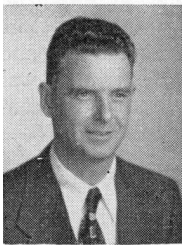
PURCHASED BY THE
U. S. DEPARTMENT OF AGRICULTURE
FOR OFFICIAL USE



Drying Stresses in Red Oak: Effect of Temperature[1]

JOHN M. McMILLEN[2]

Technologist, Forest Products Laboratory,[3] Forest Service, U. S. Department of Agriculture

The effects of kiln drying at 80° to 140° F. and controlled room drying at 35° and 80° F. on tensile and compressive stresses, perpendicular to grain, in 2-inch red oak are reported. Increasing temperature tended to increase maximum tensile strain in the outside layers at the start of drying and maximum tensile strain in the center layers after stress reversal. Maximum compressive strain in the center layers was about the same at most temperatures but considerably lower at 140° F. Temperature had little effect on tension set in the outside layers. The greater compression set in the interior layers at higher temperatures resulted in significantly greater board shrinkage.

Introduction

THIS IS THE SECOND REPORT on studies of the internal stresses set up in red oak during drying, as revealed by strain analysis. The first (6)[4] covered effects of humidity changes on tensile and compressive stresses in 2-inch red oak during kiln drying at 110° F. This one covers the effects of different kiln-drying temperatures from 80° to 140° F. when a schedule of mild humidity reductions is used. It also deals to a limited extent with the effects of controlled room drying at 35° and 80° F.

The material and procedure were similar to those of the previous study. In addition to the primary findings on internal stresses, significant data were obtained on set and shrinkage, and their far-reaching, practical implications are fully discussed.

Past research and experience show that the ultimate strength and stiffness of wood are reduced when the temperature is increased. This is especially so when the wood has a high moisture content. There also is a temperature effect on the permanent deformations or sets resulting from tension and compression beyond the proportional limit, when failure does not occur. Furthermore, there is a temperature-duration effect that progressively weakens the wood in both tension and compression.

Kiln-drying experience has shown that temperature is a strong factor in control of surface and end checking at the start of drying, honeycombing in the intermediate phases, and ultimate dimension. In view of the above, a study of the effects of temperature on the stresses set up in wood while it dries, as revealed by strain analysis, should contribute to understanding of the drying process and development of more satisfactory drying techniques.

For complete understanding, it will be necessary to have basic perpendicular-to-grain stress-strain information. Such information has been obtained for beech by Ellwood (2) and Greenhill (3). Work on the tension and shear properties of oak has been done by Kollmann (4). Data are also necessary on the effects of long-time exposure of moist wood to kiln-drying temperatures. MacLean (5) determined the effects of heating in water and previously the effects of steaming at higher temperatures. Rees and Buckman (7) have reviewed the early literature on the effects of steaming.

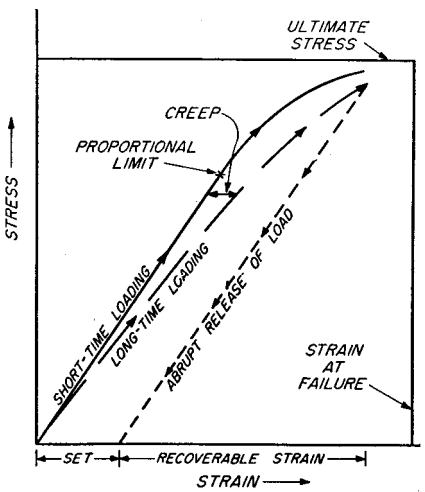


Fig. 1.--General stress–strain diagram illustrating terms used in this report.

General definitions of some of the technical terms used in this report are given below, and illustrated in Fig. 1, to promote better understanding of the subject.

Stress—Internal force exerted by either of two adjacent parts of a body upon the other across an imagined plane.

Strain—Deformation due to stress.

Proportional limit—The greatest stress that a material is capable of developing without deviation from straight-line proportionality between stress and strain.

Creep—Increase in strain with time, under stress.

Recoverable strain—That portion of the strain that is recovered when the stress is released.

Set—Deformation remaining after the release of the stress.

Material Tested

The specimens were from the first or second logs of northern red oak (*Quercus rubra* L.) trees grown on a good site in southern Wisconsin. They were about 110 years old and 82 to 100 feet high. The number of rings per inch was 7 to 10. (One specimen, which was dried at 35° F., was from similar material used in the previous study.)

The material was clear, flat-sawed heartwood and, except for one specimen noted later, strictly green. Moisture content was between 80 and 87 per cent; green specific gravity was between 0.51 and 0.60.

The principal research was done with one specimen at each test temperature. One check specimen was used at 80° F. and two at 140° F. A preliminary comparative analysis showed a high degree of conformity of the strain results at 110° F. with those of the previous study.

[1]Preliminary summary presented at Fall Meeting, Northeast Section FPRS Nov. 4–5 1954 in New. York City. Manuscript submitted for publication May 1, 1955.

[2]Much of the experimental work and data analysis was by Takeo Oguro, Chief, Wood Material Section, Government Forest Experiment Station Tokyo, a an, while a collaborator at the Laboratory. Acknowledgement is also made to assistance and suggestions by R. L. Youngs, R. C. Baltes, K. H. Boller, and R. C. Rietz of the Laboratory staff.

[3] Maintained at Madison, Wis., in cooperation with the University of Wisconsin.

[4] Numbers in parentheses refer to Literature Cited.

The Author: J. M. McMillen received B.S. and M.S. degrees from U. of Minnesota. Since 1942 he has been employed at U. S. Forest Products Laboratory has conducted research in chemical seasoning, special seasoning methods, kiln-schedule development, and analysis of internal stresses in wood during drying

Reprinted from the August, 1955, Forest Products Journal, pages 230–241
Forest Products Research Society, P. O. Box 2010, University Station, Madison 5, Wisconsin

Test Methods

The general methods of marking and measuring the specimens, operating the dry kiln, measuring the strain of the slices, determining slice moisture content, and determining board shrinkage and set were essentially the same as those used in the previous study (6).

Kiln-drying runs were made at 80° F., 95° F., 110° F., 125° F., and 140° F. in small, experimental drying chambers. A mild relative humidity reduction schedule essentially the same as that used in run 3 of the previous study was used.

The controlled room drying was done in the Forest Products Laboratory controlled temperature-humidity rooms. There was no forced air circulation directly across the specimens. One specimen was dried 35 days in the cold-storage room at 35° F. with the equilibrium moisture content at 18.5 per cent. This specimen then was kiln dried, starting at 110° F. The other two specimens were dried in a series of conditioning rooms at 80° F. Details of the drying conditions are shown on the graphs of the results, Figs. 2 through 9.

The 2- by 7-inch by 5-foot specimens were marked with 1-inch sections every 3 inches along the length. Each section was marked for 10 slices from top to bottom. The width of the green specimen was measured at each slice position for original dimensions. After each interval of drying, one section was cut off. The remainder of the specimen was end coated and replaced in the kiln.

The long dimension of each slice in the section was measured to get board shrinkage to date and the before-cutting dimension for recoverable strain measurements. The slices were measured again after they were cut, and the differences in dimension, converted to a per-inch basis, were considered unit strains. The current weight of each slice was obtained, then it was carefully dried to the ovendry condition, reweighed, and remeasured. Details are described in the previous paper (6).

A modified slice-cutting technique was used for the specimens dried at 140° F. A plywood sheet was fastened on top of the regular bandsaw table and preheated. The foil wrappers were preheated also. The section, and later the slices, were placed between two pieces of the cutoff isolation section to minimize heat losses during measurement. Thus, the heat losses for the tests at 140° F. were believed to have been held about the same as for the previous tests at 110° F. (6).

No similar modifications were made for the other temperatures. Thus, the tests at 125° F. had a little greater, and those at 95° F. a little smaller, temperature contraction effect than those at 110 F°. This contraction amounts to about 0.001 inch per inch in a slice cooled from 110° F. to 80° F. It affects the exact magnitude of the strains but not the overall results. Some warming of the sections and slices tested at 35° F. occurred before and after section measurement and slice cutting, but the elongation was of no greater magnitude than the contraction from 110° F. to 80° F.

