25	12.96
1585	53.75	12.96

Average original moisture content----32.20%

Average final moisture content--------12.96%

Average final moisture gradient------ 4.46%

Drying time--------------------------53.75 hours

Casehardening----------------------- none

Checking---------------------------- none

Warping----------------------------- none

This was the only run in which the schedule was not changed.

RUN 7

VERTICAL GRAIN HEARTWOOD----DRY BULB TEMPERATURE 170°
WET BULB TEMPERATURES--------158°, 147°, 130°.

Load Weight	Time in kiln in hours	Moisture content in per cent
2125	0	36.62
2150	.25	38.23
2155	.50	38.55
2145	.75	37.90
2135	1.00	37.26
2125	1.25	36.62
2115	1.50	35.98
2090	2.25	34.37
2025	4.75	30.19
1975	8.00	26.97
1930	11.50	24.08
"1925	12.00	23.76
1860	16.50	19.58
1825	19.25	17.33
1795	23.75	15.40
1785	27.50	14.76
"1785	28.50	14.76
1745	33.00	12.19
1735	36.25	11.54
1725	38.50	10.90
1695	47.50	8.97
1690	51.00	8.65
1685	56.25	8.33
1685	56.75	8.33

" Schedule change.

Average original moisture content----36.62%

Average final moisture content------- 8.33%

Average final moisture gradient------ 5.39%

Drying time---------------------------56.75 hours

Casehardening------------------------ none

Checking----------------------------- none

Warping------------------------------ none

RUN 8

VERTICAL GRAIN HEARTWOOD----DRY BULB TEMPERATURE 190°
WET BULB TEMPERATURES--------178°, 167°, 150°.

Load Weight	Time in kiln in hours	Moisture content in per cent
1900	0	36.20
1925	.25	37.99
1930	.50	38.35
1920	.75	37.63
1905	1.00	36.56
1870	2.00	34.05
1765	6.25	26.52
"1745	8.50	25.09
1675	12.00	20.07
1650	14.00	18.28
1625	16.00	16.49
"1600	19.75	14.69
1570	23.50	12.54
1555	26.50	11.47
1535	29.50	10.04
1530	32.60	9.68
1520	36.00	8.96
1515	38.00	8.60
1495	47.50	7.17
1490	48.75	6.81
1490	50.50	6.81

" Schedule change.

Average original moisture content---36.20%

Average final moisture content------ 6.81%

Average final moisture gradient----- 3.07%

Drying time--------------------------50.50 hours

Casehardening------------------------slight

Checking----------------------------- none

Warping------------------------------ none

Lumber steamed at end of run at 100% humidity

for one-half hour to remove casehardening.

THEORY OF DRYING

The work carried on for this paper was based on the theory that the rate of drying is dependent on the rate of diffusion of water in the wood. As the lumber is dried, the outer portions of the pieces become drier than the interior, and, since water has the natural tendency of going from a wetter to a drier region, this moisture in the interior will pass outward to the drier portion. The faster this process of diffusion can be made to occur, the faster will be the drying rate.

Temperature influences this rate since heat lowers the viscosity of water. Consequently, diffusion will be more rapid. Relative humidity has the effect of hastening the drying to the extent that the lower the relative humidity, the lower will be the equilibrium moisture content, and hence the greater will be the difference in concentrations of water at the center and at the surface of the stock. In general, the greater the difference in concentrations of water, the faster will be the drying. Koehler (2) states that the humidity may be so low as to slow up the drying by having the shell of the wood so dry that capillarity is cut off. The moisture gradient cannot be too steep, however, for serious drying defects may develop.

EQUATIONS AND CALCULATIONS

The rate of diffusion of moisture from the center of a piece of material to the outside appears to be governed by the same mathematical laws as is the transfer of heat. Hence, it was the Fourier heat conduction equations that Sherwood (4) used as a basis for his drying equations.

Two of Sherwood's equations were used as the basis for this work. Equation I applies to uniformly wet material and equation II to partially dried material where the surface is in equilibrium with the drying conditions. Practically all drying falls within the limits of these two equations.

