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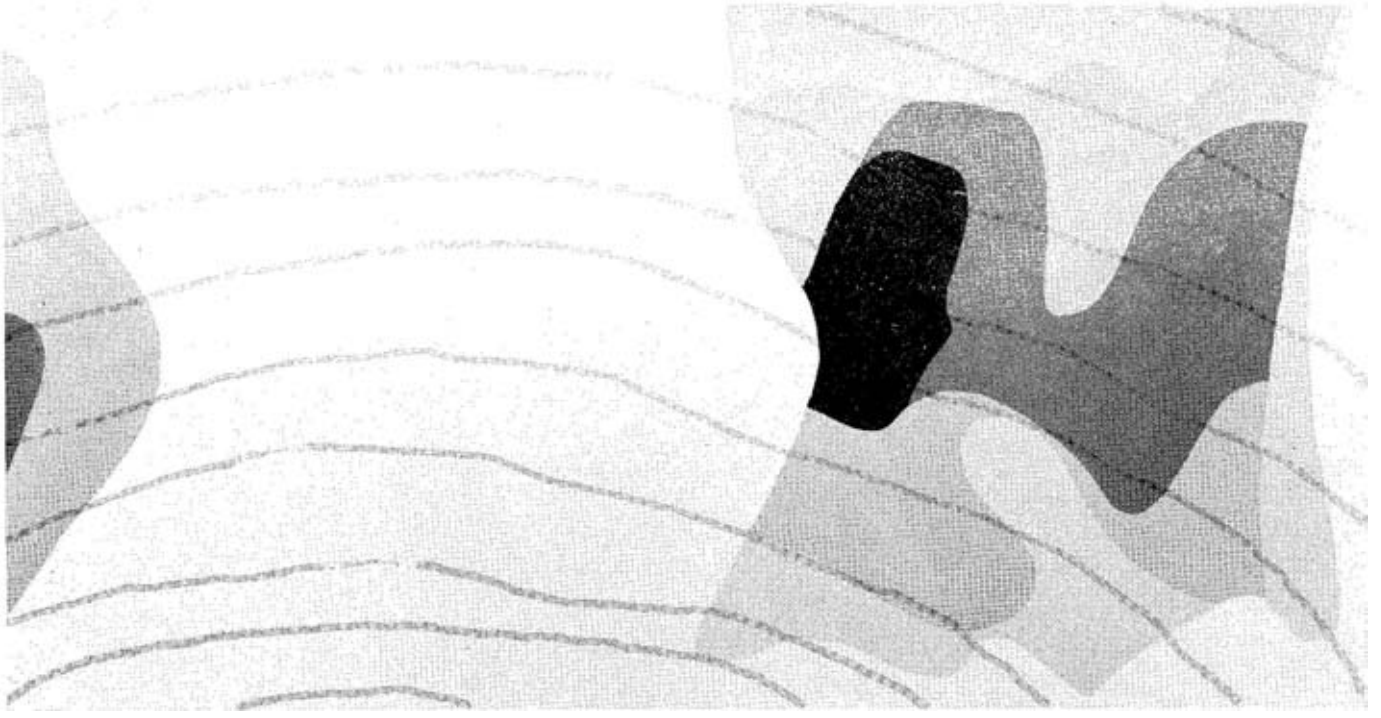
TRANSVERSE STRAINS DURING DRYING OF 2-INCH PONDEROSA PINE



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ABSTRACT

Drying is the most time-consuming step in producing softwood lumber as well as being one of the most costly. Industry feels it must improve drying methods to hold down or reduce time and costs, while simultaneously drying to lower moisture content levels and still retaining or improving quality of the stock. Substantial improvements depend on knowledge of stress-strain behavior, through which defects and degrade can be controlled as accelerated drying technology is applied.

In this study, quantitative information was developed on the strains and sets in various laminae of 2-inch ponderosa pine. At 110° F., heartwood and some sapwood developed regular patterns of tensile and compressive strains that avoided surface checking and excessive board shrinkage. With the air velocity at 600 to 800 feet per minute, some sapwood developed irregular moisture distributions that produced strains large enough to cause checking. A modified pattern of reduction in equilibrium moisture content (EMC) was devised to control such checking.

Tension set in the outer laminae built up to a moderately high value during the first half of drying. Compression set developed mainly during the middle third of drying and was generally small. Stress reversal occurred after average moisture content was at or below 20 percent with all types of wood; this confirms preliminary results with, a few other species. Residual stress and set were relieved by a 6-hour conditioning treatment.

Board shrinkage commenced at or near the start of drying. The amount of shrinkage at any given moisture level between 20 and 10 percent was not greatly affected by the conditions used, except that it was greater than average at 170° F.

The schedule of modified reduction in EMC has immediate application in reducing the checking of the denser pieces of ponderosa pine, Douglas-fir, and other species. The strain values can be used with mechanical property values perpendicular to grain to compute the actual stresses throughout the cross section at various stages of drying, a needed step in development of improved softwood drying. The irregular moisture distributions also provide a basis for improvements in the theory of moisture movement during the drying of softwoods.

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TRANSVERSE STRAINS DURING DRYING OF 2-INCH PONDEROSA PINE[1]

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INTRODUCTION

Practical procedures for drying hardwoods and softwoods without excessive shrinkage-related defects depend upon maintaining kiln conditions that accelerate drying without exceeding the maximum strength of the wood perpendicular to the grain. Research on transverse drying strains in southern hardwood species provided a basis for safely accelerating the kiln drying of hardwoods (9, 10, 12, 15, 18).[3] Research with red oak on transverse drying strains (4, 5, 8), perpendicular-to-grain mechanical properties (20), and the resultant normal and shearing stresses (21, 22) will ultimately lead to further acceleration of drying and improvement in the dried product.

The present study was undertaken to develop knowledge of the strains in a representative softwood, to improve practical drying and stress-relieving procedures, and to obtain quantitative data for use with perpendicular-to-grain mechanical data to compute actual drying stresses in softwood boards. Ponderosa pine was selected for this study because information on both heartwood and sapwood was obtainable from the same logs, and drying behavior of the species is similar to that of several other softwoods. A few of the results have been previously reported (7).

Several other workers have also studied this problem Unpublished Oregon Forest Research Laboratory studies indicated that tensile strains persisted in the surface layers until the average moisture content of Douglas-fir and western hemlock boards was below 20 percent. Stillwell (14) showed that the number of large checks in Douglas-fir increased when a drastic lowering of kiln EMC (equilibrium moisture content) was imposed at the 20 percent moisture content level. Resch and Ecklund (11) found stress reversal at 26 percent moisture content in 4/4 heavy-sort redwood boards. Maximum tensile strains

[1] The logs for this study were provided by Timber Products Corporation, Medford, Oreg. The material was selected and shipped to the Laboratory by the Pacific Northwest Forest and Range Experiment Station, U. S. Forest Service, Portland, Oreg.

[2] Assistance in measuring strains and analyzing data was provided at the Laboratory by R. C. Baltes, Physical Science Aid, G. L. Comstock, Technologist, and E. L. Schaffer, Engineer.

[3] Underlined numbers in parentheses refer to Literature Cited at the end of this report.

in the outer slices were about equal to the maximum compressive strains in the internal slices. In exploratory research with southern Rocky Mountain white fir, Engelmann spruce, and ponderosa pine, the present author found that stress reversal did not occur until average moisture content was between 20 and 15 percent.

Ugolev (16, 17) has applied a different slicing method to the stresses before and after reversal in air drying spruce and pine, after reversal in kiln drying pine, and after final conditioning treatments. Ivanov (3) pointed out limitations of Ugolev's approach, but encouraged further study, and Russian research continued (13). A specialized measuring chamber that may have application in the future when softwood drying strain studies are extended to high temperatures has been developed by Cech (1).

Our attack on the problem was divided into three parts: Effects of different types of wood, effects of EMC reduction pattern, and effects of temperature. Type of wood was studied at 110°F. using a relatively rapid time schedule for gradually reducing EMC. The influence of EMC reduction pattern also was studied at 110° F. Delayed and back-up patterns, as well as the gradual pattern of EMC reduction, were employed. In the third part, constant temperatures from 80° to 170° F. were used with delayed EMC reduction. This essentially covers the temperature range of forced air (2) and conventional kiln drying (10).

The variability in behavior of specimens was considerably greater than expected. Need for intensive study of each specimen precluded replication within individual kiln runs, and time and material limitations precluded replication of the runs. The broad approach of the study plan was continued, however, to provide a fundamental basis for further study.

For each part of the study, average moisture content, moisture distribution, and elastic strain and permanent set in the width direction are analyzed as a function of time. Board shrinkage is analyzed both as a function of time and of average moisture content. A general discussion covers suggestions for computation of drying stresses and general relationships of tensile strains to checking and of tension and compression set to board shrinkage. Also covered are implications about liquid moisture movement and application of the results to practical drying operations,

MATERIAL AND METHODS

Material

All specimens were cut from the lower 8 feet of five large upper logs of old-growth ponderosa pine (*Pinus ponderosa* Laws), from Medford, Oreg.[1] The logs were end coated, shipped by rail during cold weather, and protected by water sprays upon arrival at Madison. Oversized specimens of selected location, size, and flat-sawn ring orientation were sawed from the logs, dipped in a solution of sodium pentachlorophenate, wrapped in heavy polyethylene film, sealed, and stored at 36° F. until needed, Immediately before each experiment, the specimen was surfaced to a 2-inch thickness and a width just under 7 inches. It was then marked and measured, and end sections were taken to obtain the characteristics given in table 1.