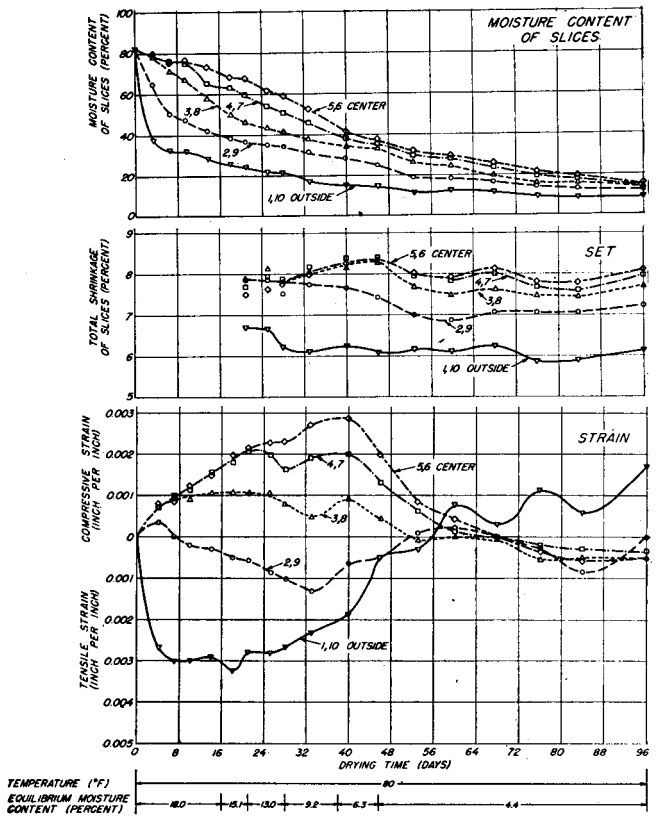


Fig. 2.—Strain, set, and moisture content of slices of 2- by 7-inch northern red oak kiln dried at 80° F.

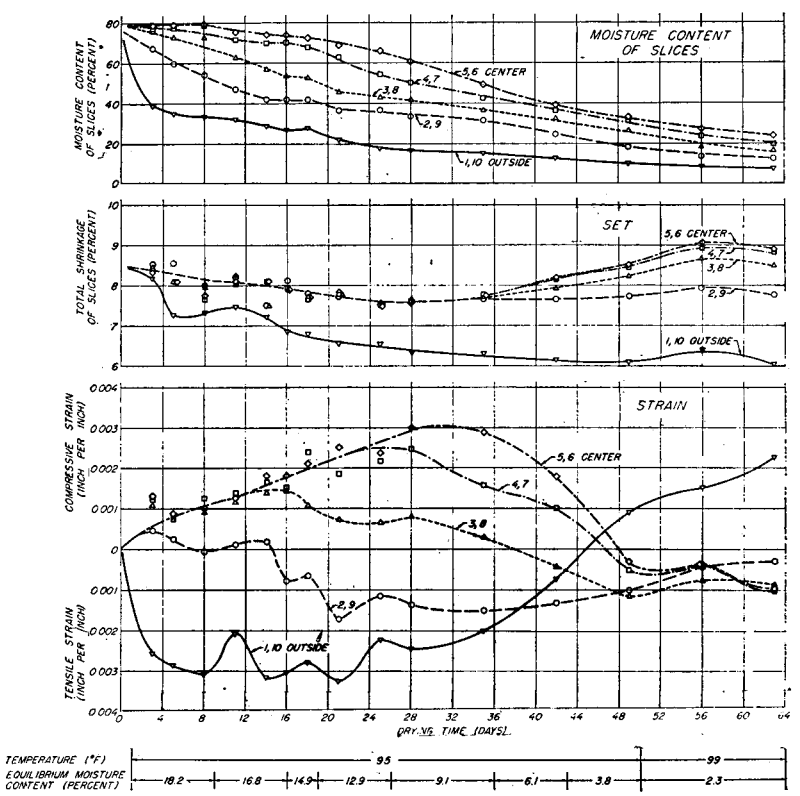


Fig. 3.—Strain, set, and moisture content of slices of 2- by 7-inch northern red oak kiln dried at 95° F.

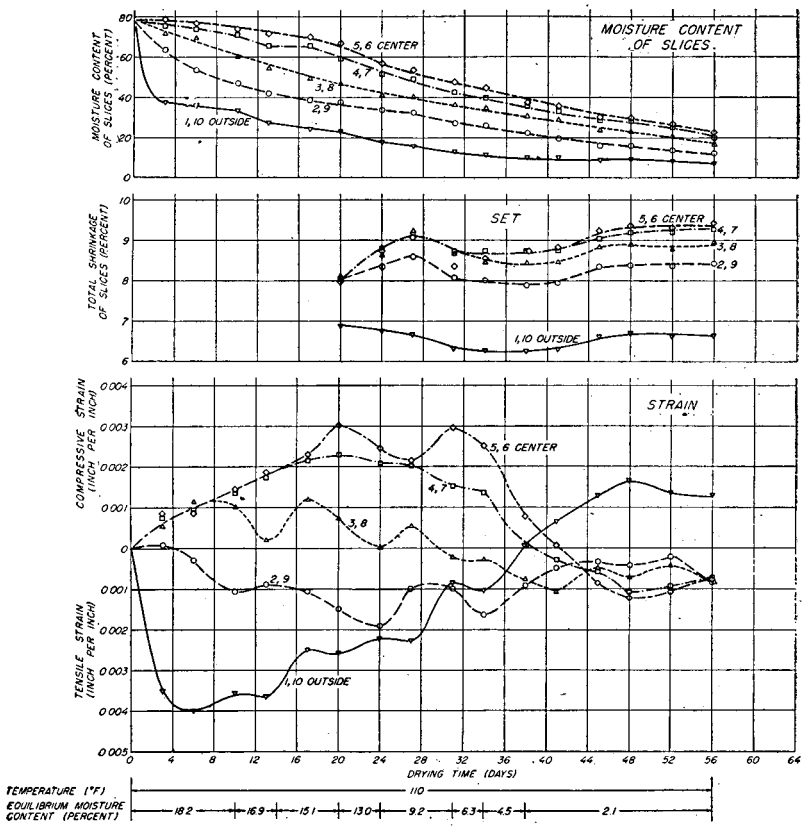


Fig. 4.-Strain, set, and moisture content of 2- by 7-inch northern red oak kiln dried at 110°F.

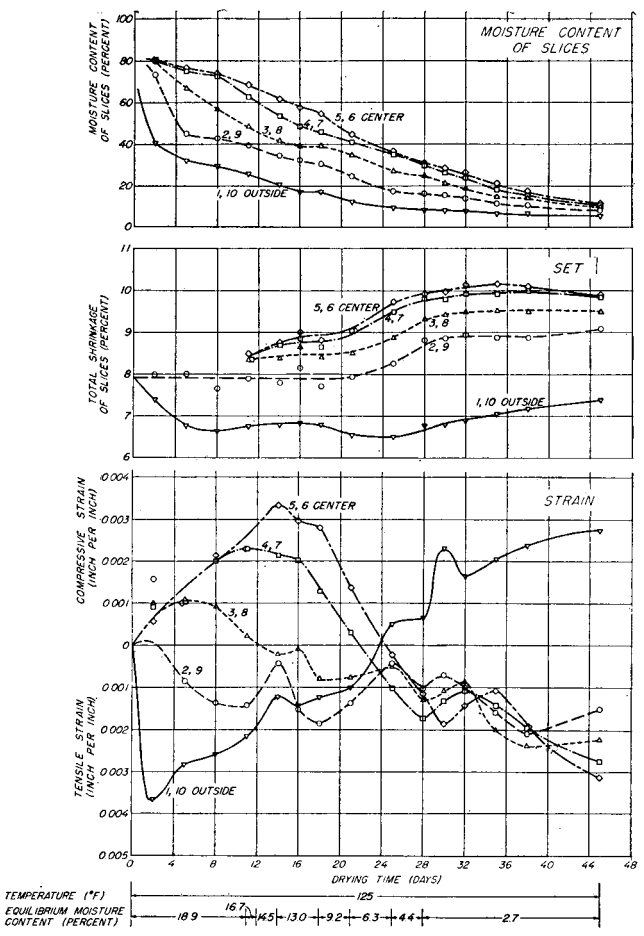


Fig. 5.—Strain, set, and moisture content of slices of 2- by 7-inch northern red oak kiln dried at 125° F.

The schedule used to dry the slices carefully for set indications was 2 days in a kiln at 95° to 120° F. and 18 per cent equilibrium moisture content, 2 days in the room, and 1 day in an oven at 214° F.

Results

Figs. 2–9 inclusive show the major results—strain in various slices, their total shrinkage indicating set, and their moisture content as a function of time. Figs. 2–6 are for kiln drying at temperatures of 80°, 95°, 110°, 125°, and 140° F. Figs. 7-9 are for controlled room drying at 35° and 80° F. In all cases, the results of the two slices equidistant from the center were averaged, and the average is shown as a single value.

Figs. 10–12 show moisture gradients at important points in the drying for the 5 different kiln temperatures. Figs. 13 and 14 show board shrinkage values as a function of moisture content instead of time.

Tables 1–4 give data on time to significant points on the strain curves and maximum strains. Table 5 gives data on the magnitude of the sets at the various temperatures of kiln drying.

