

# DRYING STRESSES IN RED OAK AND OTHER HARDWOODS <sup>1</sup>

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It is our firm opinion that the time has come when better kiln schedules, better control of material dimension, and more practical means of relieving so-called casehardening will have to be based on a more thorough understanding of the internal stresses that are set up when wood is dried. Since 1950, it has been my privilege, in the company of some able assistants,<sup>3</sup> to make limited studies in this field. The studies have been made on red oak, one of the most important woods used in the East and one of the woods that takes a long time to dry. Besides information on oak, we were striving for a real understanding of what goes on within any wood when it dries at different temperatures and different relative humidities. We hope to enlarge the study to other hardwoods and ultimately to softwoods. Today, I am going to talk about the work on red oak and about some of the work done by other investigators, including Harvey Smith of the California Forest and Range Experiment Station, on other hardwoods. I will conclude with some possible applications to the softwoods.

First, let's review what we do know about the internal stresses that are set up in wood when it is dried. We know that stresses are caused by shrinkage and resistance to shrinkage. They occur when one part of the wood dries below the fiber-saturation point and shrinks, while adjacent parts of the wood resist shrinkage because of being green or set. This action sets up forces that tend either to pull the wood apart, pack it together, or to slide one part of the wood along or past the other. The first force we know as a tension stress, the second as a compression stress, and the third as a shear stress. These are the stresses that cause surface and end checks, honeycombing, so-called ring separation, so-called casehardening, and one form of collapse.

It is easy to see how the surface of wood having a steep moisture gradient during drying can be subjected to considerable tension stress. The old principle - - for every action there is an equal and opposite reaction - - helps us to understand how the tensile stresses on the surface cause compression stresses in the interior. But, when we examine a casehardened board, we find that the surface is in compression while the interior is in tension. In other words, the stresses are reversed. This comes about because the outer zones are stressed so much early in drying that they lose their elasticity and become set. The outer zones are set in a dimension larger than they would have if they were allowed to shrink without restraint. The interior of the wood dries without the steep moisture gradient below the fiber-saturation point, that caused the set in the outer zones, and the stresses reverse because the inner zone, continuing to shrink, is restrained by the set outer zones.

1. - To be presented at the annual meeting of the Western Dry Kiln Clubs to be held at Eureka, Calif., May 13, 14, and 15, 1954.
2. - Maintained at Madison, Wis., in cooperation with the University of Wisconsin.
3. - Takeo Ogura, Chief, Wood Material Section, Government Forest Experiment Station, Meguro, Tokyo, Japan; R. L. Youngs and R. C. Baltes, U. S. Forest Products Laboratory, Madison, Wis.

Wood generally goes through the foregoing stages as it dries. The knowledge that these stresses existed, and that they reversed later in drying, is not new. We knew about them when we first set up kiln schedules with mild initial kiln conditions to control surface and end checking. We knew about them when we devised conditioning treatments to relieve casehardening. We knew about them when we started to study the stress-strain relationships of wood perpendicular to the grain back in the early '30's. We gained further information about them in the late '30's and early '40's when we were setting up means of rapidly drying certain woods that eventually led to our new accelerated kiln schedules.

Until recently, neither the Forest Products Laboratory nor anyone else fully investigated in a scientific way the whole subject of internal stresses in the wood as it dries.

The present work on red oak has so far been confined to tension and compression stresses, although we realize shear stresses of various kinds are involved and will need to be included in the final analysis.

### Test Methods

Our method of study, known as the slicing technique, consists of measuring the width of pieces of S4S wood, at various stages of drying, before and after slicing to release stresses. The green wood is marked off with a 1-inch section every 2 inches along the grain. Each section is marked for 10 slices, as shown in figure 1. One section is cut off the plank after each interval of drying. The remainder of the plank is end coated and replaced in the kiln for further drying. While still in the complete section, the width of each slice is measured to get the "before cutting" dimension. Then the section is laid on its side and cut into the 10 slices. As each slice is cut free, it contracts or elongates depending on whether the wood of the slice was under tension or compression at the time of removal from the kiln. The "after cutting" dimension is then measured. The difference, converted to an inch per inch basis, is the unit strain.