Table 1.--Properties of ponderosa pine used in drying strain studies

Variable	Specific gravity[1]	Rings per inch	Green moisture content
			Pct.
Type of Wood			
Heartwood	0.50	8	37
Both heartwood and sapwood	.43	12	65-97
Sapwood			
Specimen A	.36	17	207
Specimen B	.39	10,15	143
EMC Reduction			
Fast gradual	.41	24,16	164
Delayed	.47	12,16	138
Backup	.42	12	164
Temperature			
80° F.	.34	13	193
110° F.	.36	13	201
140° F.	.36	12	197
170° F.	.34	13	202

[1] Based on volume when green and weight when ovendry.

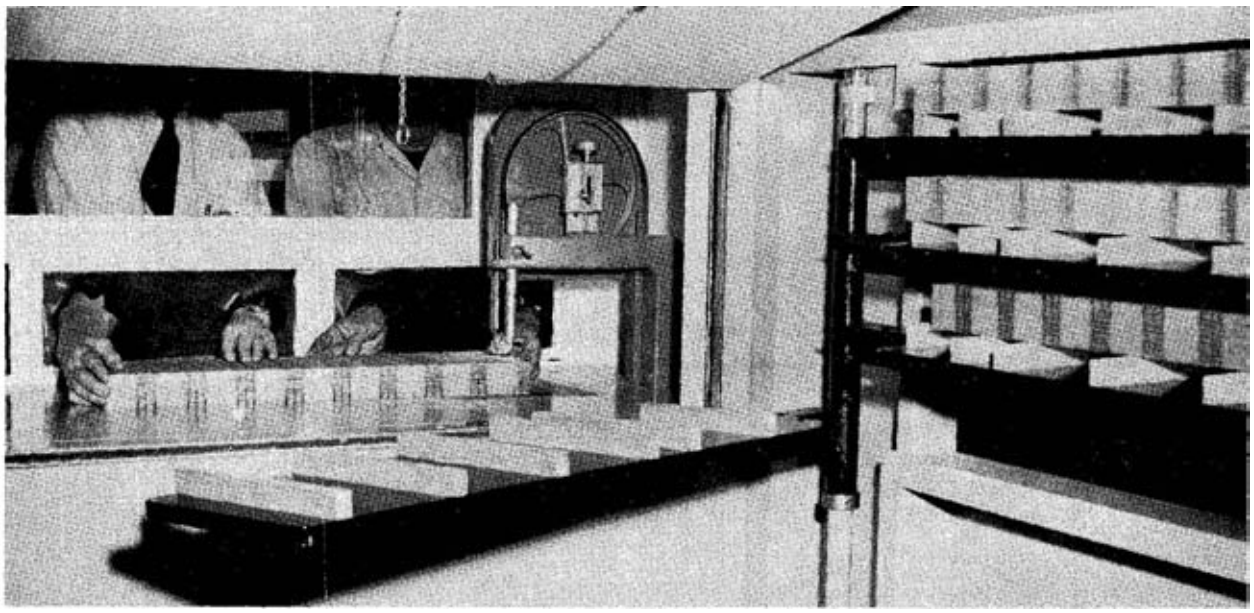


Figure 1.--Drying, dissecting, and measuring chamber showing three specimens on pivoted shelves in drying compartment baffle and strain-test section being cut from other specimen ai· reach-through window. (M 101 029)

Methods

The general method was that used previously in studying temperature effects in drying red oak (4, 5, 8). This consists of drying a test specimen in a small, internal-fan kiln with automatic control of temperature and relative humidity. Each surfaced-green specimen was marked into 1-inch sections every 2-1/4 to 3 inches along the length. Each section was marked for 10 slices, and the center of each slice end was marked with a vertical line. The slices were numbered consecutively from 1 to 10, beginning at the face of the specimen toward the convex side of the growth rings. The width of the green specimen was measured to the nearest 0.001 inch between midpoints on the ends of each slice using a dial micrometer caliper.

After each interval of drying, one section was cut from the specimen. Each slice in this section was measured before and after slicing. The differences between the green and the before-slicing measurements yielded board shrinkage. The differences between before- and after-slicing measurements yielded the recoverable or elastic strains. Total shrinkage of each slice was obtained from the green and ovendry measurements. Differences between the observed total slice shrinkage and the inherent shrinkage of the wood were considered indications of nonrecoverable strain or set.

A few of the 110° F. specimens were dried on stickers in a small rack in the kiln. Void space was baffled so that air velocity over the specimen's surface was 600 to 800 feet per minute. It was necessary to take these specimens from the kiln to cut off the section, and this was done in a preheated plywood case. Exposure of the specimen to room air was minimal. Precautions to prevent heat and moisture loss from the sections were as previously described (5). The other specimens were dried, dissected, and measured in the two-part chamber shown in figure 1. Usually, only one specimen was dried at a time, and it was supported with a single pair of "knife edge" stickers on one of the pivoted shelves. Sufficient void space was left open over the other shelves and elsewhere in the baffle so that the 600- to 800-foot per minute air velocity was maintained. At 110° F. there was no essential difference in reaction of the specimens to these exposure, dissection, and measuring conditions.

At each time of strain analysis, the door between the compartments was opened, the shelf pulled to the saw table, and the section cut off. An adjacent 1/2- or 1-inch section was cut for moisture distribution data. The exposed end of the remainder was end coated twice with an aluminum-phenolic resin end coating. While the first coat of end coating was drying, the current width of each slice, in the section, was measured to the closest 0.001 inch. Then the second coat was

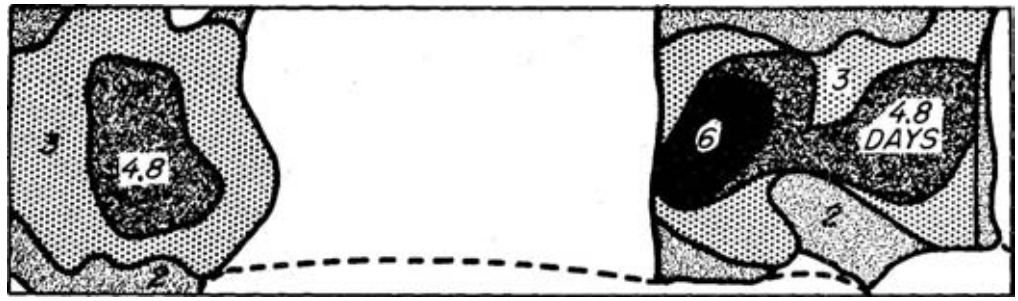


Figure 2.--Location of visibly-wet zones on cross sections of a sapwood specimen taken, successively, after 2, 3, 4-4/5, and 6 days of drying. All, except the small portions outside of the dashed line, were wet-appearing after the first day of drying. (M 123 866)

applied, the specimen returned to the drying location, and the compartment door closed.

The dissecting and measuring compartment was equipped with a triple-glass window. Prior to and during each sectioning operation, this compartment was maintained at or slightly above the drying temperature and at 75 percent relative humidity. Each test section was protected from drying by a preheated two-part metal case, One part was removed for measurement of the slices in the section, then replaced while end coating was completed. The section was removed from the case for marking and slicing but the slices were kept in the case until measured and between measuring and weighing.

After the measurements, the slices were individually taken from the compartment and weighed to the nearest 0.03 gram on an automatic balance. After drying through a series of relative humidities, the slices were ovendried and moisture content values computed. The average of the 10 slice moisture contents was used as the average moisture content of the specimen, On moisture distribution sections, visibly wet zones were outlined with a heavy solid line and moist zones with a dashed line. Some moist zones appeared uniformly moist, others as closely spaced wet spots within a dry zone. Then the distribution section was subdivided by one of three methods: (a) 0.2-inch slices were subdivided regularly into 1.00- or 1.50-inch edge portions and a remaining center portion; (b) 0.2- or 0.4-inch slices were subdivided irregularly into dry, moist, and wet zones; or (c) the wet, moist, and dry zones were cut freehand into portions of irregular shape, size, and orientation. Some dry portions were weighed together to give a composite value while borderline and some others were discarded without weighing. The location of the wet zones in sapwood specimen B at successive testing times is shown in figure 2.

Some small zones were weighed to 0.03 gram on the automatic balance; others were weighed to the closest 0.001 on an analytical balance. Accuracy of the moisture values thus obtained probably is not closer than ±3 percent because of short storage periods in a relatively large container.

The method used to dry the slices to obtain set values free of new set was to package the slices into a loosely tied stickered bundle (4, 5) and dry them through a series of humidity conditions at 110° F., then ovendry 24 hours at 214° to 221° F. The conditions were 2 days at 85 percent relative humidity, 1 day at 70 percent, and 1 day at 35 percent. Slices cut during the last one-third of each run were put immediately into the 70 percent relative humidity cabinet.

This method gave average shrinkage values for green slices within +0.1 and -0.2 percent of the shrinkage obtained by exposing slices from an adjacent section to 3 or 4 days in each of 90, 80, 65, and 30 percent relative humidity at 80° F., followed by ovendrying.

Measurements before and after slicing green sections indicated some errors of measurement

equivalent to strains of ±0.0006 inch per inch. The average error was 0.0002 inch per inch or less.

EFFECTS OF TYPE OF WOOD

Results are given for one specimen of heartwood, two of sapwood, and one containing both sapwood and heartwood (described in table 1), all dried at 110° F. All but sapwood specimen B were dried with wet-bulb depression schedules that started like the average commercial time schedule BK5[4] (10). They had 1 day each with wet-bulb depressions of 10°, 15° 20° and about 25° F. The schedule then finished with slightly larger depressions, Except for the first one, no change in kiln EMC exceeded 2 percent and no wet-bulb depression greater than 35" F. was used. At the end of the drying, all specimens except the heartwood were conditioned 6 hours using a 10° F. wet-bulb depression at 160' F.