Kiln Drying: The strain patterns shown in Figs. 2–6 are generally the same for all temperatures studied and similar to the pattern for a mild humidity reduction at 110° F. in the previous study (6).

The tensile and compressive strains shown in Figs. 2–6 and elsewhere in this report are recoverable strains, the amounts of strain recovered when the stresses are released by the slice-cutting

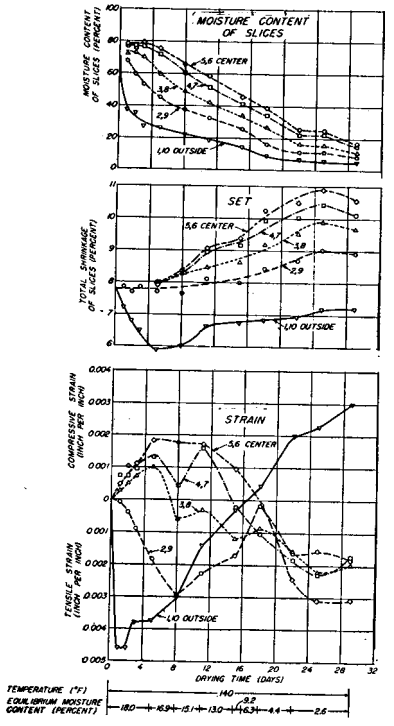


Fig. 6.—Strain, set, and moisture content of slices of 2- by 7-inch northern red oak kiln dried at 140° F.

operation. The total strains include set. To shorten the terminology in this report, the recoverable strains will be referred to hereafter simply as tensile strain and compressive strain.

Briefly, the outside slices go into tension and the inner slices into compression right from the start. The tensile strain reaches a maximum, then subsides to zero. The outside slices then go into compression until the end of the run. The center slices continue in compression to a maximum strain. Then the compressive strain subsides to zero and the center slices go over into tension.

The graphs show actual data points and general deviation of the curves to connect the data points, whereas, for purposes of simplification, the curves in the previous paper (6) were smoothed between data points. It is not the purpose of this paper to speculate on the causes of the irregularities; rather, the data will be used to bring out significant temperature effects.

Table 1 gives the time to maximum tensile strain in the outside slices and the value of the strain. Moisture content data and equilibrium moisture content conditions are also shown to indicate the stages of drying when the maximums occurred. The higher the temperature, the earlier the maximum tensile strain occurred. There also was a trend toward higher strains at the higher temperatures. The general order of magnitude of the maximum tensile strain, 0.0031 to 0.0046 inch per inch, was the same as that observed for red oak in the previous study (6), and earlier for sweetgum heartwood in a study made by W. K. Loughborough and H. H. Smith. The results of that study were reported by Rietz (8).

Table 1.—STRAIN AND MOISTURE CONTENT AT TIME OF MAXIMUM TENSILE STRAIN IN OUTSIDE SLICES

Temperature °F.	Time to maximum strain Days	Maximum tensile strain In./in.	Average moisture content Per cent	Equilibrium moisture content in kiln Per cent
80	18	0.0032	49.0	15.1
95	8	.0031	63.5	18.0
110	6	.0040	61.9	18.0
125	2	.0037	70.9	18.0
140	1	.0046	66.0	18.0

Ellwood (2) briefly reported preliminary experiments showing only a slight effect of temperature on maximum tensile strain of the outside slices for American beech. From this he concluded that studies using the slicing technique had limited value. Ellwood used his strength data to calculate stresses and strains occurring in a hypothetical beech board, and he combined the data of Loughborough and Smith (8) for slice elongation and contraction with their data for set to calculate total strains.

It is not the purpose of the present paper to apply the author's results to the whole drying-stress problem, but rather to present them as a broader base for future analyses of the problem and to draw some conclusions that have some immediate application.

The present study offers evidence of some differences of tensile strain in the outside slices as a function of temperature within the general order of magnitude observed and a more important effect on compressive strains. It also shows significant effects on the amount of set as discussed under a later heading.

At all temperatures the maximum compressive strain in the center slices occurred considerably later than the maximum tensile strain in the outside slices. Note that the time scale in Fig. 2, for 80° F., is half the time scale at the higher temperatures.

In the experiment on sweetgum heartwood (8), the compressive strain of the center slices did not reach a maximum until the tensile strain in the outside slices was nearly back to zero. This was not the case in the present experiment. This difference gives further evidence that sweetgum and oak heartwood have considerably different seasoning characteristics so far as internal stress-strain relationships are concerned.

With all five temperatures used in this work, there was considerable tensile strain in the outside slices when the maximum compressive strain in the center slice was reached. Also, the compressive strain in the center slices was nearly back to zero when the stresses in the outside slices reversed.

The maximum compressive strain in the center slices is the resultant of the stresses of all slices in tension. A certain amount is due to tensile stress in the outside slices. This is augmented by tensile stresses in the second and ninth slices and sometimes by those of the third and eighth slices. Each slice also may go through a stage where it is partially in tension and partially in compression, and shear stresses between these tensile and compressive forces are concentrated within the slice.

In considering how the tensile stresses of the outer slices work to build up the maximum compressive strain in the center slices, it should be remembered that the values shown in the lower part of Figs. 2–6 are strains, not stresses. As the outside slices get drier, the amount of stress represented by a given amount of strain increases.

The maximum compressive strain in the center slices, as shown in Table 2, is approximately the same, about 0.003 inch per inch, for all temperatures except 140° F. The fact that this strain in the center slices was considerably smaller at 140° F. than at the lower temperatures is one of the most significant findings of this work. This result was confirmed by two check runs at 140° F. in which the center slices reached maximum compressive strains of 0.0023 and 0.0028 inch per inch, respectively.

Table 2.—STRAIN AND MOISTURE CONTENT AT TIME OF MAXIMUM COMPRESSIVE STRAIN IN CENTER SLICES

Temperature °F	Time to maximum strain Days	Maximum compressive strain In./in.	Average moisture content Per cent	Equilibrium moisture content in kiln Per cent
80	40	0.0029	31.6	6.3
95	30	.0030	40.5	9.2
110	20	.0030	40.7	15.1
125	14	.0033	42.6	14.5
140	8	.0018	47.0	16.9

Although there is a possibility that, between the data points, there occurred a sharp increase to a higher maximum strain followed by an abrupt decrease, there was no indication that this may have happened in any of the 3 runs at 140° F. The low compressive strain at 140° F. is directly related to the amount of compression set in the center slices, which will be discussed later.

In general, for temperatures of 95° F. and above, the third and eighth and fourth and seventh slices reached maximum compressive strains before the center slices did. The strains were less than those of the center slices, and they subsided to zero before the strains of the center slices reached zero.

The behavior of the third and eighth and fourth and seventh slices at 140° F., as shown by Fig. 6, differed sharply from the general pattern. On the 11th day these compressive strains increased sharply, with the fourth and seventh slices approaching the maximum compressive strain of the center slices. This may be related to the extreme maximum tensile strain, about 0.003 inch per inch, in slices 2 and 9 after 8 days of drying. At lower temperatures the tensile strain of slices 2 and 9 did not exceed 0.002 inch per inch.

In the check runs at 140° F. there were no such major irregularities in the strain lines for the third and eighth and fourth and seventh slices, but compressive strain maximums for the latter pair of slices coincided with the maximums for the center slices. The maximum tensile strain for slices 2 and 9 was 0.0026 inch per inch in the second and 0.0021 inch per inch in the third check run. There was a slight peak in the maximum tensile strain in the outside slices for the sec-

ond but not for the third check run. The maximum tensile strain was 0.0039 inch per inch for both specimens.

As indicated in Table 2, the time required to reach maximum compressive strain in the center slices was considerably shorter at the higher temperatures. The average moisture content was fairly low for 80° F., somewhat higher for the next two temperatures, only slightly higher for 125° F., but considerably higher at 140° F. As indicated by the equilibrium moisture content values, this point occurred a little later in the drying schedule for the lower temperatures than for the higher temperatures. In all cases, however, the average moisture content values were above 30 per cent and the center slices were considerably above the fiber saturation point.

After the tensile strains of the outside slices attained their maximums, they returned to zero. While under tension, the wood in these slices took on a set that tended to hold its dimension greater than it would have been if shrinkage had been unrestrained. Then, as the interior slices continued to shrink, the outside slices were forced into compression.

The time at which the outside slices changed from tension to compression is shown in Table 3. The higher the temperature, the earlier this occurred and the higher was the average moisture content. At 95° F. and higher, the average moisture content was not far from 30 per cent. At this average moisture content, the outside slices were below the fiber saturation point and the interior slices were above it. This average moisture content, however, is where the first, mildest changes in temperature are recommended in the Forest Products Laboratory standard kiln schedules (9).