Equation I

$$E = \frac{8}{\pi^2}\left[e^{-\left(\frac{\pi}{2}\right)^2\frac{K\theta}{R^2}} + \frac{1}{9}e^{-9\left(\frac{\pi}{2}\right)^2\frac{K\theta}{R^2}} + \frac{1}{25}e^{-25\left(\frac{\pi}{2}\right)^2\frac{K\theta}{R^2}} + \text{---------}\right]$$

Equation II

$$E' = \frac{96}{\pi^4}\left[e^{-\left(\frac{\pi}{2}\right)^2\frac{K\theta}{R^2}} + \frac{1}{81}e^{-9\left(\frac{\pi}{2}\right)^2\frac{K\theta}{R^2}} + \frac{1}{625}e^{-25\left(\frac{\pi}{2}\right)^2\frac{K\theta}{R^2}} + \text{-------}\right]$$

Nomenclature:

E is the ratio of the evaporable water content at any time to the initial evaporable water content.

E' is the ratio of the evaporable water content at any time to the evaporable water content after a moisture gradient is set up and the surface of the stock is in equilibrium with the drying conditions prevailing.

K is the diffusion constant.

R is one-half the thickness in inches.

θ is the time in hours.

e is the natural base of logarithms (2.718).

In spite of their complicated appearance, these formulas are simply relations between E and $K\theta/R^2$ and E' and $K\theta/R^2$. In other words, they show the relation between the amount of evaporable water to the rate of diffusion. The following table shows values for E and E' at various values of $K\theta/R^2$. The values were calculated by Sherwood (5) by substituting various values of $K\theta/R^2$ in the equations and then solving for E and E'.

TABLE I

VALUES OF E AND E' CALCULATED FROM EQUATIONS I AND II FOR CORRESPONDING VALUES OF $K\theta/R^2$

$K\theta/R^2$	E	E'
0	1.0	1.0
0.02	0.840	0.951
0.05	0.749	0.880
0.10	0.643	0.775
0.15	0.563	0.684
0.20	0.496	0.605
0.30	0.387	0.473
0.50	0.236	0.290
1.00	0.069	0.086

A chart showing the relations of E and E' to $K\theta/R^2$ plotted from this table is shown on page 32. For this work it was necessary to use semi-logarithmic paper in order that the relation be a straight line. These curves eliminate the algebraic solutions of equations I and II and from them the values for E and E' can be read for any value of $K\theta/R^2$ or vice versa.

By observing these two curves it will be noticed that the curve for equation I is not a straight line at the beginning but drops rapidly from the origin. This is due to the rapid loss of moisture from green material at the beginning of the drying period. In order to compare experimental data with the theoretical curve, a special plotting paper was constructed using a uniform abscissa scale but so changing the ordinate scale as to force the