If wood were perfectly elastic, the unit strain would be proportional to the unit stress. In other words, we could, by a few simple tests, convert the strain data to stress data. But, because the proportional or elastic limit of the material is exceeded, a situation that invariably exists when we are drying wood, we cannot get at the exact magnitude of the stresses. Another reason why we cannot easily get at the magnitude of these stresses is because the stress-strain relationship changes as the moisture content changes. Measurements of strain give some indication of magnitude of stress, however, and they indicate the direction of stress, whether tension or compression. We recognize and accept these and other limitations in our method of analysis, but we believe the information gained helps a great deal in the understanding of the basic fundamentals of the drying of wood.

### Discussion of Results

Let us look now at some of the strains in a 2- by 7-inch northern red oak at various stages when dried by a mild schedule, as shown in figure 2. At the end of 5 days of drying, this specimen had dried to 77 percent moisture content, and the maximum tension strain of about 0.003 inch per inch had been indicated in the outer slices.

Only the outer zones were in tension. The second and ninth slices were in slight compression. The other interior slices all had a compression of about 0.001 inch per inch. At the second stage, after 10 days of drying and one slight change in relative humidity, the wood was at 64 percent moisture content. There still was a great deal of tension in the outer slices. The second and ninth slices had gone into tension. The interior slices had greater compression. At 18 days, moisture content had dropped to 50 percent, and the second and ninth slices reached their maximum tension of about 0.0017 inch per inch. The first and tenth slices still had a greater amount of tension, however. The center slices reached a maximum compression, with the same order of magnitude as the maximum tension in the outer slices at the first stage. Compression strain in slices 3 and 8 had dropped almost to zero. At the fourth stage, after 28 days of drying, the moisture content was at 35 percent, and reversal of stresses had started. In the fifth stage, reversal of stresses was complete, after 36 days of drying. Moisture content was down, on the average, to 17 percent, but the moisture content of the central portion of the center slices was around the fiber-saturation point. The compression in the outside slices reached a maximum of almost the same order of magnitude as the maximum tension in the outer slices at the start. Remember, these are strains, not stresses. The stresses for the same strains become considerably greater as moisture content goes down.

Reviewing the stress patterns in terms of the effect of the stresses on wood, we find the danger of surface checking was the greatest during the first stage of drying, when we had maximum tension stress in the outer zones. The possibility of compression set or compression collapse was the greatest when the compression stress in the center zone was greatest. The condition promoting honeycombing was the worst when the outer zones were at maximum compression stress and the inner zones at maximum tension stress. The final condition we recognize as case-hardening. Figure 3 shows a linegraph of the same data at 110° F.

In a more recent study we investigated the effect of temperature, using the same relative-humidity type of schedule. The temperatures studied were 80°, 95°, 110°, 125°, and 140° F. The results at 110° were similar to those obtained in the first tests. The maximum compression strain in the center was the same order of magnitude, 0.003 inch per inch, but the maximum tension strain in the outer slices went to 0.004 inch per inch.

Figure 4 shows a linegraph of results obtained at a lower temperature. At 95° F., we got the same general pattern and a similar order of magnitude of strains. The maximum tension strain in the outer slices was obtained more slowly. Its magnitude was 0.003 inch per inch. The center slices reached a maximum compression strain of 0.003 inch per inch in 30 days. Reversal occurred at 45 days. After reversal, there was one important difference. The maximum tension occurred in slices 3 and 8 instead of in slices 5 and 6. The order of magnitude of the maximum strain there was low, 0.001 inch per inch. There should be no honeycombing at this temperature unless it comes from a surface or end check.

Figure 5 shows results at a higher temperature. At 140° F., there was the same general pattern but some other major differences. The maximum tension strain in the outer slices was reached in one day, and it was 0.0046 inch per inch.

The time at maximum tension strain was much shorter. The maximum compression strain in the center slices was much lower, 0.0018 inch per inch. The central zone was stressed away beyond its proportional limit and failed, or compressed, considerably. This did not occur in any such degree at 125° F. or the lower temperatures. There also was a greater tension strain in slices 2 and 9, 0.003 inch per inch as compared to 0.0017 in the first tests. After stress reversal, the magnitude of the strains was much greater. Tension in the center slices went to 0.003 inch per inch. Compression in the outer slices also went to 0.003 inch per inch. The danger of honeycombing was much greater at 140° F. than at lower temperatures. The drying time of 29 days was considerably shorter than the drying time of 63 days for 95° F.