Table 3.—MOISTURE CONTENT AT TIME OF STRESS REVERSAL IN THE OUTSIDE SLICES

Temperature °F.	Time to reversal Days	Average moisture content Per cent	Equilibrium moisture content in kiln Per cent
80	56	22.9	4.4
95	45	27.0	3.8
110	38	27.6	4.5
125	24	30.0	6.3
140	16	33.0	6.3

It will be noted from Figs. 2–6 that, when the outside slices go into compression, slices 3 and 8 and 4 and 7 have compressive strains close to zero or slight tensile strains and the compressive strains in slices 5 and 6 are less than 0.001 inch per inch. Thus, minor changes in temperature would not be expected to have great effect here.

Shortly after the outside slices changed from tension to compression, the center slices went into tension. The tensile strains of the center slices, except at 80° F., generally proceeded to a maximum, then receded slightly toward zero. Table 4 shows the time at which the first maximum tensile strain occurred, the value of the strain, and the average moisture content. At this stage of drying, the moisture content in the center of the specimen is relatively high coincidental with relatively high tensile stresses. This is the period during which honeycomb might occur if the stresses were great enough to exceed the ultimate strength of the wood. The amount of this strain is greater at the higher temperatures than at the lower temperatures.

Table 4.—STRAIN AND MOISTURE CONTENT AT TIME OF FIRST MAXIMUM OF TENSILE STRAIN IN CENTER SLICES

Temperature °F.	Time to maximum strain Days	Maximum tensile strain In./in.	Average moisture content Per cent	Equilibrium moisture content in kiln Per cent
80	(1)	(1)	(1)	(1)
95	52	0.0005	21.2	2.3
110	48	.0012	21.2	2.1
125	30	.0018	19.6	2.7
140	25	.0031	15.8	2.6

(1) This point not definitely established at 80° F.

The maximum tensile strain in the center slices is of considerable significance at two temperatures, being about 0.002 inch per inch at 125° F. and about 0.003 inch per inch at 140° F. The corresponding values were 0.0028 and 0.0024 inch per inch, respectively, in the second and third check runs at 140° F.

These high tensile strain values for the center slices resulting from high temperatures during drying confirm previous general observations that too high an average temperature during the first stages of kiln drying may lead to honeycombing later. The fact that central-slice tensile strain rapidly attains a maximum after stress reversal explains why a sudden application of high temperature before all of the wood is below the fiber saturation point also can cause honeycombing.

The strain pattern at 80° F. differs somewhat from that of the higher temperatures, although there are some special similarities at the next higher temperature, 95° F. As previously noted, the time scale for Fig. 2 is one-half the scale in Figs. 3–6.

Of first interest is the prolonged time at approximately maximum tensile strain in the outside slices about 28 days. This was fairly well duplicated in the run at 95° F. Second was the low value of the tensile strain in slices 2 and 9. Third is that slices 3 and 8 and 4 and 7 stayed in compression about as long as slices 5 and 6, and they essentially held their maximum compressive strain until slices 5 and 6 had reached maximum.

Finally, stress reversal was rather confused and drawn out. Slices 2 and 9 returned to compression and all the interior slices then went together into tension, with tensile strains of low magnitude. At 95° F. stress reversal was more clear cut, but the first maximum tensile strain of slices 5 and 6 was not as great as the tensile strains in the other interior zones.

The strain curves for the check run at 80° F. had irregularities that differed from those of the original 80° F. run, but significant points were very similar. For instance, maximum tensile strain in the outside slices occurred at 18 days and was 0.0033 inch per inch. Maximum tensile strain in slices 2 and 9 was 0.0013 inch per inch and occurred at. 28 days, although a strain of about this magnitude lasted until the 33rd day. Maximum compressive strain in slices 5 and 6 was 0.0030 inch at 33 days, but the strain was still 0.0028 inch per inch at 40 days.

Compressive strains in slices 3 and 8 and 4 and 7 held near their maximum values until the 40th day. The same general pattern of stress reversal occurred, with the strains of interior' slices closely bunched from the 60th day to the end of drying. The average tensile strain at the 76th day was about 0.0006 inch per inch.

Controlled Room Drying: Drying in controlled temperature-humidity rooms is similar to air drying in respect to low temperature and low rate of air circulation across the board surfaces, but differs in that temperature and relative humidity do not fluctuate.

The strain pattern shown in the 35° F. portion of Fig. 7 is relatively simple and regular. Half scale was used on only the first 32 of the 35 days of drying. The tensile strain in the outside slices was comparatively low and probably did not exceed the proportional limit, even though the equilibrium moisture content was approximately the same as that used in the kiln runs. The top portion of the figure shows that considerable drying had taken place in the outside slices, but the second and ninth slices also had dried considerably, so that the moisture gradient was not steep. Compressive strains in the interior slices were very small.

The data fail to disclose any reason for the tensile strain line of slices 1 and 10, returning almost to zero at the end of air drying. The entire specimen was brought from the cold atmosphere to room temperature for sawing, but the time of section cutting, measurement, slicing, and remeasurement was not prolonged and the effect would be little different from that of cutting the previous sections in the

cold atmosphere, then bringing them to the saw room for measurement and slicing.

The 110° F. portion of the kiln drying of this specimen gave results differing somewhat from those for kiln drying from the green condition. Maximum tensile strain in the outside slices was reached in 3 instead of 5 or 6 days. The strain, 0.0031 inch per inch, was less than that obtained with the 110° F. specimen in this experiment, but about the same as that obtained in the previous study (6), the material of which this specimen matched. Tensile strain in these outside slices returned fairly quickly to zero.

Slices 2 and 9 fairly rapidly attained a tensile strain of 0.0017 inch per inch, then went slightly into compression. The fact that all slices were neutral or in compression from the 48th to the 59th day indicates some flaws in technique or analysis methods. Similar periods occurred under some of the other conditions. However, the magnitude of the discrepancies does not appear great enough to obscure real differences.

The low value of maximum compressive strain in the center slices was quickly attained. The strain relations at the 38th day, or after 3 days of kiln drying, are abort the same as those at 20 days of kiln drying from the green condition at 110° F. The moisture gradients, as shown by the upper portions of Figs. 3 and 6, are not too far apart, although the lower equilibrium moisture content at 20 days of kiln drying has resulted in lower moisture content values for the two outer pairs of slices.

A strong build-up of compressive strain apparently started in the outside slices between the 48th and 52nd days of drying, with correspondingly low compressive strain in slices 4, 5, 6, and 7. Why this compressive strain dropped back to the neutral region is unexplained, since the humidity reduction schedule was no more severe than those used in other runs and there were no errors in kiln operation.

Use of 120° and 130° F. between the 59th and 69th days resulted in rapid drying of the outside slices to low moisture content values and a new buildup of compressive strain to a value higher than was obtained in any of the other runs, except the second and third check runs at 140° F., which also dried the specimens to very low moisture content values. The center slices built up high tensile stresses by drying to low moisture content values at 130° F.

It is interesting to note, in view of Churchill's (1) results on relief of stress and set, that the 5-day period at 180° F. did not reduce compressive strain in the outside slices but did relieve somewhat the tensile strain in the inside slices. The 2-day conditioning period at 180° F. and 12.2 per cent equilibruim moisture content obviously relieved the set and stress and gave a slight stress reversal.

Controlled room drying of a green specimen at 80° F. gave strain results as shown in Fig. 8 somewhat similar to the drying at 35° F. as long as equilibrium moisture content conditions were high (20.4 per cent). Compressive strain in the interior slices was very low.

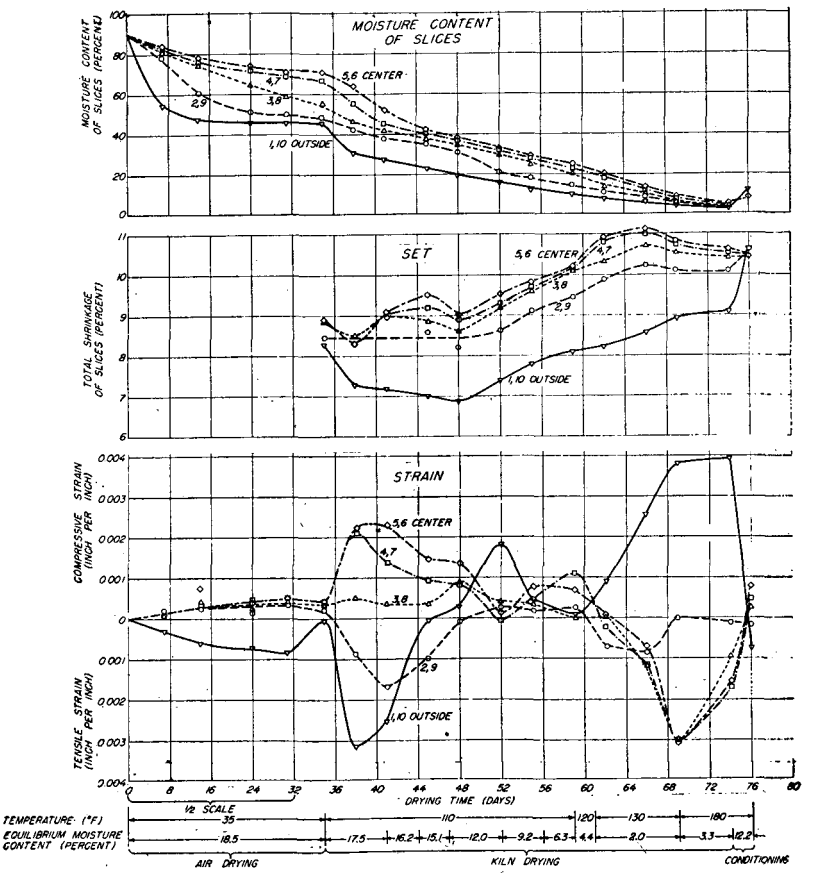


Fig. 7.--Strain, set, and moisture content of slices of 2- by 7-inch northern red oak under controlled-room, or air, drying at 35° F.