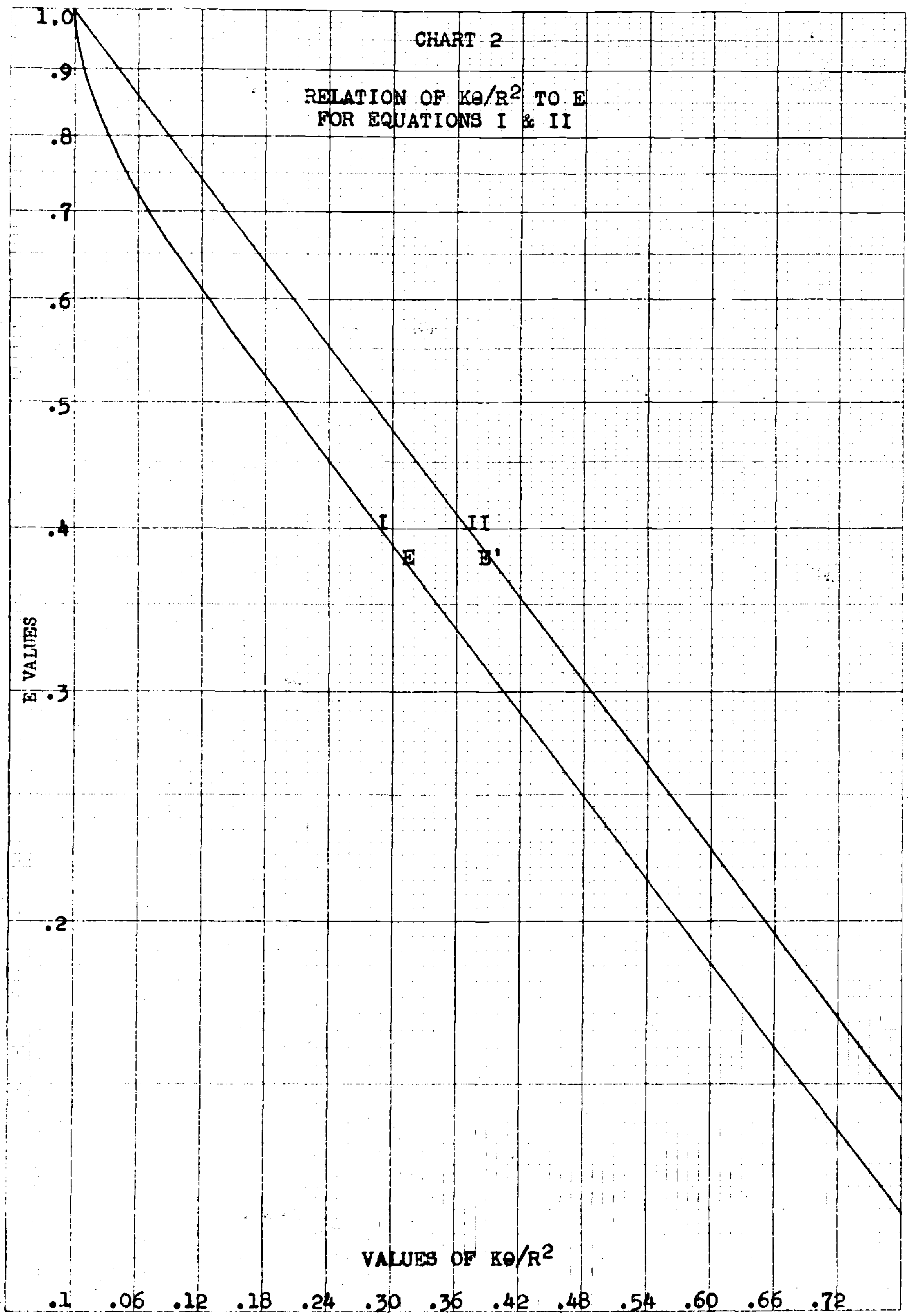


CHART 2
RELATION OF Kθ/R2 TO E
FOR EQUATIONS I & II
1.0
.9
.8
.7
.6
.5
.4
.3
.2
.1
E VALUES
I
II
E
E'
VALUES OF Kθ/R2
.06
.12
.18
.24
.30
.36
.42
.48
.54
.60
.66
.72

theoretical relation into a straight line. With this special paper, since the abscissa scale is uniform, data following the theoretical relation will fall on a straight line when plotted as E versus time. By noting the time taken to reach a value of E for which $K\theta/R^2$ is known the K value can be determined. The chart on page 32 can be referred to to find $K\theta/R2$ for any value of E or E'.

For each of the eight runs from which the data for this work were taken, diffusion constants were calculated. The constants may be calculated as follows:

1. Determine the moisture contents of the lumber at the various recorded times in the drying period.
2. Calculate E for each of these moisture contents by using the equation

$$\frac{M_t - M_e}{M_o - M_e} = E,$$

where M_o is the average moisture content at the beginning, M_t the average moisture content at any time, and M_e the equilibrium moisture content. As an example let us say that the average moisture content at the beginning is 30.04%. At a later time, the average moisture content is 28.65% and the drying conditions produce an equilibrium moisture content of 10.8%.

Substituting in the equation,

$$E = \frac{28.65\% - 10.8\%}{30.04\% - 10.8\%} = .928$$

The value of E for each moisture content was so determined.

3. Plot these E values and times on semi-logarithmic paper on which the special scale has been constructed.
4. Draw a straight line through these points.
5. If the line does not go through the point where E equals one and time zero, draw a parallel line that does. (There are only two cases when this line will go through the origin. These are when the lumber is uniformly wet and dries according to equation I or when the material is partially dried to the point where the surface is in equilibrium with the drying conditions and drying follows equation II.) Run number five plotted in this way is shown on page 35.
6. On this straight line choose any E value for which $K\theta/R^2$ is known. The known value of $K\theta/R^2$ may either be taken from the table on page 31 or direct from the chart, page 35. Substitute the value of time in hours at this E value and the thickness of the material in inches. Then solve for K.