Sapwood specimen B was dried with a so-called backup schedule, the major part of which was a "delayed" BK3[4] (10). In this set of conditions, the wet-bulb depression used on the first day was 10° F., for the second and third day 5° F., and succeeding depressions (the next 1.8- and 1.2-day periods) were 8° and 14° F., respectively. The heartwood specimen and sapwood specimen B developed no surface checking. Sapwood specimen A checked considerably between the fourth and fifth day. The specimen containing both types of wood checked badly on the sapwood face between the first and second day. In general, the checks didn't interfere with the major strain development and the sections selected for strain analysis had a minimum of checking. The development of checking under the gradual intensification of severity of the wet-bulb depression schedule was the reason for employment of the backup schedule. The effect of EMC reduction pattern will be illustrated later in this paper.

Drying Curves

The heartwood dried at a slower rate than the other specimens and had the highest moisture content at 8 days (fig. 3). The largest wet-bulb depression in this schedule was 27° F., however,

The sapwood specimen with the highest initial moisture content (A) dried most rapidly. Part of this could be attributed to more severe EMC conditions but imbalance in moisture content distribution and prolonged massive capillary moisture movement probably contributed heavily to maintaining rapid drying to almost 20 percent moisture content.

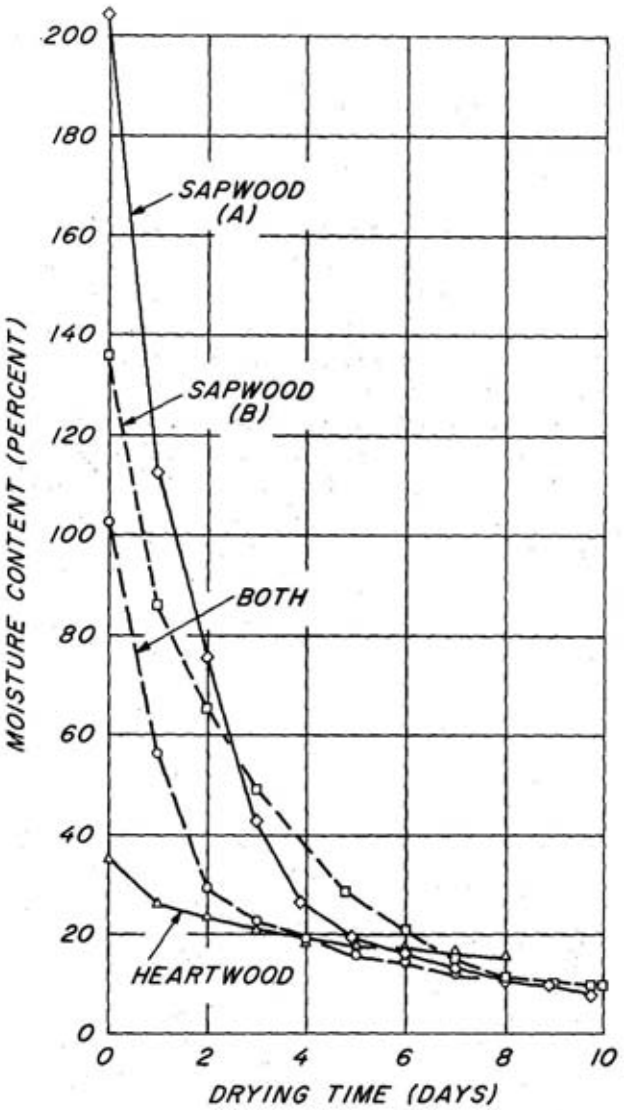


Figure 3.--Drying curves for the different types of wood. (M 131 354)

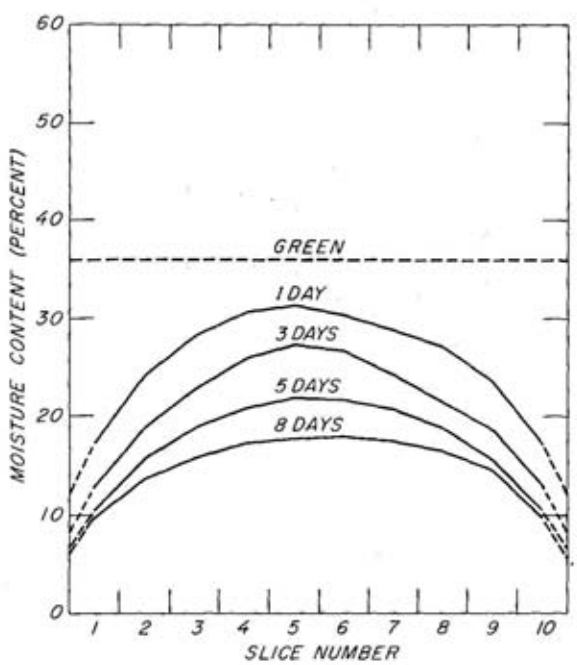
[4]The BK designation indicates wet-bulb depression changes made at 24-hour intervals, the number is the particular set of wet-bulb depressions used, and the "delay" a prolongation of the mildest step of the schedule.

For sapwood specimen B, the drying rate was high to a moisture level of 80 percent but slow for the rest of the drying period, even though the severity of the wet-bulb depression schedule was increased considerably after the end of the third day. This specimen had a more balanced moisture distribution.

For the specimen containing both heartwood and sapwood, the drying rate to 30 percent was approximately the same as that of the wettest sapwood specimen. Thereafter its drying rate generally was slower than that of all other specimens except the heartwood.

Heartwood Reactions

Whole-slice moisture gradients, drying strains, and sets are shown in figures 4 and 5. The moisture gradients and elastic strains were very similar to those previously obtained with oak heartwood. The tensile and compressive strain maximums also were generally similar to the values obtained with oak dried under normal kiln schedules. The average moisture content was 16 percent at the time of stress reversal. No unusual reaction to drying below 15 percent moisture content would be anticipated.



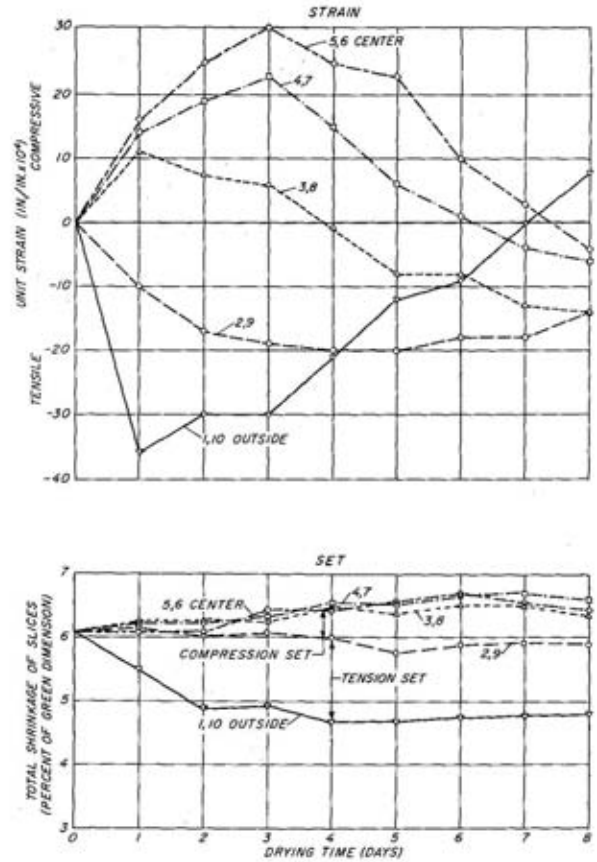


Figure 5.—— Immediately recovered strain and permanent set in heartwood specimen, by pairs of slices. (M 132 007)

As in the oak, tension set began with the start of drying and increased during the first 4 days. In softwoods, compression set development is considerably less than inhardwoods. Doubt may be

Both Heartwood and Sapwood

Moisture gradients are shown in figure 6. On the heartwood side, the surface moisture content rapidly dropped below fiber saturation point and to approximate EMC. On the sapwood side, the outer slice was above fiber saturation point at 1 day, and surface moisture content was still above EMC at 2 days. The sapwood dried very rapidly up to this time, but thereafter it dried almost as slowly as the heartwood. The final moisture gradient is the result of the conditioning treatment.

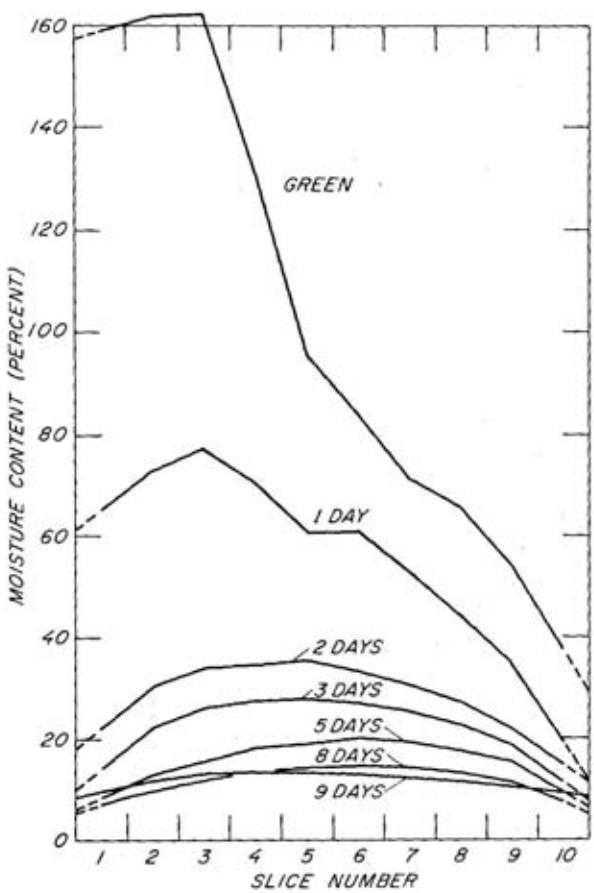


Figure 6.--Slice moisture gradients in specimen containing both sapwood and heartwood. Slice 1 is on the sapwood side and 10 on the heartwood side.