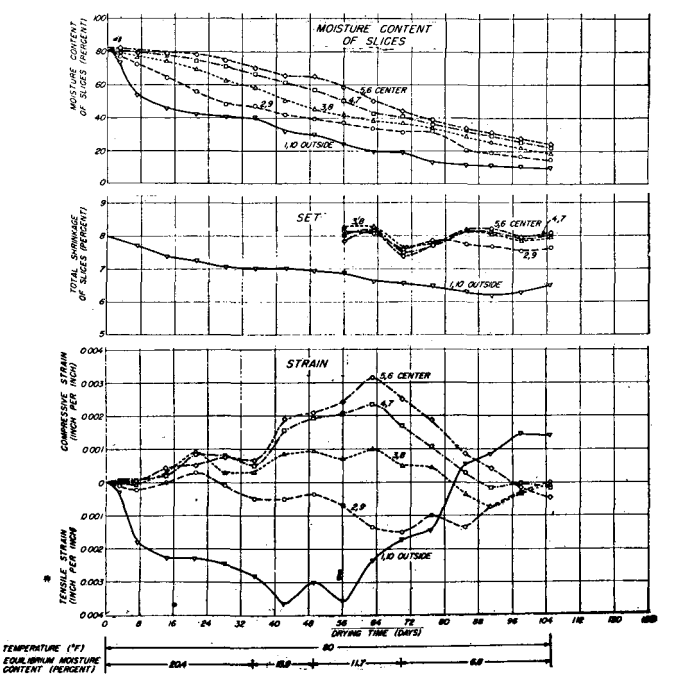


Fig. 8.—Strain, set, and moisture content of slicer of 2- by 7-inch northern red oak under controlled-room drying at 80° F., from the green condition.

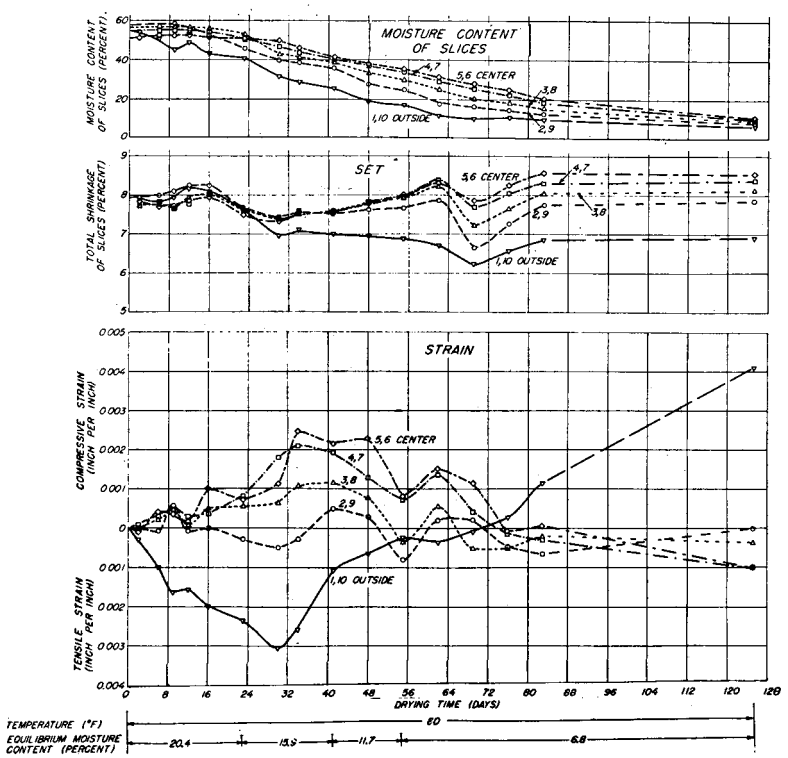


Fig. 9.—Strain, set, and moisture content of slices of 2- by 7-inch northern red oak under controlled-room drying at 80° F., from the partly dry condition.

When the equilibrium moisture content was dropped even a little, to 15.9 per cent, strains similar to those obtained in kiln drying were found. The tensile strain in the outside slices went to a higher value than for kiln drying at 80° and 95° F.

The development of compressive strain of the interior slices was about the same as in kiln drying at 80° F. The same may be said of stress reversal for the outside slices and the position of the strain curves for slices 4 and 7 and 5 and 6 at this point. Tensile strain of the center slices and compressive strain of the outside slices were comparatively low following stress reversal, but drying was terminated at a relatively high moisture content for this specimen.

Similar results were obtained in controlled room drying of a partly dried specimen at 80° F., as is shown in Fig. 9. When controlled drying was started, the specimen was moved along to the rooms maintained at lower equilibrium moisture content faster than the green specimen. A slightly lower maximum tensile strain was obtained in the outside slices and a lower maximum compressive strain in the centerslices.

Reversal of stresses was somewhat confused, with the drop in equilibrium moisture content from 11.7 to 6.8 per cent at the 55th day apparently causing a small increase in tensile strain, and possibily a more important increase in tensile stress, at that point.

At the final low moisture content, compressive strain in the outside slices was high while tensile strain in the interior slices was low. The data points are not close enough together, however, to indicate the course of the curves between 82 and 126 days.

Moisture Gradients: The moisture distributions at which the maximum tensile strain occurred in the outside slices during the kiln-drying runs are shown in Fig. 10. The moisture gradients were steep near the surface, steepest at the higher temperatures where the maximums occurred much earlier in the drying process than in the runs at lower temperatures. Except for 95° F., the average moisture content of the outside slices was above 30 per cent, a general value for the fiber saturation point.

With the equilibrium moisture content about 18 per cent, a small portion of the slice, perhaps 1/16 inch, was below fiber saturation point. It was this portion of the wood, actually trying to shrink but restrained by adjacent portions, that created the tensile stresses within itself. It also created compressive stresses on the inside.

Strains shown in Fig. 2–9are averages for the entire slices. Undoubtedly the stresses are much higher at the surface than for the outside slice as a whole.

The moisture distributions at the time of maximum compressive strain in the center slices are shown in Fig. 11. At 95° F. and above, the average moisture content of the center slices was considerably above the fiber saturation point, and no doubt the moisture content at midlength of the slices, is higher still. Slices 3 and 8 and 4 and 7 also were well above the fiber saturation point.

The outside slices were definitely below the fiber saturation point, and the second and ninth slices perhaps had a small portion below the fiber saturation point, with the rest being just slightly above. The moisture gradient for 80° F. is conspicuously lower and flatter than those of the other temperatures.

Fig. 12 shows the moisture distributions at the time of first maximum of tensile strain in the center slices.

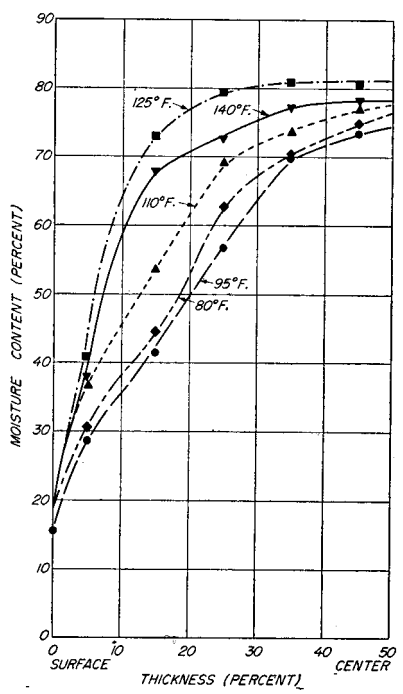


Fig. 10.—Moisture gradients, as indicated by whole slices, at time of maximum tensile strain in outside slices.