The foregoing gives a fairly good picture of what happens in oak at various temperatures under a fairly mild schedule for lowering relative humidity. The effect of width of specimen is shown in figure 6. Because of the shorter drying time of the narrow specimen, an evaporable moisture content basis was used instead of a time basis to plot the strain curves for the different widths. The ratio of the evaporable moisture left in the wood at any time to the original amount of evaporable moisture is represented by the symbol "E". It is determined by the formula:

$$"E" = \frac{\text{Current moisture content} - \text{E.M.C.}}{\text{Original moisture content} - \text{E.M.C.}}$$

E.M.C. = equilibrium moisture content.

Wider width stock produced more rapid tension stress in outer slices, but maximum strains were about the same. For some reason, the compression strain of the center slices went up as width increased.

Other questions arise: What about other hardwoods? Do they behave the same as oak? What about the effect of other humidity-reduction patterns? What about softwoods? Figure 7 shows the results of 2-inch red oak in comparison with results obtained by Harvey Smith and W. Karl Loughborough<sup>4</sup> on sweetgum. When 2-inch sweetgum heartwood was dried at 135° F., maximum tension strain in the outer slices was 0.0037 inch per inch, which is about the same as the maximum observed with oak. At the sixth day, Smith and Loughborough attempted to hold this maximum by first gradual, then drastic reduction of wet-bulb temperature. They reasoned that if the wood would stand such a maximum strain at 2 days, accelerated kiln schedules could be developed by trying to hold that same strain while rapidly lowering the relative humidity. It was impossible to hold that strain. Tension in slices 1 and 10 began to fall off towards zero. Slices 2 and 9, however, developed a rapid maximum tension strain of 0.0028 inch per inch at 10 days, while the interior slices reached a maximum compression strain of 0.0036 inch per inch at the same time. At 13 days, the outer slices had gone into compression. The stresses reversed between the 13th and 25th days. The compression strain in the outer slices went up to 0.0033 inch per inch.

When we attempted a similar drastic lowering of E.M.C. to about 5 percent with red

4. Forest Products Laboratory, ANC-21, Kiln Certification. Published by Aeronautical Board, Washington, D.C., 1945. Also, Rietz, R.C., Accelerating the Kiln Drying of Hardwoods. Southern Lumberman, July 1, 1950.

oak after the tension strain in the outer slices had fallen off about one-quarter from its maximum, we got an increased tension strain in the outer slices. There was also an increase in the compression strain of the interior zones. No checking occurred, however. Perhaps the fact that the specimen had only a 7-inch width may have been partly responsible for its not checking.

The stresses in other hardwoods follow the same general pattern. Peck<sup>5</sup> made stress analyses on a number of easier-drying southern hardwoods, such as magnolia, sycamore, and blackgum sapwood. Peck was looking for the point of stress reversal as the point after which he could make drastic changes in relative-humidity conditions. With easy-drying woods, reversal occurred very early. Drastic lowering of relative humidity then caused no surface checking.

At the start of World War II, Smith made a stress analysis on 8/4 black walnut. The strains were similar to those found in northern red oak. The maximum tension in the outer slices was reached fairly rapidly at 6 to 8 days; the magnitude was 0.003 inch per inch. Slices 2 and 9 first went into compression and then swung into tension. Maximum tension was about 0.002 inch per inch. Slices 5 and 6 continued on to a maximum compression strain of 0.0026 inch per inch. Reversal of stresses came at 24 days, and the maximum interior tension strain, about 0.001 inch per inch, was reached by slices 3 and 8. The type of schedule was a fairly long period of high relative humidity with an accelerating drop in relative humidity following that.

One stress analysis on quaking aspen was run by S. M. Ishaq, Forest Service, Pakistan, another of the wood technologists who have come to the Forest Products Laboratory from other countries to study seasoning. The overall pattern was similar. Slices 1 and 10 approached maximum tension strain at 2 days of drying, and the strain was 0.003 inch per inch. This maximum was held for 3½ days. Then the drop to zero strain was gradual. The maximum compression strain of slices 5 and 6 was somewhat higher than that of oak, which was 0.004 inch per inch. The stresses reversed on about the thirteenth day.