(M 123 857)

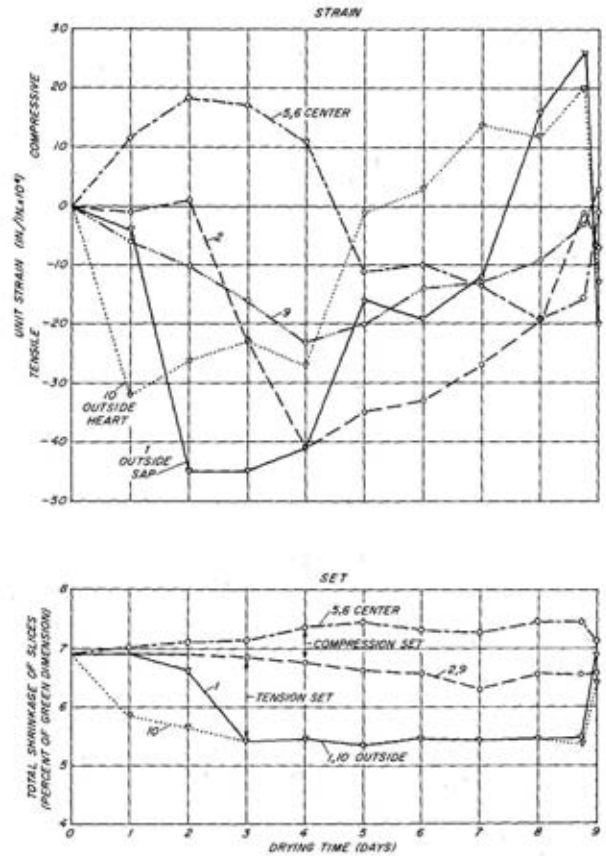


Figure 7.--Immediately recovered strain and permanent set in specimen containing both sapwood and heartwood. (M 132 326)

The strains of greatest magnitude have been shown in figure 7. The outside heartwood slice developed maximum tensile strain during the first day. This maximum was lower than that of the outside sapwood slice, which developed by the second day and was somewhat greater than the maximum in the all-heartwood specimen (fig. 5). The compressive strain in the center slices, however, was less than that in the heartwood specimen. Development of major tensile strains in the second and ninth slices lagged behind that of the outside slices by a day or more, and their maximums were slightly smaller. The strains of slice pairs 3, 8 and 4, 7 were similar to those of slices 5, 6 but of lower magnitude. Stress reversal occurred between 4-1/2 and 7-1/2 days. The final stress-set state (casehardening) was fully relieved by the conditioning.

Major tension set developed first in the outside heartwood slice (10), but by the third day

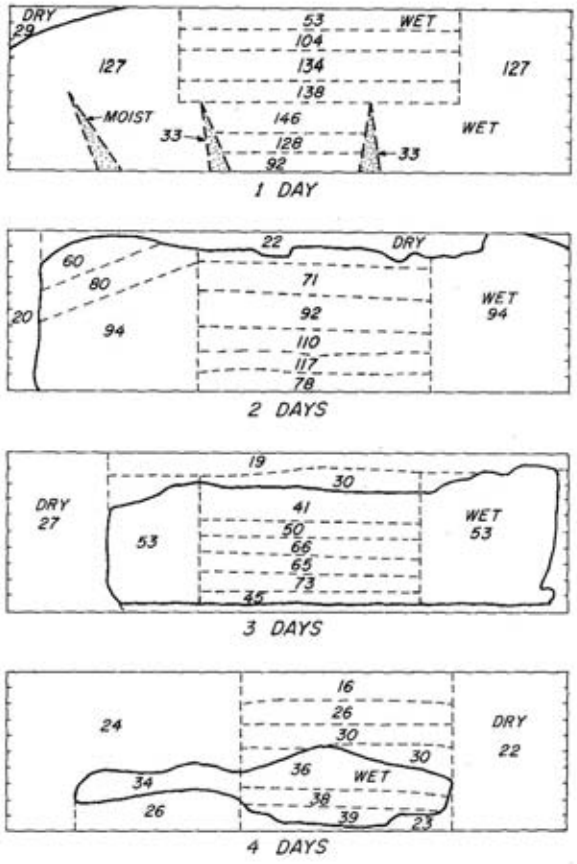


Figure 8.--Moisture distribution in faster drying sapwood specimen (A) after 1, 2, 3, and 4 days of drying. Values shown in various zones are percentages of moisture content. (M 131 356)

slice 1 developed an equal amount. Thereafter, set in these two slices remained identical until the ninth day, Slight compression set in slices 5, 6 appears to have developed from the start, but major compression set did not occur until after the third day. The magnitude was rather small, as was the general case with most specimens. There probably was slight tension set in slices 2, 9. The conditioning treatment appears to have principally affected tension set in the outside slices, but there was some relief of compression set in slices 5, 6.

Sapwood, Fastest Drying

Sapwood specimen A was the fastest drying one in the entire study, even though some others were dried at higher temperatures. Some of this fast drying can be attributed to the more severe EMC schedule, but the unbalanced moisture distribution that developed is also considered significant. The irregular moisture distributions are shown in figure 8.

After 1 day of drying, there was only one area on the cross section that appeared dry. Such dry areas were generally near or below 30 percent moisture content in this and succeeding sections. There were three very small moist areas which had an average moisture content slightly above 30 percent. The remainder of the cross section was visibly wet, and various moisture content values are indicated in the zones outlined by dotted lines. There was some gradient within the visibly wet zone, but a plateau of very high moisture content, 127 to 146 percent, extended to within one zone of the bottom of the specimen. The whole interior wet area, however, was considerably lower in moisture content than the original 207 percent.

At the second day, the entering-air edge, at the left, and most of the top surface was dry. Moisture content values in the "plateau" area were 92 to 117 percent. The location of this very wetplateau and the high average moisture content of the lower left and extreme right portions (94 percent) indicate there may be a massive capillary moisture movement toward the bottom and leaving-air portions of this specimen. After 3 days, the wettest area is found in the central portion of slice 9. There is a dry area in slice 10 and on the leaving-air edge. At 4 days, most of the cross section is dry. Approximately the same moisture content prevails throughout the remaining wet zone. Massive capillary movement of moisture has ceased. Thereafter, drying probably proceeds fairly uniformly around the perimeter of the area by vapor and bound water diffusion.

In interpreting figure 8 and similar moisture distribution patterns, it should be borne in mind that there probably is some longitudinal moisture movement, although no appreciable drying occurred from the well-coated ends. Sections for successive days are likely to exhibit some lengthwise variation as well as progressive changes.

An irregular moisture distribution should have some effect on strain and set. The top of figure 9 shows the effect on the strains. Only the slices with major strains are shown, as all slices must

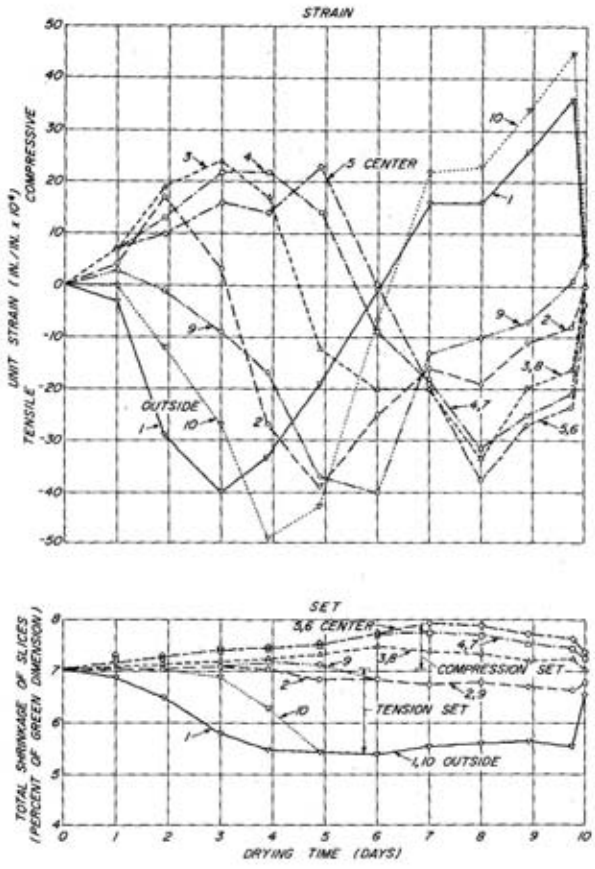


Figure 9.--Immediately recovered strain and permanent set in the faster drying sapwood specimen (A).