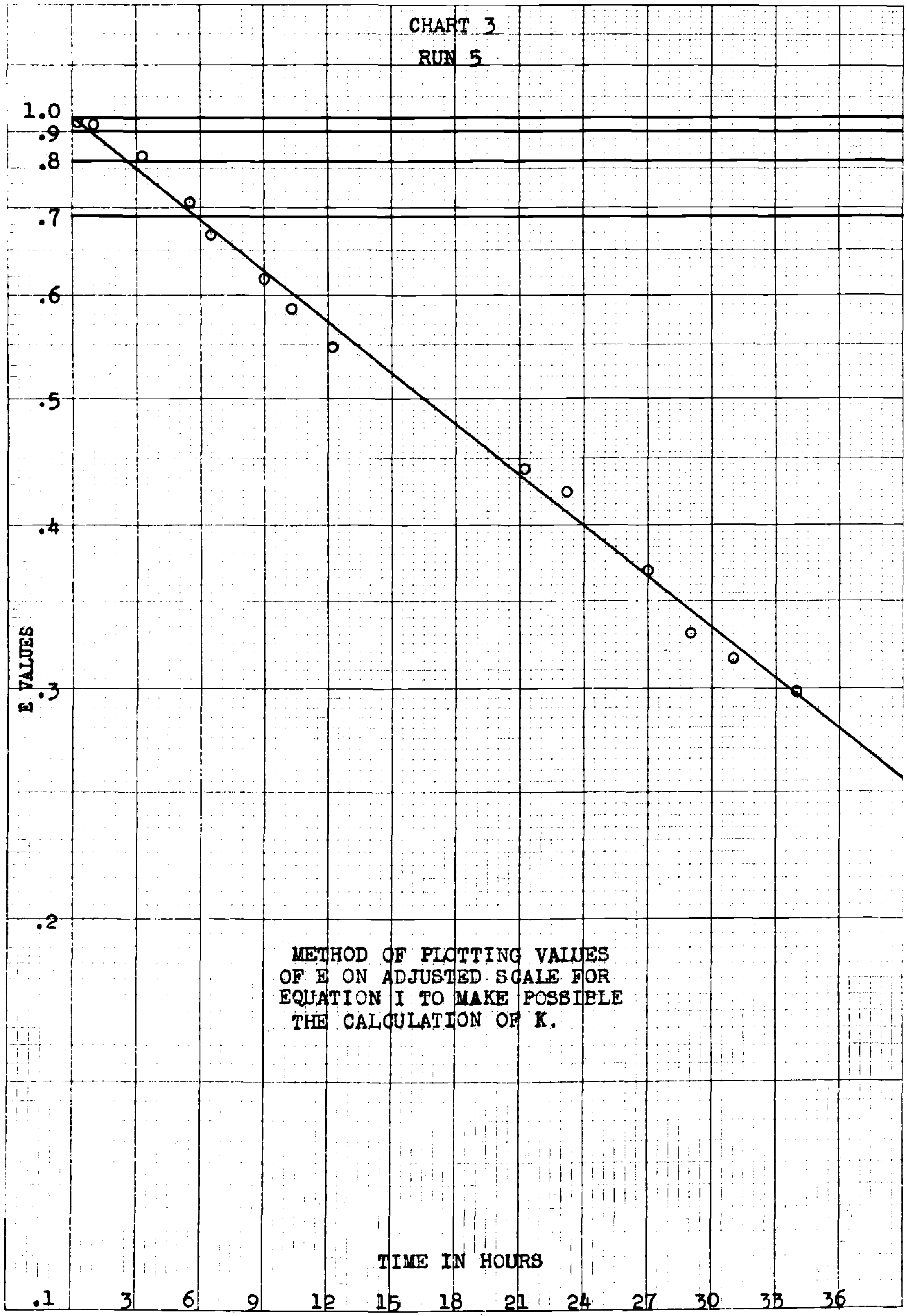


CHART 3
RUN 5
1.0
.9
.8
.7
.6
.5
.4
E VALUES
.3
.2
METHOD OF PLOTTING VALUES
OF E ON ADJUSTED SCALE FOR
EQUATION I TO MAKE POSSIBLE
THE CALCULATION OF K.
TIME IN HOURS
.1
3
6
9
12
15
18
21
24
27
30
33
36

Using run number five as an example, from the table on page 31, $K\theta/R^2$ is .25 when E is .440. From the chart of run number five, page 35, it will be noted that the time is 20.75 hours at this E value. The thickness is one inch. Therefore to solve for K the equation becomes,

$$K\theta/R^2 = .25 \text{ when E is } .440$$

$$K \times 20.75/(\tfrac{1}{2})^2 = .25$$

$$4K \times 20.75 = .25$$

$$K = .25/4 \times 20.75$$

$$K = .0030$$

This means that the diffusion constant is .0030 square inches per hour.