Before departing from the consideration of hardwoods, I must point out again that when we speak of a specific elongation or contraction, we are discussing a strain. In general, stresses are proportional to the strains at any given moisture content, but at a lower moisture content, the stresses for various strains would be greater. The stresses are what cause seasoning defects. We will not understand the whole picture on drying stresses until we have enough information about the actual strength of wood across the grain under kiln conditions. Such information will come from strength tests at the temperatures used in kiln drying and with the wood at the moisture-content values found in the different portions of the cross section during various stages of drying. Substantial studies are being made in this field. Eric Ellwood, an Australian wood technologist taking a doctor's degree at Yale, studied the tension and compression properties of beech across the grain. He has written a very fine thesis on this,<sup>6</sup> and a part of the work has been published in the Forest Products Research Society Journal.<sup>7</sup>

5. Peck, E.C., A New Approach to the Formulation of Hardwood Dry-Kiln Schedules, Southern Lumberman, December 15, 1940.
6. Ellwood, E.L., Strength of American Beech in Tension and Compression Perpendicular to the Grain as a Function of Temperature and Moisture Content, Doctorate Thesis, Yale University, 1953.
7. Ellwood, E.L., Properties of Beech in Tension Perpendicular to the Grain and Their Relation to Drying, Forest Products Research Society Journal, Vol. III, No. 5, P. 202, December 1953

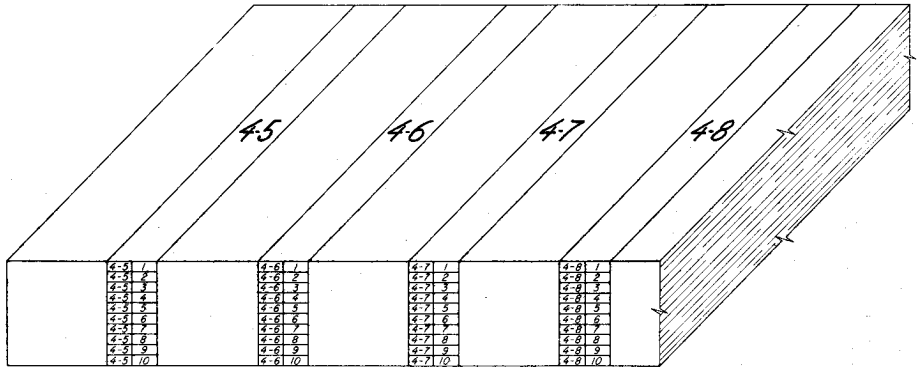
Now for the \$64.00 question. Does the same stress pattern hold for softwoods? If not, what is the stress pattern in softwoods? Two years ago at the joint meeting of the western dry-kiln clubs at Redding, Calif., Leif Espenas, Oregon Forest Products Laboratory, reported about a study on Douglas-fir. He reported that it did not appear as if the softwoods followed the same pattern. At a constant temperature and a high E.M.C., he wasn't able to detect a reversal of stresses. In later work using constant conditions but a lower E.M.C., compression stresses developed in the outer slices, but not early in drying. The complete reverse picture was not found until the moisture content of the center slices was down to 20 percent. Also, it appeared that stresses were not stable at the lower moisture-content levels but that, by lowering the E.M.C. sharply, the outer zones could be thrown into tension again.

This may not be too different from what we would obtain with some hardwoods under the same conditions. We believe that major drying stresses are set up by a steep moisture gradient. If the drying schedule is manipulated so as not to bring on such a steep moisture gradient, or if the wood itself lets water move through it so rapidly that a steep moisture gradient is not set up, we would not expect to find stresses. Our results in some all-sapwood maple bowling pins were about the same as Espenas observed in softwoods. With the bowling pins, the moisture gradient was very flat during the early part of the run on a mild kiln schedule. Although there were difficulties in measuring strains in a round item, we did get some useful data. It was only after the moisture content was down around 30 percent that maximum tension appeared in the outer slices. We think that in many of your rapidly drying western softwoods, regardless of temperature and humidity schedule, you have a fairly flat moisture gradient. During this period of the run you would not expect to get tension stresses set up. A large portion of the outer zone is considerably above the E.M.C. of the kiln. The wood is not much below the fiber-saturation point. When the free water is used up, the surface moisture content then starts to drop down to the E.M.C. Then you begin to set up your stresses. A drastic change in E.M.C. at this time might cause surface checking.