(M 131 997)

be handled individually until after stress reversal. For the last 3 days, however, the behavior of all interior slices was regular enough to permit combining them into customary pairs. Major tensile strain developed in slice 1 on the second day, as would be expected from the moisture distribution. Some tensile strain developed in slice 10, although its moisture content generally averaged above the fiber saturation point. Major compressive strain started after the first day and then it was confined to slices 2 through 5. Slices 6, 7, and 8 also developed compressive strain at the start, but the strains were of lower magnitude than those of the other slices.

The maximum tensile strain in slice 1 was 0.0040 inch per inch. This developed in 3 days. A larger tensile strain developed in slice 10, 0.0050 inch per inch at 3.9 days. After starting with considerable compression, slice 2 developed considerable tensile strain by the end of 5 days. Slice 9 also started in compression, then developed major tensile strain of about 0.0040 inch per inch by the fifth day. Reversal of stresses occurred fairly precisely at 6 days. Thereafter, slices 1 and 10 and 2 and 9 behaved essentially as pairs. Very near, but not complete, relief of stresses was obtained by the conditioning treatment.

The diversity of behavior of the slices in strain was not generally reflected in the development of set, although there were some differences for slices 1 and 10 and 2 and 9. Here again, major tension set has developed in slices 1 and 10 and a small amount in slices 2 and 9. There was some compression set in the other slices, although small in magnitude, The conditioning treatment had major effect on tension set in the outside slices, but also relieved the minor tension set in slices 2 and 9 and compression set in the other slices.

Sapwood, Slower Drying

The "gradients" derived from slice moisture content values in sapwood specimen B, dried with a backup and 'delayed" BK3 schedule, are shown in figure 10. The effective moisture gradients were regular enough so that strain and set values from top and bottom halves of the sections could be analyzed and plotted together, The actual moisture distributions that make up these apparent balanced conditions were very irregular, however.

The extent to which portions of all slices rapidly dried below a visibly wet moisture content are shown in figure 2. At 1 day, only the leaving air edge of the board and a portion of the bottom indicated by the dotted line were dry. At 2 days, a large central dry zone, with a regular moisture gradient, extended from top to bottom. The wet zones did not have much of a gradient within them. Results with this specimen indicated that relatively small wet zones, at or just under the surface, developed conditions for rapidly evaporating water and simultaneously pulling water massively from the whole wet interior by capillary action. After all remnants of the wet zones disappeared, normal moisture gradients existed toward all surfaces. In the early stages of drying there were dry areas of about 29 percent moisture content immediately adjacent to wet areas of 85 percent or higher,

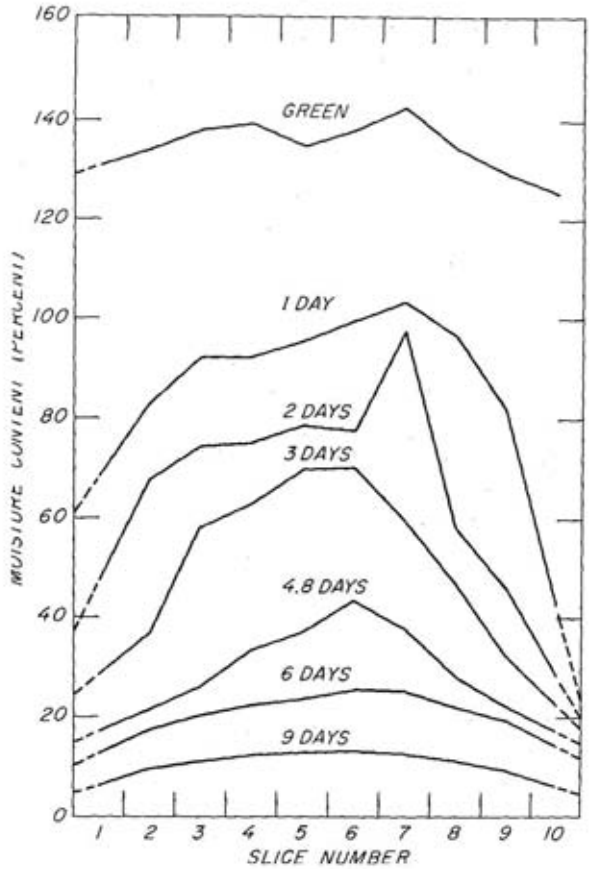


Figure 10.--Slice moisture gradients in slower drying sapwood specimen (B). See figure 2 for location of visibly wet and dry zones after 1 to 6 days drying. (M 123 858)

Tensile strain in slices 1, 10 reached a maximum of 0.0040 inch per inch at 4.8 days (fig. 11). After a short period of slight compression, slices 2, 9 developed tensile strain to a maximum of 0.0029 inch per inch. A comparatively low maximum compressive strain of 0.0009 inch per inch was reached by the center slices in 4.8 days. Stress reversal was completed between 7 and 8 days, Tension set in slices 1, 10 did not start until the second day and did not increase greatly until after the third day. Some tension set developed in slices 2, 9. Slight compression set appeared in slices 4 to 7 after the sixth day. Residual sets and strains were almost, but not completely removed by conditioning.

Board Shrinkage

The extent to which the widths of the specimens of the different types of wood were reduced as a

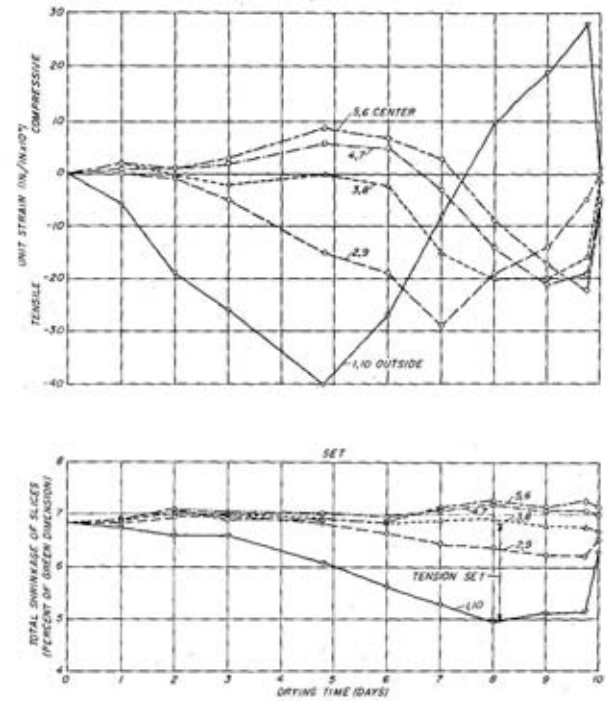


Figure 11.--Immediately recovered strain and permanent set in the slower drying sapwood specimen (B). (M 132 181)

function of drying time is shown in figure 12. The curves represent the difference between the green and the "before-slicing" measurements of slices 5, 6 expressed as a percentage of the green dimension. All but one sapwood specimen shrank considerably from the start. The specimens containing heartwood exhibited a fairly uniform gradual shrinkage. The sapwood specimens had S-shaped curves, with stress reversal occurring at the inflection point. Board shrinkage increased as a result of conditioning.

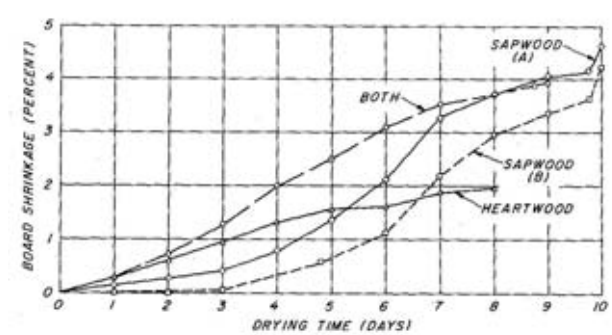


Figure 12.--Board shrinkage as a function of time. (M 131 975)

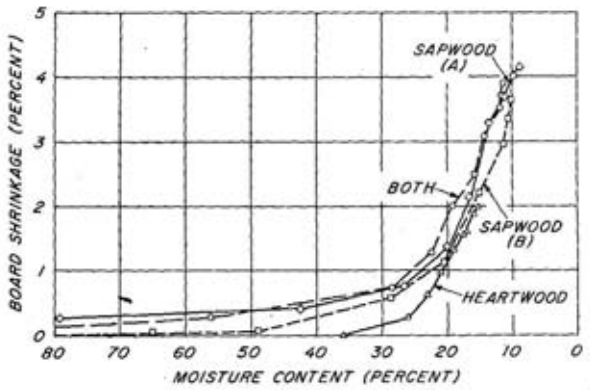


Figure 13.--Board shrinkage as a function of average moisture content of specimen. (M 131 976)

When plotted as a function of decreasing moisture content (fig. 13), the board shrinkage of all specimens becomes more closely comparable. Some shrinkage occurred at high moisture contents, but it didn't approach 1 percent until average moisture content was below 30 percent. All specimens were within a 3/4 percent shrinkage range at any moisture value between 20 and 10 percent.

EFFECTS OF EMC REDUCTION PATTERN

Initial EMC is not so critical in drying softwoods as it is with hardwoods. In commercial kiln drying (air velocity about 300 feet per minute), a wide variety of initial EMC's is used. When investigating the effects of type of wood, surface checking was not caused by the initial EMC's but occurred later. Thus, EMC reduction pattern, rather than initial EMC, was chosen for investigation.

One sapwood specimen was dried under each of a fast-gradual,[5] a delayed, and a backup EMC reduction pattern. The "fast-gradual" parallels common commercial practice using time schedules, the "delayed" relates to moisture content schedules. The backup pattern was included after considering the moisture distributions found under the other patterns. The drying temperature was 110° F. and the relationships between EMC, time, and average moisture content for each pattern are given in table 2.