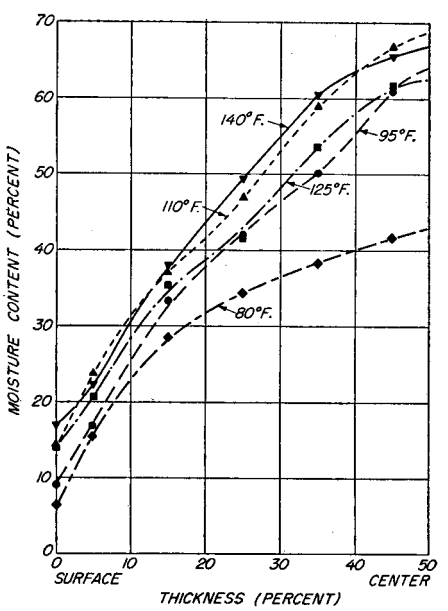


Fig. 11.—Moisture gradients, as indicated by whole slices, at time of maximum compressive strain in center slices.

A fairly flat moisture gradient has been reached by this time. The 140° F. curve is lower because the stage of drying at which this analysis was made was later in the drying period on a moisture content basis. Except at 80° F., the average moisture content of the center slices was 25 per cent or above. At the midlength of the slices the moisture content was considerably higher.

Some moisture content data on the central 3 inches of the center slices obtained at the time of first maximum of tensile strain in the center slices or nearby points on the strain curves are as follows

Drying temperature °F	Moisture content of center slices	
	Entire slice Per cent	Central portion Per cent
95	24.3	27.6
110	26.9	32.8
125	26.5	31.7
140	25.4	38.7

The moisture content data for the specimens dried in controlled temperature-humidity rooms, shown in another form at the top of Figs. 7–9, have already been discussed.

The curves at the top of Figs. 2–6 give additional information on moisture content during kiln drying at the different temperatures. In general, the moisture content of the outside slices drops off very rapidly from the green moisture content. At the higher temperatures, the moisture content of the second and ninth slices also drops off rapidly. The moisture content curves of the other slices fall at a fairly uniform rate throughout the drying.

Set: This has been generally defined as a permanent deformation or strain remaining in a previously-stressed body after release of the stresses. It could be conceived of as permanent deformation resulting from stress beyond the proportional limit under short-time loading or form creep under long-time loading at stresses below the proportional limit.

While under tension, the wood in the outside slices was stressed for several days. The set that occurred in these slices would tend to reduce the apparent shrinkage resulting from loss of moisture to a value below the normal shrinkage. In seasoning terminology this has been called tension set because it occurred while the wood was under tensile stress. Set also occurs in the interior slices under the influence of compressive stress, and this has been called compression set. Its effect is to increase apparent shrinkage.

In this work, set is evidenced by the difference between the normal shrinkage of the wood and the actual shrinkage as influenced by the self-imposed loads or stresses. The amount of set can be obtained from the slice-

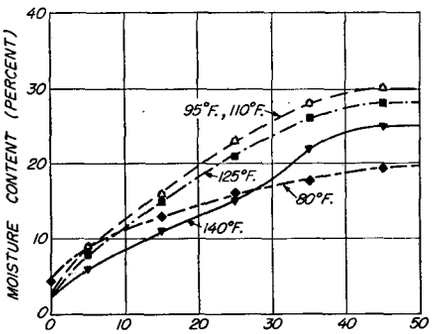


Fig. 12.-Moisture gradients, as indicated by whole slices, at the time of first maximum of tensile strain in center slices.

shrinkage data in the central portion of Figs. 2–9. The data shown are for total shrinkage of the slices from the green to the ovendry condition as the resultant of two drying processes: 1. Drying of the specimen under the conditions of the experiment; 2. Drying of the individual slices without restraint under the mild conditions described in this report.

The normal shrinkage value for each specimen was obtained from the shrinkage of slices 2 and 9 during the first stages of drying. The strain curves for these slices generally did not depart greatly from the neutral line. Normal shrinkage was also indicated by the Y intercept of the shrinkage curves for the outside slices.

During slice drying, when the slices were removed from the kiln too soon, superimposed tension set somewhat complicated the results. Thus, in the early stages of some of the runs, data for some or all of the slices have been omitted.

The immediate development of tension set in the outside slices and the delayed development of compression set in the interior slices were fully established in run 5 of the previous paper (6) and confirmed in the runs covered by this paper where proper slice-drying conditions prevailed.

The general pattern of set is illustrated best in Fig. 3. All data points are shown. The normal shrinkage (slices 2 and 9) gradually decreased for 25 days of drying; thereafter it was the same. The shrinkage of all the interior slices was the same as the shrinkage of slices 2 and 9 for 35 days of drying.

By the third day the outside slices had developed a slight amount of tension set, as shown by the difference between the curve for slices 1 and 10 and the curve for slices 2 and 9. A considerably greater amount occurred by the fifth day. The first maximum amount of tension set in the outside slices was achieved as the wood in these slices was approaching maximum tensile strain. After some slight decrease at the 8th and 10th days, the tension set continued to increase gradually until the 46th day. This was about the time the tensile strain in slices 1 and 10 had receded to zero.

There may be some question as to why set should continue to increase while strain is decreasing, but it is believed that the set increases as long as there is any tension stress at all, until the slice goes into compression. This is due to creep. In the usual concept, creep is thought of as continued deformation under a constant dead load. Here it apparently continues under a decreasing load. As Ellwood (2) has pointed out, the set is a part of total strain, the other part being the recoverable strain shown by the lower portions of Figs. 2–9.

Although tension set has been widely recognized as having an effect on the shrinkage and warping of wood, compression set often has not been recognized or has been neglected in shrinkage considerations. This study shows the very important part played by compression set.

During the latter stages of drying the stresses are reversed, so that the outside slices are under compressive stresses and the interior slices are under tensile stresses, yet the direction of the set does not change unless sufficiently affected by new stresses. Thus finally the wood with a tension set is under a compressive stress and the wood with a compression set is under a tensile stress.

Compression set did not begin in the interior slices until the maximum compressive strain was reached in the center slices. Then a greater-than-normal shrinkage began for all slices except 2 and 9. At 95° F, it appears as if the shrinkage curves for slices 4 and 7 and 5 and 6 go up together. The amount of set is again considered to be the difference between the neutral line of slices 2 and 9 and the shrinkage curve of the interior slices. Here again the compression set increased and the maximum was not reached until the center slices passed from compression into tension.

After 49 days of drying there was an upswing of the shrinkage-time curve for all slices. This is also evident in the curves for the higher temperatures. The upswing generally followed reversal of stresses.

Because of a difference in the general pattern, the slice shrinkage results at 80° F. are considered separately. Tension set in the outside slices built up quite strongly, but there also appeared to be some tension set in slices 2 and 9. This same dropping of the shrinkage curve for slices 2 and 9 occurred in the check run at 80° F. Thus

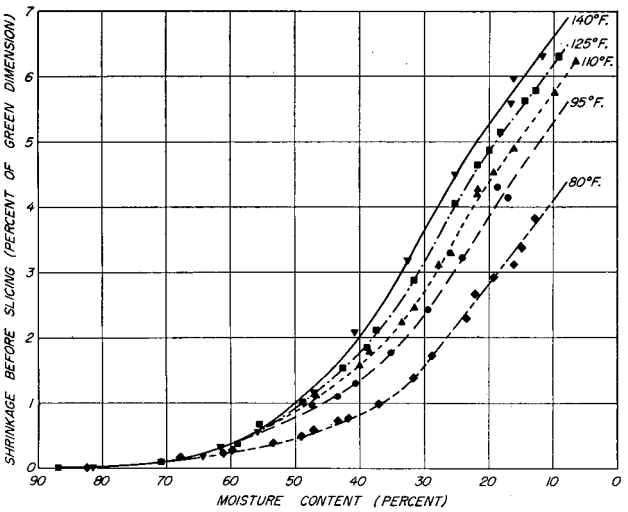


Fig. 13.—Board shrinkage, os shown by center slices in situ, for 2- by 7-inch northern red oak kiln dried at different temperatures os o function of overage moisture content of the whole boards.

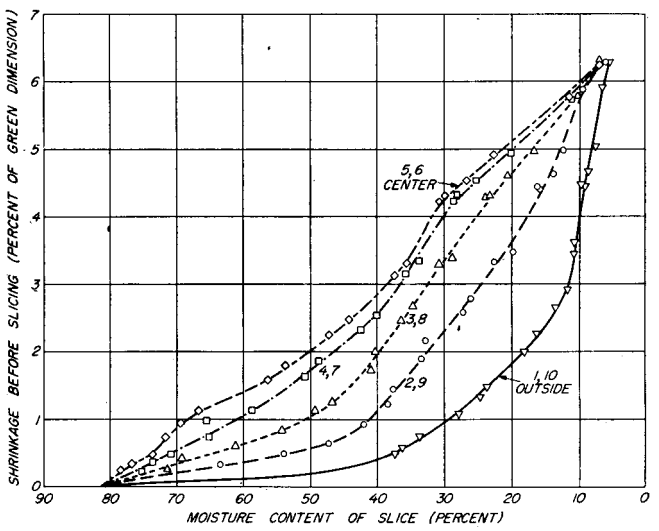


Fig. 14.—Shrinkage of slices while in whole board, as a function of slice moisture content; 2- by 7-inch northern red oak kiln dried at 110° F.

it seems that normal shrinkage is better represented by slices 3 and 8 at 60 days. The amount of compression set at this temperature is very low.