Perhaps a look should be taken at how a kiln operator could manipulate a softwood schedule to set up stresses early for his advantage. Perhaps low humidities during the first part of the run should be used to bring on early tension stress and tension set. From then on the wood should be able to stand almost any condition without surface checking.

Honeycombing is not such a problem in softwoods. Perhaps the need for temperature control to maintain the maximum strength of the wood is not so necessary. So-called ring separation in Douglas-fir may be an exception, however. Some of your western softwoods collapse. Some of this collapse may be due to the maximum tension stress on the outside compressing the inside. In woods that do collapse, the avoidance of high temperatures is desirable from stress considerations as well as from the standpoint of resistance to liquid tension.

The information we have on hardwoods and the understanding it yields as to what goes on inside wood as it dries makes the study of stresses and strains in softwoods seem very attractive to those who would like to see our commercial kilns used to the greatest advantage.



N 8766 P

Figure 1. - Method of marking test specimens.

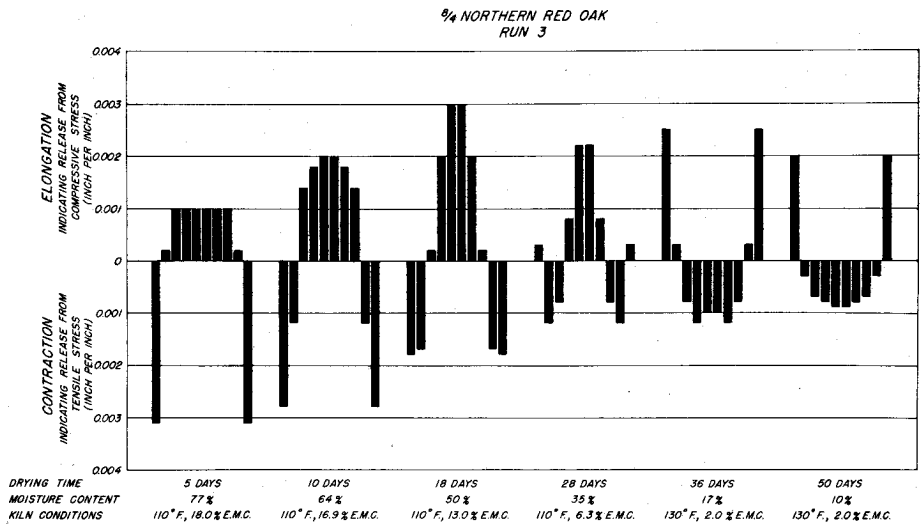


Figure 2. - Strain diagram for 2-by 7-inch northern red oak dried at 110° F.

3/4 NORTHERN RED OAK  
RUN 3

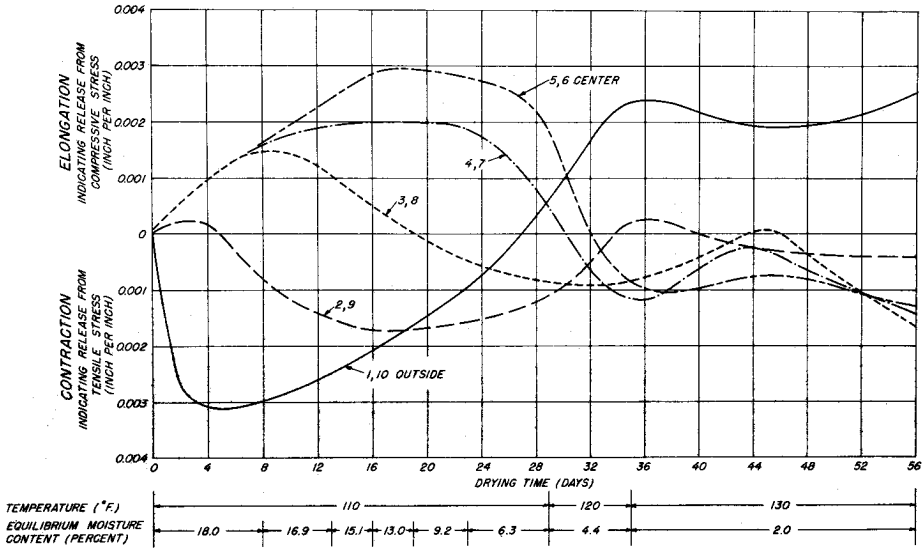


Figure 3. - Strain curves for 2-by-7-inch northern red oak dried at 110° F.