A table showing the K values for the eight runs is shown below. It is the general belief that flat grain lumber dries faster than vertical grain stock, but the results of this work show very little difference in the K values for the two kinds of material used (mainly 1 x 4 and 1 x 6 inch strips).

TABLE II

K VALUES DETERMINED FROM EXPERIMENTAL WORK
FOR FLAT AND VERTICAL GRAIN HEARTWOOD

Flat Grain		Vertical Grain	
Temperature	K value	Temperature	K value
190°	.0055	190°	.0055
170	.0047	170	.0049
150	.0041	150	.0040
130	.0033	130	.0030

Since K values at only four temperatures were determined due to insufficient time, these values were plotted, and from the resulting curve, values for other temperatures were taken to make the following table:

TABLE III

DRY BULB TEMPERATURES FOR VARIOUS K VALUES

Temperature	K value
200°	.0058
195	.0057
190	.0055
185	.0053
180	.0052
175	.0050
170	.0048
165	.0046
160	.0044
155	.0042
150	.0040
145	.0038
140	.0036
135	.0033
130	.0031
125	.0029
120	.0026

To put this material in a form so it will be of practical use, two calculating charts, one for each equation, were devised. (Pages 38 and 39). They were constructed by determining the times at various K values and one value of E using the same method as in solving for K except in this case time was the unknown quantity. An arc was drawn by using the point E = 1, and time = 0, as if it were the center of a circle. The K values were