Likewise, the compression set is low in material that has been room dried at 35° F. before it is kiln dried at 110° F. or room dried at 80° F. from either the green or partly-dry condition.

As pointed out in the introduction, the data in this paper on the effect of temperature on set and consequent board shrinkage are considered-highly significant. To bring out this relationship, the maximum tension set in the outside slices and the maximum compression set in the center slices at temperatures from 95° to 140° F. are given in Table 5.

Table 5.—SET VALUES AND EXCESS SHRINKAGE EXPRESSED AS A PERCENTAGE OF GREEN DIMENSION

Temperature °F.	Tension set slices 1 and 10 Per cent	Compression set in slices 5 and 6 Per cent	Excess shrinkage in slices 2 and 9 Per cent
95	1.56	0.76	0.25
110	1.59	.78	.48
125	1.60	1.38	1.00
140	1.88	1.63	1.16

The degree to which tension set is affected by temperature is minor. The amount of set is fairly large at the three lowest temperatures and not significantly different. It is slightly higher at 140° F. Thus it would seem that previous general observations that low-temperature, low-humidity kiln schedules give more tension set than high-temperature, high-humidity schedules should have referred only to the relative humidities involved.

From these data, it does not appear that the temperature itself is an important factor in controlling tension set or that such set in the outer portions of the boards is' important in controlling shrinkage and warp during kiln drying.

On the other hand, temperature has a profound effect upon compression set in the center slices and the other interior slices. As shown in Table 5, the compression set in slices 5 and 6 is low at the 2 lower temperatures, considerably higher at 125° F., and was about twice as great at 140° F. Because of the great difference between compression set at low and high temperatures and the fact that compression set is evidenced by 6 of the 10 slices, compression set of the interior slices would be expected to have a considerable effect upon board shrinkage. The greater the temperature the greater the board shrinkage that would be expected. That such is the case is shown in the following discussion of board shrinkage data.

The last column of Table 5 shows the amount of upswing of the shrinkage-time curve for slices 2 and 9 after stress reversal. There very definitely is a temperature relationship in this phenomenon.

Board Shrinkage: The effect of temperature on board shrinkage is shown as a function of the average moisture content of the whole boards in Fig. 13. The moisture content scale is shown as the reverse of the usual plotting so as to conform to the time concept used in plotting board shrinkage of the previous study (6).

Fig. 13 shows definitely that the higher the temperature, the greater the shrinkage. At 10 per cent moisture content the specimen dried at 140° F. had 6.7 per cent shrinkage while the specimen dried at 80° F. had 4.1 per cent shrinkage. The relationship between temperature and shrinkage seems to be fairly regular between 95° and 140° F. The board dried at 80° F. had considerably less shrinkage than the one dried at 95° F.

The greater shrinkage of the specimens dried at 95° F. and higher would appear to be tied in with greater amounts of compression set and with the fact that only slices 1 and 10 are. under tension set while 6 slices are under compression set. At 80° F. the value of compression set is small. If, on Fig. 2, it is assumed that the shrinkage line for slices 2 and 9 between the 21st and 40th days of drying extended to intersect the line for slices 3 and 8 at 60 days of drying is normal shrinkage, then compression set in the center slices is somewhere between 0.40 and 0.70 per cent.

Tension set in slices 1 and 10 is about 1.56 per cent, about the same as at 95° to 125° F. Only 4 slices have compression set, and slices 2 and 9 appear to have some tension set. The combination of all these things would appear to account for the considerably lower shrinkage at 80° F.

In the previous paper (6), board shrinkage was shown, as a function of time, for the center of the board as represented by slices 5 and 6, and for the outside layers as represented by slices 1 and 10. There was a sharp increase in shrinkage rate as the outside slices changed from tension to compression. The higher rate continued until the interior slices reached their first maximum of tensile strain after reversal of stresses.

Throughout the entire run, as well as during the first stages, the outside slices had a smaller dimension than the center slices. This was explained on the basis that the outside slices always are drier than the center slices.

In order to show the effect of moisture content more clearly and also to bring out the effect of stresses on dimensions of the individual slices,

a rather unorthodox plotting of the decrease in dimension of each slice before it was cut is shown in Fig. 14 as a function of that slice's moisture content.

At any particular moisture content, Fig. 14 shows that the outside slices decrease in dimension less than the center slices. The shrinkage of the outside slices, or more probably that of only a portion of the outside slices, tends to compress the entire interior of the board before its cells have lost moisture below the fiber saturation point.

Application of Results

Strain and set data of the type given in this paper have a bearing on kiln schedules for oak and other hardwoods in two aspects-control of seasoning defects, such as surface checks and honeycomb, and control of ultimate dimension and warping.

The general pattern of internal stress development and reversal in hardwoods indicated by previous research has been amply confirmed by the present study for red oak at temperatures from 80° to 140° F. Tensile stress in the outside layers builds up to a maximum comparatively early in the drying run.

Ellwood (2) has suggested that total strain, or the recoverable strain plus set, is more significant than the recoverable strain alone in determining whether or not the wood will check. On the other hand, if recoverable strain drops off considerably, as it does soon after its maximum is passed at 110° F. or above, relative humidity can be lowered at a progressively increasing rate.

The permissible abruptness of the relative humidity drop would depend upon the avoidance of a combination of recoverable strain and set that equals the ultimate strain at failure. With some woods, such as sweetgum heartwood, this drop can be very abrupt. The results of the previous study (6) indicate there is need for further knowledge of the basic stress-strain relations perpendicular to the grain before it can be concluded that an abrupt drop in relative humidtiy would be safe for red oak.

The present study indicates, however, that a gradually accelerating relative humidity reduction that brings the equilibrium moisture content down to *4.5* per cent by the time the wood is down to about 30 per cent average moisture content causes no undue disruption of the strain pattern. Therefore, the safeness of the standard Forest Products Laboratory kiln schedules (9) is generally confirmed for even the more refractory hardwoods as far as relative humidity reduction and avoidance of surface checking are concerned.

The data indicate that at the higher temperatures used in this work, there is a more rapid approach to maximum tensile strain and a steeper moisture gradient at that stage of drying. In this report these facts are considered to show the desirability of using higher relative humidities, or equilibrium moisture content values, and of being more careful to avoid mistakes in kiln operation during the first day or two when high temperatures are used to dry a refractory wood. The data further suggest that high temperatures probably should be avoided at the start when drying refractory woods.

One of the moot questions of strain analysis studies directly aimed at kiln schedule development has been: How thick should the outside slice be? The answer was desired so as to be able to examine such a layer experimentally and, when it was found to be set, to proceed with rapid relative humidity reduction. The present study shows that, for 95° F. and higher, the layer set in tension was one-tenth the total thickness and that there was a gradation of set across the slice.

In view of these findings and the fact that relative humidity reduction can be essentially completed before one-tenth of the thickness has changed from tension to compression, it appears that strain analysis of the type used in this study will be more valuable in helping to project basic stress-strain findings to the surfaces, where failures can occur, rather than as operating techniques.

Ellwood (2) has put for the concept that, in order to keep the outside layers from being strained to the point of failure, the interior zone must be in condition to be readily compressed. With the present study showing that the resisting central core comprises at least six-tenths of the bulk of the wood during the stage where maximum tensile strain is occurring, and that the compressive stresses in the interior are below the proportional limit, the steepness of the outer moisture gradient and the tensile properties of the outside layers would seem of greater importance in surface checking problems.

In all the kiln-drying runs, a regular stress-reversal pattern occurred before the interior of the wood was below the fiber saturation point. This means that the interior is subjected to stresses that could cause honeycombing if they were great enough. In view of the greater compression set of the interior at the higher temperatures, there is a greater amount of interior tensile stress following stress reversal and, consequently, a greater tendency to honeycomb. This has been borne out by experience. The other factor, of course, is the weakening effect of long-time heating of moist wood.

Honeycomb can come about by three ways: deepening of a surface check followed by closure at the surface (bottle-neck checks); extension of an end check; and spontaneous formation. The data clearly show a greater amount of tensile strain progressing in from the surface as temperature is increased. Presumbably, a similar effect would take place in the zones underlying the end surfaces. There was also a profound effect of temperature on tensile strain of the center slices. Thus, use of too high a temperature would be conducive to all types of honeycomb formation.