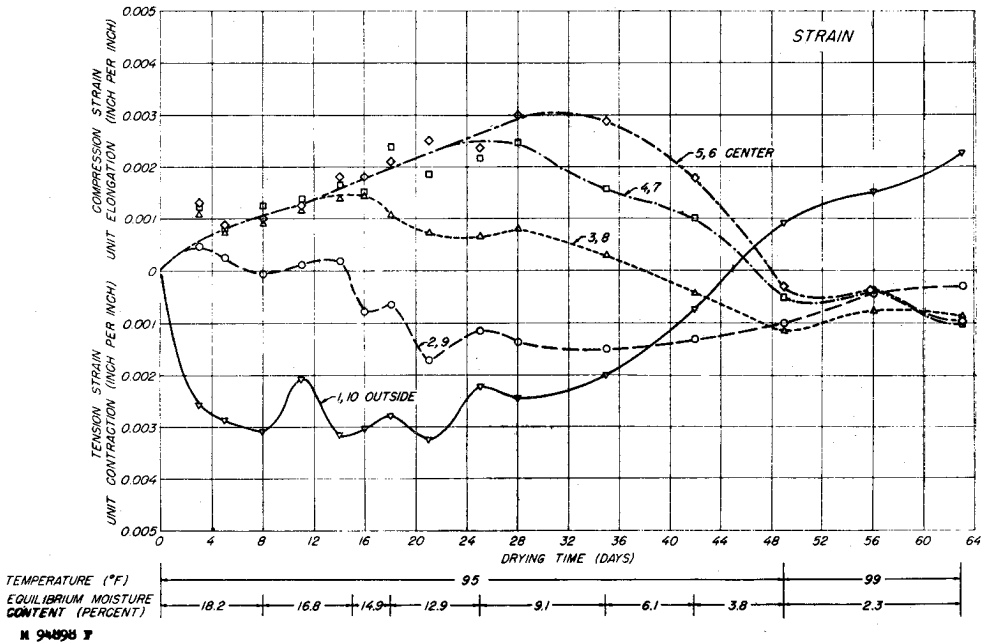


Figure 4. - Strain curves for 2-by-7-inch northern red oak dried at 95° F.



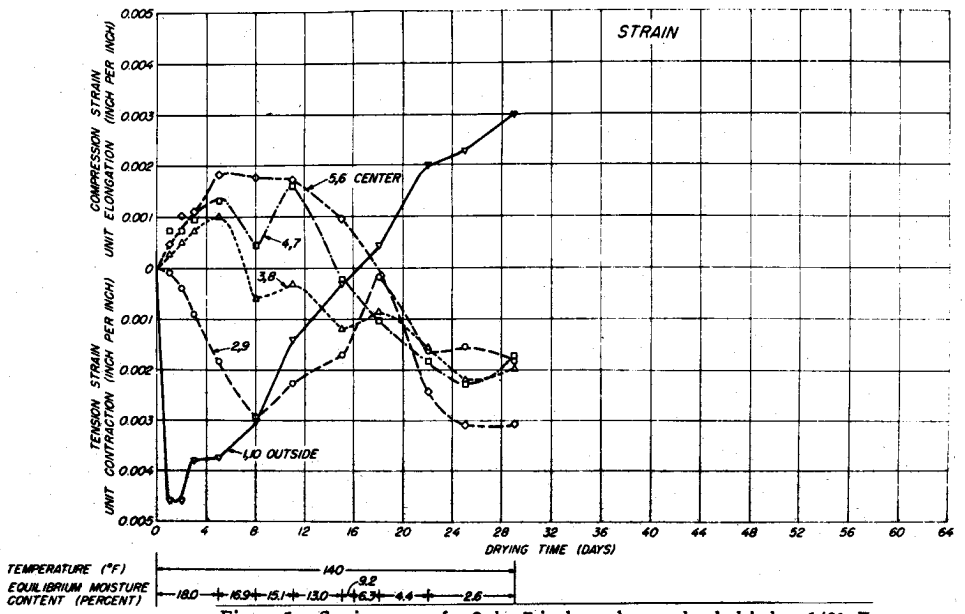


Figure 5. - Strain curves for 2-by 7-inch northern red oak dried at 140° F.