Table 2.--Time under each EMC condition and moisture content at its start for different EMC reduction patterns

Fast gradual pattern			Delayed pattern			Backup pattern		
EMC	Time	Moisture content	EMC	Time	Moisture content	EMC	Time	Moisture content
Pct.	Days	Pct.	Pct.	Days	Pct.	Pct.	Days	Pct.
--	--	--	--	--	--	12	1	164
--	--	--	--	--	--	16	2	99
12	1	170	12	3	138	13	2	53
9-1/2	1	77	9-1/2	1	33	10	1	30
7-1/2	1	42	8	1-4/5	24	7-1/2	1	28
6-1/2	2	29	6-1/2	1-1/5	19	--	--	--
--	--	--	5	3	18	5	1	18

[5] "Gradual" is used in the sense of progressive, uniformly timed steps.

Drying Curves

Although the same initial EMC was used for all specimens, the fast-gradual and backup specimens dried faster than the delayed-change specimen the first day (fig. 14). During the second and third days, the fast-gradual and the delayed-change specimens dried at about the same rate, but drying of the backup specimen slowed considerably. Such differences in drying behavior might be expected to influence strain development. The isolated data points (square symbols) for separate sections of the backup specimen at 3-1/4 and 6 days illustrate how moisture content, and consequently drying strain, can vary greatly a short distance along the length of a specimen under some circumstances,

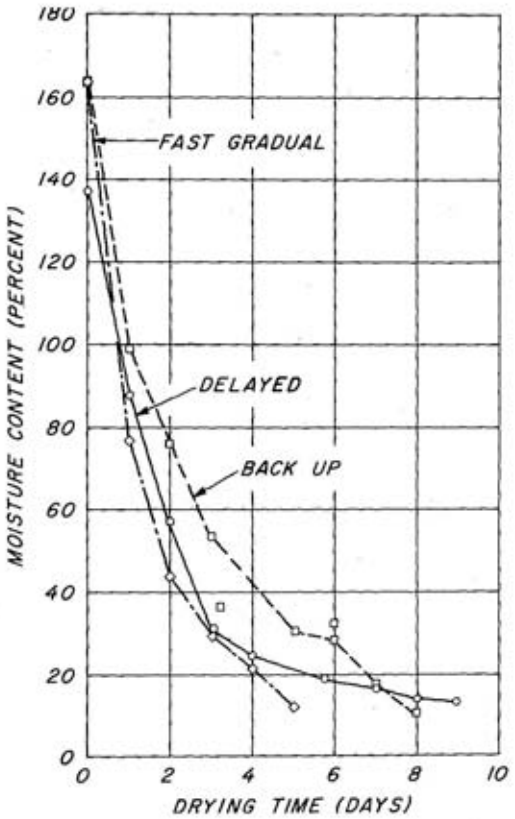


Figure 14.--Drying curves for the different EMC reduction patterns. (M 132 327)

The two sapwood specimens (A and B) in the section of this paper on "Effects of Type of Wood" were dried under essentially the same conditions, respectively, as the fast-gradual and backup specimens in figure 14. Their drying behavior

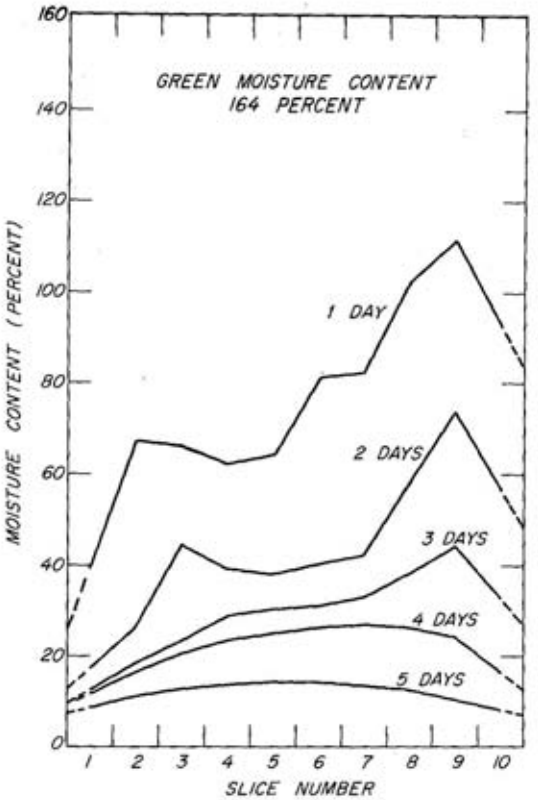


Figure 15.--Slice moisture gradients in the fast-gradual EMC reduction specimen. (M 132 328)

was very similar to that of these specimens except that specimen B dried slightly slower than the backup specimen on the second and third days.

Generally speaking, the fast-gradual and delayed EMC reduction pattern specimens, as well as specimen A, developed unbalanced moisture distributions during drying. The backup specimen developed a balanced distribution at first but later changed to an unbalanced one. Specimen B developed a balanced distribution. An unbalanced distribution appears to promote faster early drying.

Fast-Gradual EMC Reduction

Whole-slice moisture gradients, drying strains, and sets are shown in figures 15 and 16. The moisture distribution became definitely unbalanced, with slices 8 and 9 staying above 30 percent moisture content through the third day. This necessitated analysis of all slices, except 5 and

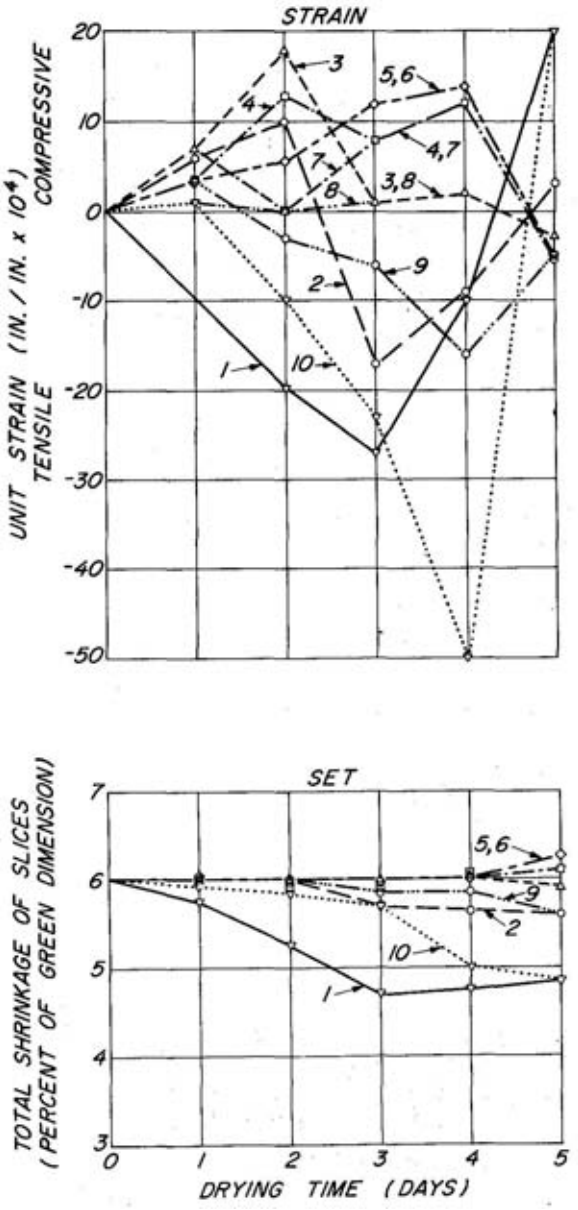


Figure 16.--Immediately recovered strains and permanent sets in the fast-gradual EMC reduction specimen. (M 132 003)

6, separately for strain and set. Slice 8 had essentially no strain throughout. The greatest compressive strain during the first two days was in slices 2, 3, and 4. Slice 10 stayed neutral one day, then developed the greatest tensile strain (0.0050 inch per inch) at four days. Some surface checking occurred on the bottom face at this time. Of the "type of wood" specimens dried by this EMC pattern, the heartwood did not check, the sapwood-heartwood checked in the sapwood, and sapwood specimen A checked slightly. The development of tension set in slice 10 was slower than in slice 1.

Delayed EMC Reduction

This is similar to drying by a moisture-based wet-bulb depression schedule like C5 (table 20, Dry Kiln Operator's Manual (10)). In this schedule, the initial condition is held until the average moisture content of the controlling kiln samples is at 40 percent, then EMC is changed frequently at 5 percent moisture content intervals. Several mills have used delayed (time basis) schedules for some items of ponderosa pine.

Moisture distributions in sections taken adjacent to the strain sections during the first 3 days of drying are shown at the left in figure 17, under "right side up." Whole-slice moisture gradients would have little meaning the second day. The early unit strains computed on the basis of total green width of the slices (fig. 18) also have limited meaning. After the third day, however, normal gradients prevailed, and computation of unit strain on a total-width basis is valid.