The data for the controlled room drying runs show that these conditions are less likely to produce surface and interior checks than the kiln-drying conditions. Where experience has shown that woods surface check more under actual air-drying conditions, it must be assumed that low relative humidity and surface moisture content are responsible. Evidence along this line is given by the fact that abrupt lowering of relative humidity had the effect shown in Fig. 8.

Drying experience has shown that abrupt raising of temperature to very high values will cause honeycombing of oak that has been partially air dried to 30 per cent moisture content or above. This can be explained on the basis that the rapid drying of the core sets up high tensile stresses while the outside layers, being dry and having a high compressive strength, do not yield sufficiently. Also, the strength of the wet wood in the center layers is decreased as temperature is raised drastically. In the present experiment, the use of 180° F. to finish the kiln drying of the specimen room dried at 35° F. came so late in the drying that no honeycombing occurred.

Regarding the influence of drying temperature on ultimate dimension and warping, the present study provides data of considerable importance. It has generally been observed that, together with the greater shrinkage that occurs when wood is kiln dried at the higher temperatures, there is greater warping. The data in the present study clearly indicate the basic reasons.

Temperature has little effect on tension set in the outer 1/10 of the wood. A large amount of tension set occurred at all temperatures from 80° F. to 140° F. under kiln-drying conditions. Also, at 95° F. and above, such tension set gradient as there was occurred within the outside slice. With slices 2 and 9 essentially neutral, the

6 interior slices all showed a compression set. This set was shown to be of major importance because it was greatly influenced by temperature.

The set in the center slices at 140° F. was twice as much as it was at 95° F. The fact that 6/10 of the total thickness is under the influence of compression set and that the effect of temperature is so great makes it inevitable that high initial drying temperatures would cause more shrinking than low temperatures.

The above conclusion and general drying observations to this effect are well borne out by the data shown in Fig. 13. On the other hand, it must be concluded also that the larger portion of the board thickness having a tension set when 2-inch oak is dried at 80° F. is an added factor in the use of low temperature for shrinkage control.

If lower temperatures also permit lower initial relative humidities, the amount of tension set would be greater and probably would have a greater beneficial influence on shrinkage.

Warping is directly related to shrinkage. The shrinkage of an ordinary board is never normal; it is influenced by tension set in the outside layers and by compression set in the interior. Air drying and low-temperature kiln drying have in the past been considered to be conducive to low shrinkage and low warping because of the tension set in the outside layers. The present data indicate the very considerable effect of temperature on compression set in the core.

In spite of the fact that tension set is created in the exterior layers while the bulk of the wood is holding the piece straight, warping is influenced more by the greater bulk of the interior layers that tend to shrink unequally in accordance with the grain and ring pattern of the wood.

Higher costs and other factors have in recent years promoted the use of higher kiln temperatures and kiln drying green from the saw. Better knowledge of drying stresses and better kiln equipment permitted use of higher temperatures to accelerate drying while avoiding drying defects. This has been accomplished with some sacrifice of ultimate dimension and straightness of lumber.

It would appear wise, therefore, to make use of the data in the present study and other pertinent information to help maintain maximum dimension and minimize warping. Air drying under conditions conducive to rapid drying without surface and end checking would be a step in the right direction. Some study has been made in this field during the last few years, but there would seem to be considerable room for more study. Before making unqualified recommendations for air drying, however, all of the cost factors common to air drying should be recognized.

Since the first water removed in the drying of green wood comes out rather easily at low temperatures, there would seem to be a big opening for more low-temperature predriers. These can be constructed at much lower cost than ordinary kilns because little or no heat needs to be used and they need not be insulated to prevent heat loss. High rates of air circulation are desirable to remove moisture from the surface of the lumber. Some control of humidity can be obtained by regulating the amounts of air vented and recirculated. Greater control can be gained by regulating the amount of heating of the enclosed air above the temperature of the outdoor atmosphere.

This suggests study of the relationship of permissible initial humidities and temperature, because conditions in a loosely built predrier-type of structure will have to be more in keeping with the outdoor temperature than with any prescribed optimum. Operation would be simplest for the drying of woods that can stand very low humidities at low temperatures, such as the softwoods.

Another consideration under this aspect is how best to combine low initial temperatures in a predrier or a kiln with the higher temperatures necessary to complete the drying in the kiln economically. The general procedure of maintaining a comparatively low temperature until the wettest spot in the wood is below the fiber saturation point, so as to avoid honeycombing, is in line with keeping temperature low during the first part of the run in order to avoid excessive set in the interior. All the compression set is built up before stress reverses.

The findings do not, however, explain the great amount of excess shrinkage shown by slices 2 and 9 in the specimen kiln dried after controlled room drying at 35° F. This excess shrinkage was largely built up while the wood was drying at 110° and 120° F., although slightly more was added at 130° F. With present knowledge, the results of this run cannot be considered typical of what would be expected when lumber dried by ordinary air drying or in a predrier is kiln dried.

High final drying temperatures tend to relieve both tension and compression set slightly. The effect appears to be greatest on the compression set.

Summary and Conclusions

1. At temperatures from 80° to 140° F. under forced-circulation kiln-drying conditions, the general pattern of stress development previously indicated by elastic strain analysis for northern red oak and other hardwoods was confirmed.

2. In contrast to previously published information on strains in sweetgum heartwood, considerable tensile strain still existed in the outside slices of oak specimens when maximum compressive strain in the center slices occurred, and the compressive strain in the center slices was nearly zero when stresses reversed in the outside slices.

3. Using the same moisture content-relative humidity reduction schedule for temperatures from 80° to 140° F., time to maximum tensile strain in the outside slices was reduced and the value of the maximum increased as temperature was raised.

4. Likewise, time to maximum compressive strain in the center slices was reduced as temperature was raised, but the maximum strain was essentially the same at all temperatures except. 140" F., where a considerably lower maximum occurred.

5. Stress reversal in the outside slices occurred at an average moisture content of about 30 per cent except at 80° F., where the value was about 23 per cent.

6. Under controlled room drying conditions, both maximum tensile strain of the outside slices and maximum compression strain of the center slices were very low at 35° F. and about the same at 80° F. as those during kiln drying at that temperature.

7. Steeper moisture gradients prevailed at the time of maximum tensile strain in the outside slices at the higher temperatures.

8. Moisture content was still at or above the fiber saturation point throughout the center slices at the time they were under maximum compressive strain. The middle portions of these center slices also were at or above 30 per cent moisture content when the first maximum of tensile strain occurred.

9. Tension set in the outside slices was comparatively large and unaffected by temperature from 80° to 125° F. It was slightly larger at 140° F.

10. Compression set in the center slices was greatly affected by temperature, being small at 80° to 110° F. and about twice as large at 140° F.

11. Board shrinkage was found to be profoundly influenced by temperature, with increasing amounts of interior compression set causing greater amounts of board shrinkage as temperature was increased from 95° to 140° F. Decreasing interior compres-

sion set plus an increasing portion of the thickness under the influence of tension set caused decreased board shrinkage as temperature was decreased from 95° to 80° F.

Literature Cited

1. Churchill, J. W. 1954. The effect of time, temperature, and relative humidity on the relief of casehardening stresses. Jour. Forest Products Research Society 4(5):264–270.
2. Ellwood, E. L. 1954. Properties of American beech in tension and compression perpendicular to the grain and their relation to drying. Yale School of Forestry. Bull. 61, 82 pp., illus.
3. Greenhill, W. E. 1936. Strength tests perpendicular to the grain of timber at various temperatures and moisture contents. Jour. Counc. Sci. Ind. Res., (Australia). 9:265–278.
4. Kollmann, F. 1950. Untersuchungen über die Ursachen von Schäden bie der Trocknung von Grünen Eichenholz Zugleich Mitteilung über Festigkeits Prüfungen an Holz in Hochfrequenten Wechsfeld. Svenska Traäforskningsinstitutet, Träteknikska Avdelningen Neddelande 21.
5. MacLean, J. D. 1954. Effect of heating in water on the strength properties of wood. Proc. Amer. Wood-Pres. Assoc. 50:253–281.
6. McMillen, J. M. 1955. Drying stress in red oak. Forest Products Jour. 5(1): 71–76.
7. Rees, L. W. and Buckman, S. J. 1940. Effect of steaming on the physical properties of southern pine. Proc. Amer. Wood-Pres. Assoc. 36:331–360.
8. Rietz, R. C. 1950. Accelerating the kiln drying of hardwoods. Southern Lumberman. 181(2262):43, 44, 46.
9. Torgeson, O. W. 1951. Schedules for the kiln drying of wood. U. S. Forest Products Laboratory Report No. 1791, 9 pp.