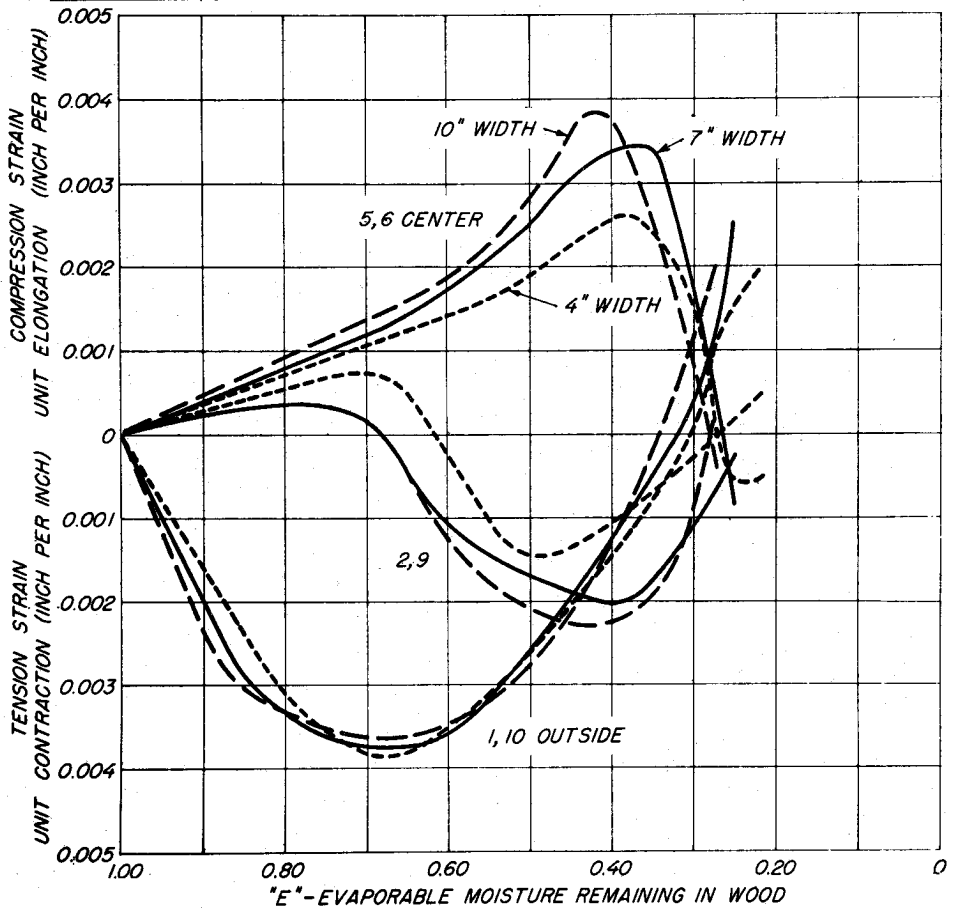
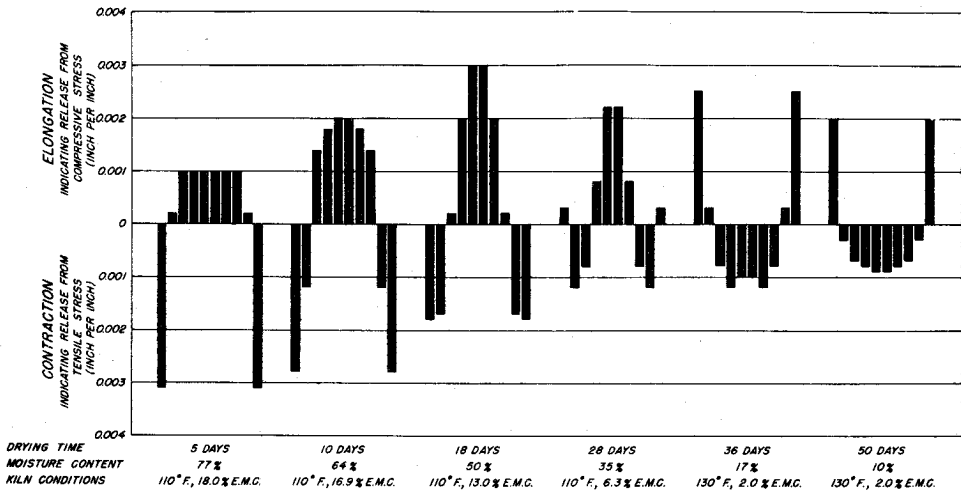
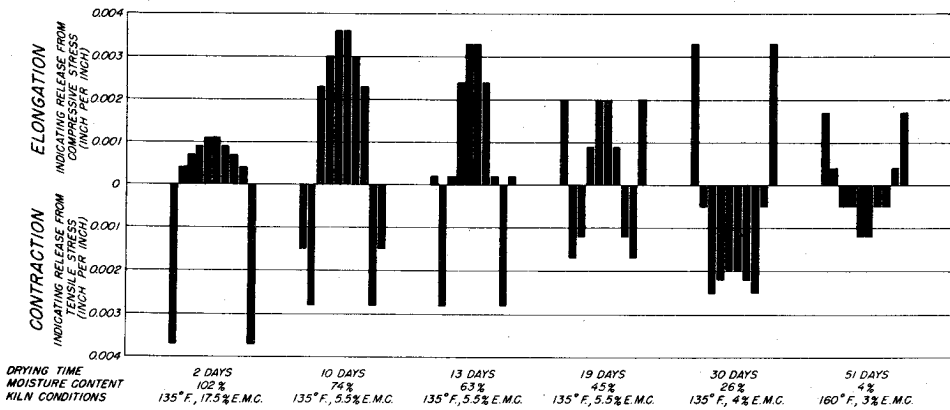