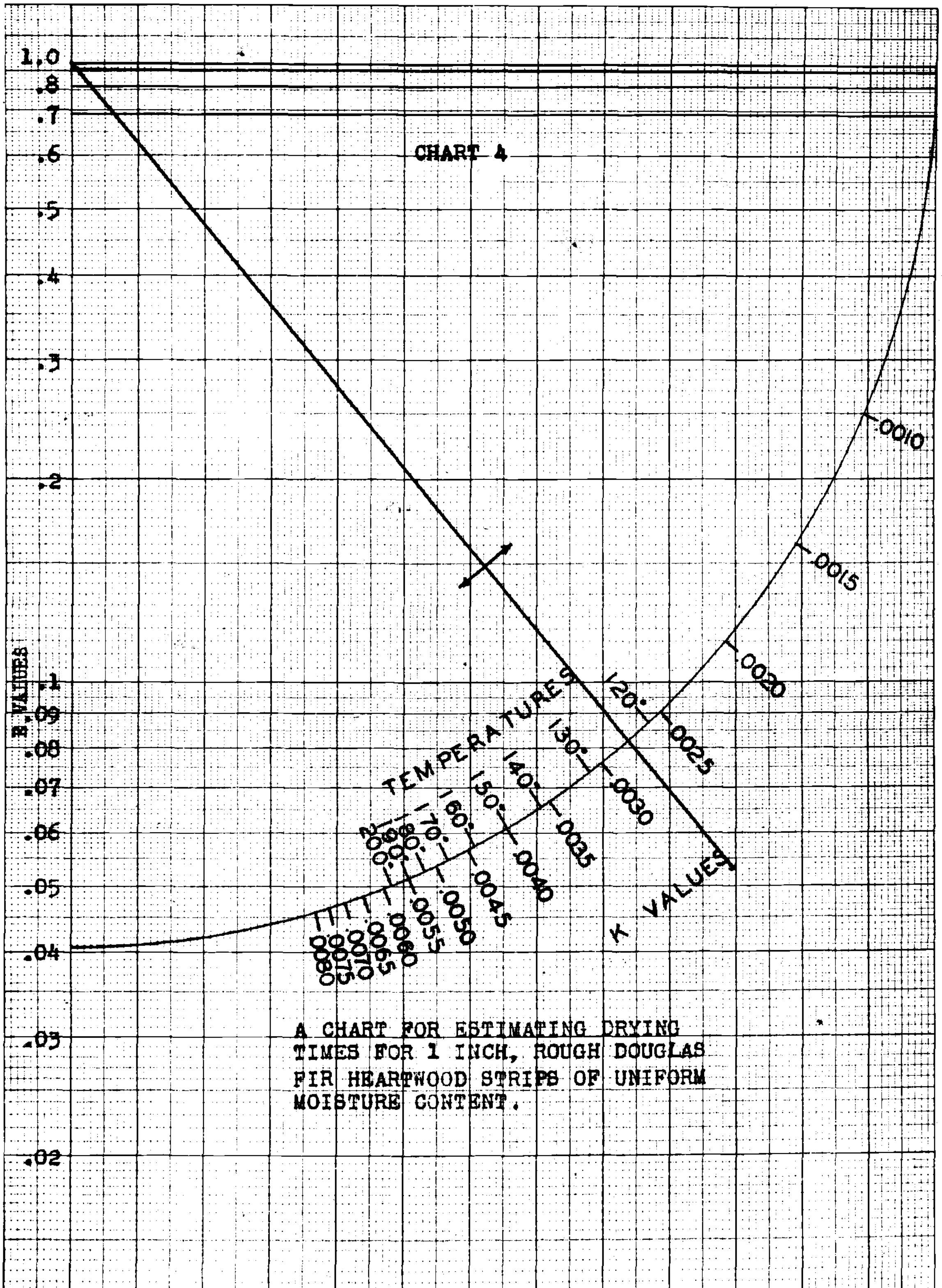
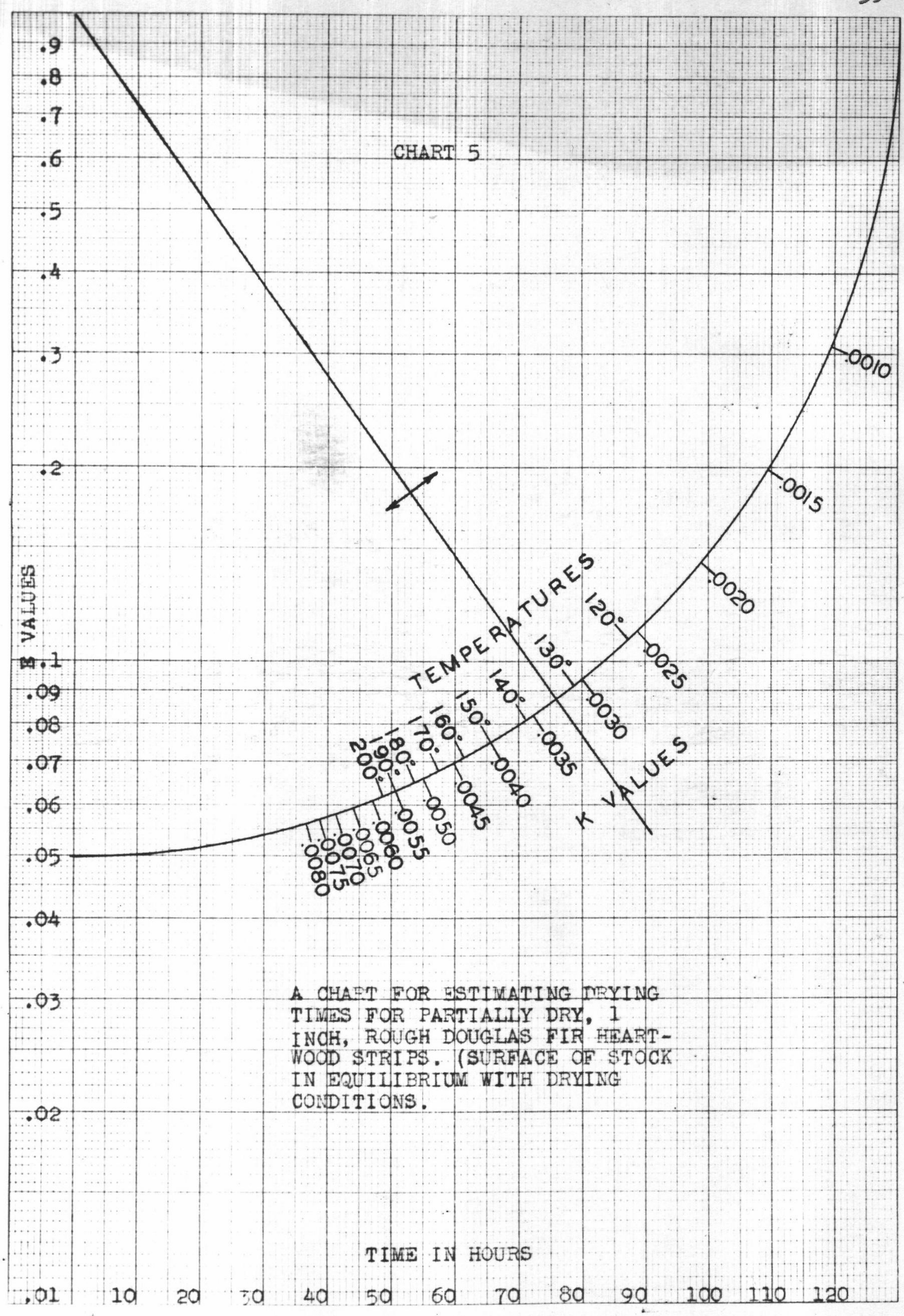