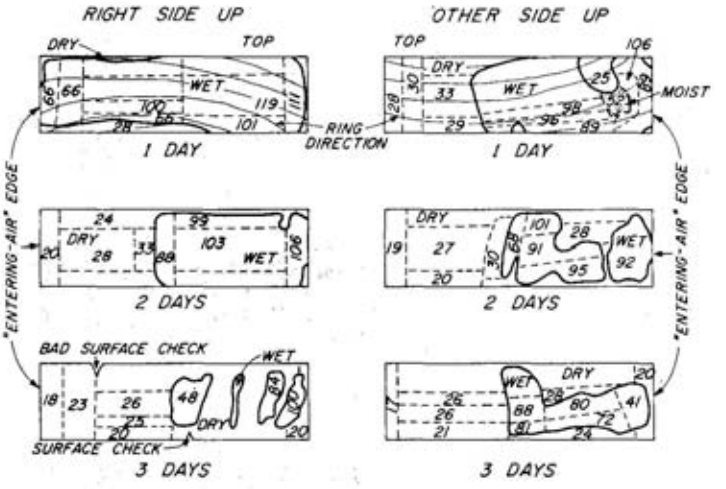


Figure 17.--Moisture distributions after 1, 2, and 3 days of drying for portions of the delayed EMC reduction specimen that were right side up and the other side up in the drying chamber. (M 131 353)

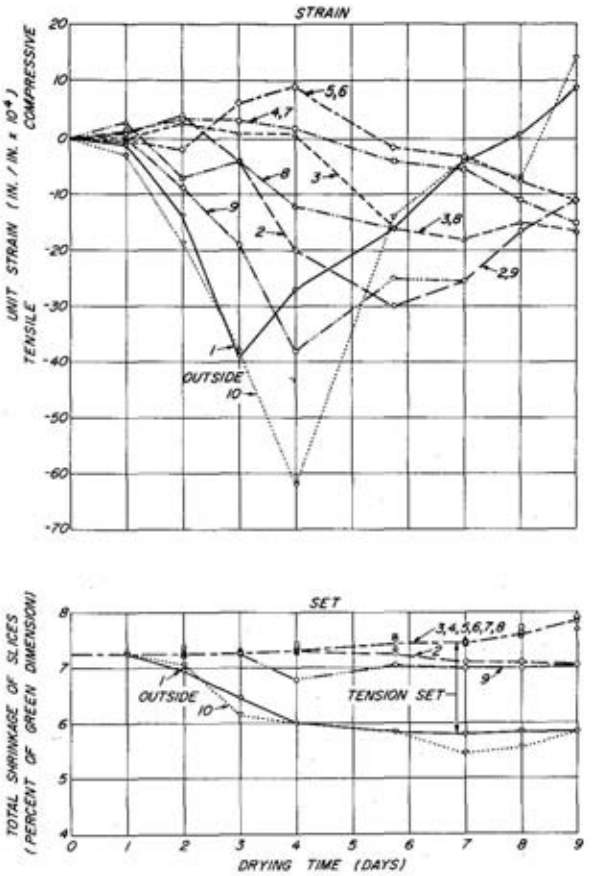


Figure 18.--Immediately recovered strains and permanent sets in the delayed EMC reduction specimen. (M 132 002)

The distributions labeled "other side up" were obtained from a separate portion of the specimen placed with the concave side of the growth rings up. This was to check the possibility that air-flow characteristics resulting from apparatus design would dry the upper side of the specimens considerably faster than the lower side. This specimen gave no clear-cut evidence to that effect. Rather, it indicated that inherent differences in wood properties are more influential in setting up an irregular moisture distribution. There appears to be some indication that massive moisture flow continued longest toward the same face and edge of the specimen regardless of whether it was up or down or in entering or leaving air.

By the third day, the top and bottom of the "right side up" specimen were checked. Actual unit strains in the local zones where checking occurred probably were larger than shown (fig. 18). Because of breakage, the exact value of the tensile strain in slice 10 on the fourth day is doubtful. Increase in inherent shrinkage along the length of the specimen would result in tension set as indicated, with slight compression set in slices 4, 5, 6, and 7 during the eighth and ninth days.

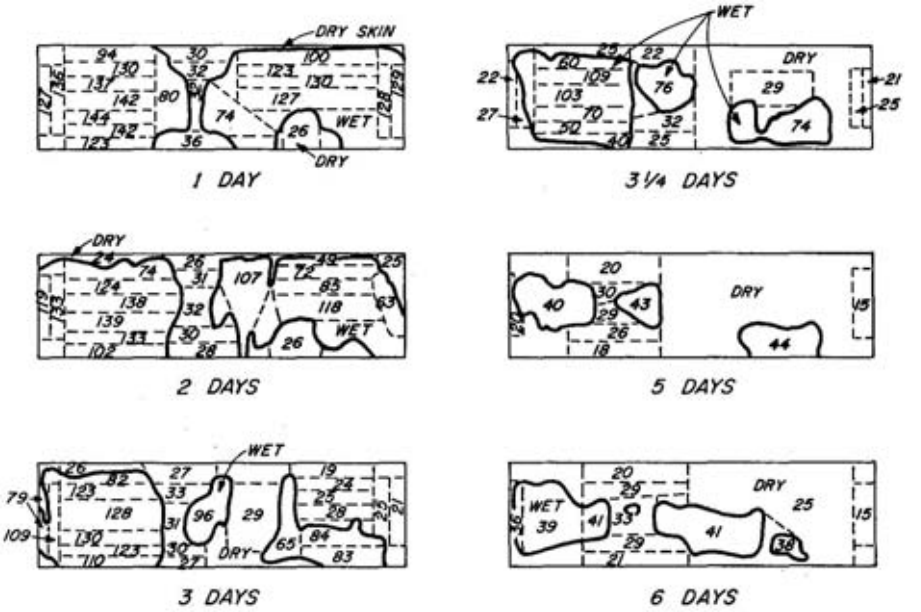


Figure 19.--Moisture distribution in the backup EMC reduction specimen after I, 2, 3, 3-1/4, 5, and 6 days of drying. (M 131 969)

Backup Schedule

The fact that sapwood specimens stayed visibly wet, without major strain or checking, during the first day but often developed such strain shortly afterwards suggested using a relatively severe EMC the first day followed by mild subsequent conditions. Certain mills have used schedules of this type for some Idaho white pine items. The actual schedule is given in table 2.

The early moisture distributions were irregular (fig. 19). The strain data collected showed all slices in tension at 3 days (fig. 20), while slices 4, 5, 6, and 7 were in compression at 3-1/4 days. There was no change in the scheduled EMC between 3 and 3-1/4 days. While slices 4, 5, 6, and 7 may have shrunk during the measuring operation at 3 days, it appears more likely that the longitudinal capillary pull of moisture to adjacent wetter zones caused the moisture in significant portions of these slices to go below 30 percent and thus created tensile strains in all slices. At 3-1/4 days the average moisture content was considerably lower (fig. 14), but the strains were more nearly normal. The slice moisture contents at 7 and 8 days were greatly lower than those at 6 days. A large tensile strain developed in slice 1 at 7 days, causing checking. It is not possible to tell whether slices 3 and 8 developed tension set or slices 4, 5, 6, and 7 compression set.

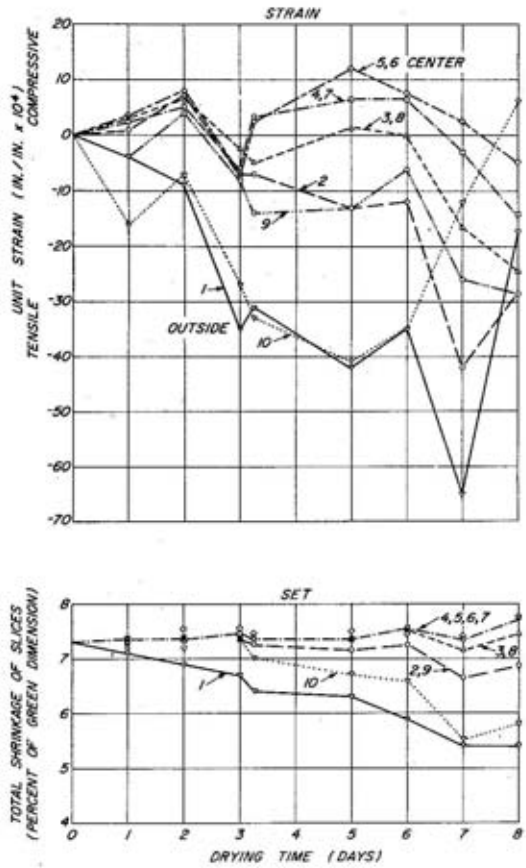


Figure 20.--Immediately recovered strains and permanent sets in the backup EMC reduction specimen. (M 132 001)

Board Shrinkage

Minor board shrinkage occurred in all specimens above 30 percent moisture content (fig. 21). Below 30 percent, the specimens dried under the delayed and backup EMC reduction patterns shrank about the same as the faster drying sapwood and the heartwood-sapwood specimens under "Effects of Type of Wood." The fast-gradual specimen shrank less. This is probably related to its low shrinkage from green to ovendry, 6.0 percent compared with 7.2 and 7.3 percent for the other specimens. The small early shrinkage corresponds to small tensile strains early in drying, due to gradual drying of the outer slices. The small differences in shrinkage at 15 percent moisture content may be due to there being no major compression set in any of the interior slices and no major differences intension set of the outer slices.