Figure 6. - Strain curves of 4, 7, and 10 inch wide 2-inch northern red oak dried at 110° F.

3/4 NORTHERN RED OAK  
RUN 3



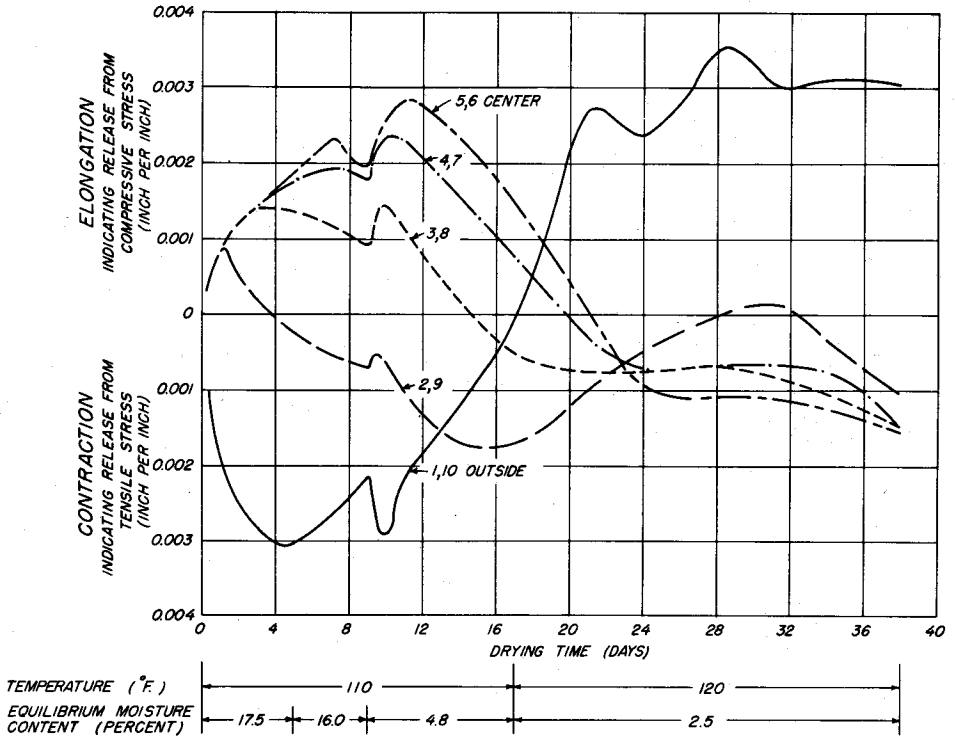
3/4 SWEETGUM



H 95950 F

Figure 7. - Strain diagram of 2- by 10-inch sweetgum heartwood dried at 135° and 160° F. in comparison with strains of 2- by 7- inch northern red oak dried at 110° F.

3/4 NORTHERN RED OAK  
RUN 5



X 95948 F

Figure 8. - Strain curves for 2-by-7-inch northern red oak subjected to very rapid relative humidity reduction.