CHART 4
E VALUES
1.0
.8
.7
.6
.5
.4
.3
.2
.1
.09
.08
.07
.06
.05
.04
.03
.02
.01
TEMPERATURES
120°
130°
140°
150°
160°
170°
180°
190°
200°
K VALUES
.0010
.0015
.0020
.0025
.0030
.0035
.0040
.0045
.0050
.0055
.0060
.0065
.0070
.0075
.0080
A CHART FOR ESTIMATING DRYING TIMES FOR 1 INCH, ROUGH DOUGLAS FIR HEARTWOOD STRIPS OF UNIFORM MOISTURE CONTENT.
TIME IN HOURS
10
20
30
40
50
60
70
80
90
100
110
120



A CHART FOR ESTIMATING DRYING TIMES FOR PARTIALLY DRY, 1 INCH, ROUGH DOUGLAS FIR HEARTWOOD STRIPS. (SURFACE OF STOCK IN EQUILIBRIUM WITH DRYING CONDITIONS.

located on this arc by drawing straight lines through E equals 1 at zero time and the times computed for various values of K. The points on the arc cut by these lines were then labelled with the proper values for the diffusion constants. In addition, to simplify use of the charts, the temperatures corresponding to the diffusion constants were also placed on the arc. Since there were no significant differences between the diffusion constants for flat grain and vertical grain strips, only one set of temperatures is shown on the charts.

HOW TO USE THE CHARTS

To use the charts for calculating drying times for any conditions of relative humidity, moisture content, or temperature within the range of the charts, the following rules are given for four cases of drying.

CASE I. Where the stock is uniformly green and the drying is carried on under a constant temperature and constant humidity schedule throughout:

1. Use Chart 4.
2. The average original moisture content of the lumber must be known.
3. The equilibrium moisture content corresponding to the particular relative humidity-temperature combination must be known.

4. To find the time required to dry lumber from one moisture content to another the fraction of evaporable water, E, that is left at the time the lower moisture content is reached must be calculated.
5. When E has been found by step 4, a string or straight edge should be placed on the chart so that it strikes off a straight line from E equals one at zero time, and extends through the proper K value on the arc (or through the temperature used).
6. Where this line intersects the E value found in step 4, read on the horizontal scale the time required for drying from the first to the second moisture content.

<u>CASE II</u>. Where the schedule involves more than one stage of constant temperature and constant humidity conditions:

1. For uniformly green material use Chart 4.
2. For the first stage of drying follow the procedure in Case I.
3. For the second stage, a new E value will have to be calculated based upon the original moisture content of the stock and the moisture content of

the stock at the end of the first stage of drying. This new E will have to be determined with the new equilibrium moisture content.

4. Likewise, the E value which will exist for the moisture content of the stock at the end of the second stage must be calculated.
5. Strike off a straight line again through E equals one at zero time and the appropriate E value or temperature used.
6. To find the time required, note the time on the horizontal scale corresponding to the last E value calculated and from this time subtract the time indicated by the new E value calculated for the moisture content at the beginning of the second stage of drying.
7. If three stages exist, proceed as previously outlined for stage two.

CASE III. When the material is partially dried and the surface is at equilibrium with the drying conditions (lumber which has been stored for only a few days awaiting kiln drying):

1. Use Chart 5.
2. Proceed as for Case I or II, depending on the number of drying stages involved.

<u>CASE IV.</u> When lumber has been air seasoned, an approximation of the drying time may be determined as follows:

1. Use Chart 4.
2. Use the average moisture content prevailing in the region for green material (36% to 38% in this area) as the original moisture content.
3. Proceed as for Case II.

For a clearer understanding of the use of the charts, three examples of finding drying times are shown below.

<u>CASE I.</u> Assume original moisture content to be 36.62% based on oven dry weight and that the stock is to be dried under constant temperature and humidity conditions to 23.76% moisture content. The temperature of 170° F corresponds to a K value of .0048 and the humidity used causes a 10.8% equilibrium moisture content.

$$E = \frac{23.76\% - 10.8\%}{36.62\% - 10.8\%} = \frac{12.96}{25.82} = .501$$

Using Chart 4, the time is observed to be 10.5 hours.

<u>CASE II.</u> Assume the same data as in Case I, but change the schedule so that the relative humidity is lowered to produce an equilibrium moisture content of 7% at a moisture content of 23.76%. The stock is to be dried to 14.76% under these new conditions. What is the time

required in this stage?

1. Use Chart 4.

2. Calculate an E value based on the original moisture content of 36.62% and 23.76% using a 7% equilibrium moisture content.

$$E = \frac{23.76\% - 7\%}{36.62\% - 7\%} = \frac{16.76}{29.62} = .516$$

3. Calculate an E value for the moisture content of 14.76% using the original moisture content of 36.62% as a basis.

$$E = \frac{14.76\% - 7\%}{36.62\% - 7\%} = \frac{7.76}{29.62} = .262$$

4. Note time at E = .262 to be 23.8 hours.

5. Note time at E = .516 to be 9.7 hours.

6. Subtract time of 5 from 4 and get 14.1 hours as required time for the second stage of drying.

<u>CASE III.</u> This is a theoretical case at the present time, since no runs have been made to check experimentally. Let us assume that the stock is air dried to an average moisture content of 18%, and that the kiln conditions are set so that the stock will be dried at a temperature of 170° corresponding to a K value of .0048 and an equilibrium moisture content of 7%. The average moisture content of the stock is 36% as it comes from the saw, and is to be dried to 11%.

1. The E value at the start of the drying period based on an original moisture content of 36% is:

$$E = \frac{18\% - 7\%}{36\% - 7\%} = \frac{11}{29} = .379$$

2. The E value for 11% moisture content is:

$$E = \frac{11\% - 7\%}{36\% - 7\%} = \frac{4}{29} = .138$$

3. Time observed when E = .138 is 37.2 hours.

4. Time observed when E = .379 is 15.2 hours.

5. Subtract 4 from 3 and the time is 22.0 hours.

In each of these cases, to find the total drying time required, the time necessary to heat the kiln and lumber at the beginning must be added to the time read on the chart. Where lumber is dried under more than one set of conditions, the sum of the drying times for each stage plus the time to heat the lumber will give the total drying time.

PRACTICAL VALUE OF CHARTS 4 AND 5

As the dry kiln operator becomes accustomed to the use of these charts, he will find that they are of value in a number of ways:

1. They can be used for determining necessary drying conditions to dry lumber in a certain specified time.

2. Using a specified set of conditions, the time required can be found.
3. Since these charts were based upon conditions which closely approached the theoretical maximum drying rate, they can be used to measure performance in an already existing kiln. This knowledge will help to determine whether the expenditure of money for new equipment is justified. If the lumber on the leaving side of the load, in a practical operation, does not dry as fast as indicated by the charts, a faster air circulation is needed.
4. It makes possible the determination of the most efficient drying schedules.

PROBABLE SOURCES OF ERROR

The only source of error which might occur in the data from which the calculating charts were made is in reading the scale weights. Since the scale was graduated in 25-pound divisions, the weights could be estimated only to the nearest five pounds. This largely was compensated for in drawing average curves through the points plotted.

Another possible source of error in calculating the diffusion constants might be found in the equilibrium moisture contents used. While much work has been done in determining them, not too much is known about their exact values, particularly at low relative humidities. The choice of an erroneous equilibrium moisture content would have the effect of changing the value of the fraction of evaporable water contained in the lumber. This, of course, would change the slope of the drying curve, leading to the calculation of an erroneous diffusion constant. For the range of humidities and temperatures used, the likelihood of serious error in this connection is small.

SUMMARY

Diffusion constants have been calculated and two charts were constructed which indicate the approximate minimum time required to dry one-inch, rough Douglas fir strips from practically any condition of original moisture content to any other moisture content within a range of 130° F. to 190° F. and at various relative humidities. The use of times indicated by these charts necessitates the following conditions: (1) constant temperature and constant humidity during the drying stage, (2) drying mainly from two faces of the stock, and (3) a velocity of air sufficient to reduce the surface of the lumber in all parts of the load to the same equilibrium moisture content at the same or nearly the same time. These charts also give a more accurate measure of the efficiency of a particular kiln and give the operator information which will allow him to make his installation more flexible to meet changed production schedules.

Diffusion constants calculated were practically the same for flat and vertical grained material. Future work should be directed to a verification or revision of these constants, and, in addition, diffusion constants should be determined for wide boards of the heartwood class as

well as for sapwood material.

The results of the work used as a basis for this paper seem to substantiate the drying equations developed by Sherwood.

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