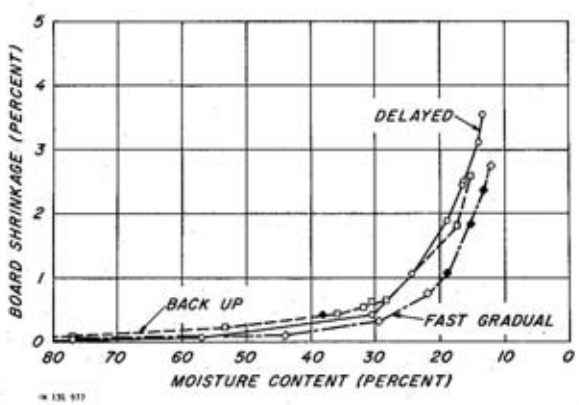


Figure 21 .--Board shrinkage as a function of average moisture content of EMC reduction study specimens. Solid symbols are for sections not in direct sequence with those used for strain analysis (Fig. 16). (M 131 977)

Table 3.--Time under each EMC condition and moisture content at its start for the different temperatures

EMC	80° F.		110° F.		140° F.		170° F.	
	Time	Moisture content	Time	Moisture content	Time	Moisture content	Time	Moisture content
Pct.	Days	Pct.	Days	Pct.	Days	Pct.	Days	Pct.
12	--	--	1	201	--	--	--	--
14	6	193	4	175	3-3/4	197	2-3/4	202
[1]12	4	80	2	95	1-1/4	73	2	96
[2]10	14	54	3	69	1-1/4	53	1	55
[3]8	--	--	2	43	1-1/2	35	2	28
6-1/2	--	--	--	--	--	--	1	10

[1] 11-1/2 percent for 80° F.
[2] 9 percent for 80° F.
[3] 7-1/2 percent for 110° F.

EFFECTS OF TEMPERATURE

Elevation of temperature accelerates drying markedly because both evaporation rate and moisture movement tend to increase exponentially with temperature. In this study, one specimen each of closely matched sapwood material from one log was run at each of 80°, 110°, 140°, and 170° F. Results of the faster drying sapwood under "Effects of Type of Wood," specimen A, are included in some of the discussions. This specimen was from the same log and dried at 110° F. The specimendried at 80° was end matched with the 170° F. specimen, and the 110° F. specimen with the 140° F. All were of similar green moisture content, specific gravity, and rings per inch (table 1). A delayed EMC reduction pattern was used for three of the specimens; a backup and delayed pattern for the other. Details of the relationships between EMC, time, and average moisture content are given in table 3.

For the 140° and 170° F. temperatures, cotton-insulated double-layer neoprene gloves were used in handling and measuring the specimen, section, and slices. A combination section holder and pusher was required for safety during slicing.

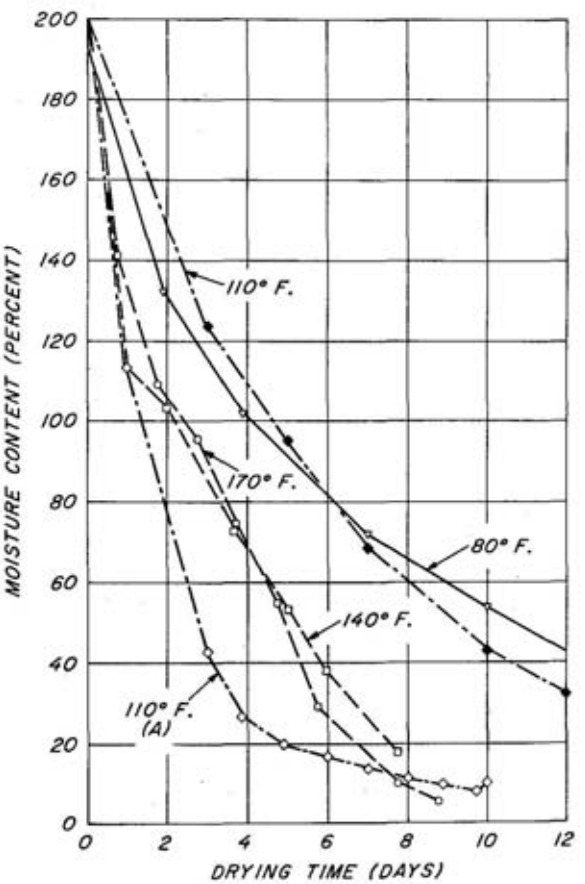


Figure 22.--Drying curves for the temperature study specimens, with results for specimen A at 110° F. included for comparison. (M 131 361)

Though limited in significance because of the few specimens, the results permit some inferences on the effects of temperature on strains and sets. They also provide additional information on moisture distributions during drying of sapwood and their influence on strains and sets.

Drying Curves

The 140° and 170° F. specimens and 110° F. specimen A from "Effects of Type of Wood" dried at the same rate (fig. 22) at the start. The EMC for the first two was 14 percent, for the latter 12 percent. During the second and third days, the higher temperature runs dried slower than specimen A, which was in a 9-1/2 percent EMC the second day and 7-1/2 percent the third. From about 100 percent moisture content down to 55 percent there was no major difference in drying rate for the 140° and 170° F. specimens, but thereafter the latter dried faster.

The 80° F. specimen dried at a slow rate throughout, By 16 days it had reached 20 percent moisture content and by 24 days, 14 percent. The 110° F. specimen (directly matched to the 140° F. specimen) dried at a slower rate than the 80° F. specimen down to 130 percent moisture content in spite of the EMC being lower the first day. Between 130 and 100 percent moisture content they dried at about the same rate. Thereafter the 110° F. specimen dried at a faster rate than the 80° F. specimen but not as fast as the other specimens.

The generally balanced moisture distributions are considered to be the reason for the relatively slow drying of all except specimen A. To what extent the delayed EMC reduction contributed to development of such distributions is not known. The prolonged exposure to 14 percent EMC would in itself influence drying rate if the controlling factor were evaporation rate, but neither temperature nor evaporation rate appears to be controlling from the green condition to about 100 percent moisture content.

80° F. Specimen

Moisture distributions were irregular (fig. 23) through the thirteenth day, but regular thereafter. Massive moisture flow appeared to have occurred toward the leaving-air edge and adjacent bottom

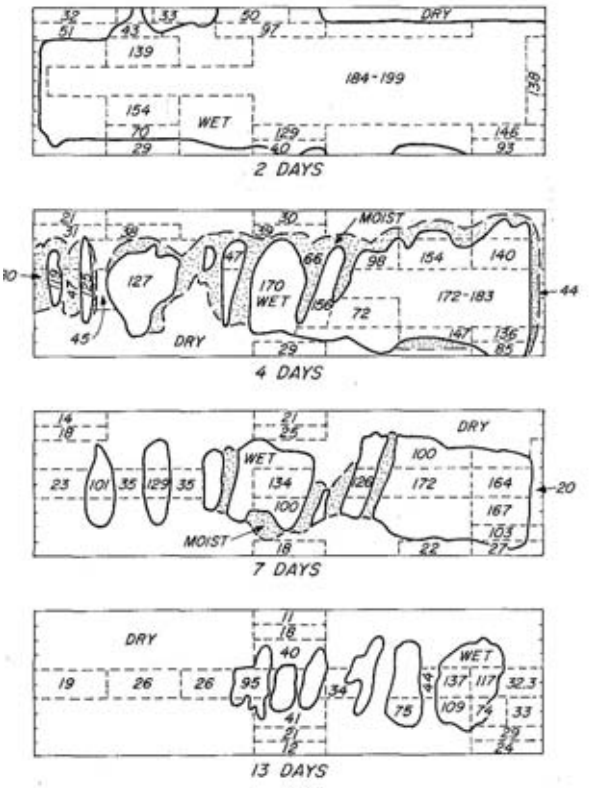
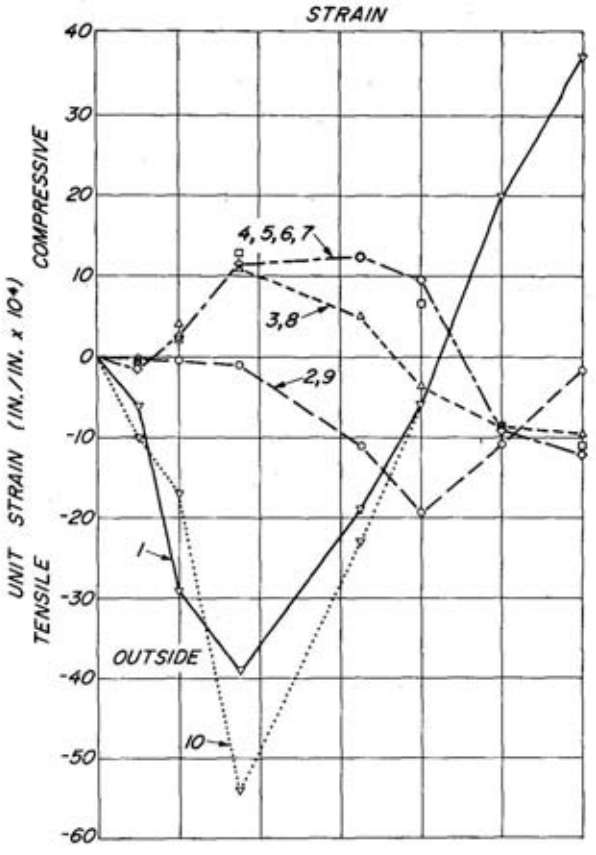


Figure 23.--Moisture distribution in the 80° F. specimen after 2, 4, 7, and 13 days of drying. (M 131 358)

through the seventh day. Then the wet zone broke up into vertically oriented remnants that tended to stay in place. Because of their centrallocation thicknesswise, slice moisture gradients appeared normal and strains were balanced. Tensile strains in the outer slices were large (fig. 24) and the bottom face checked at seven days. Tension set in these slices also was large. After stress reversal (at 18 percent average moisture content), their compressive strain became very large, Compression set developed in the interior slices in spite of low compressive strains. Maximum compressive strain was held along time, however.



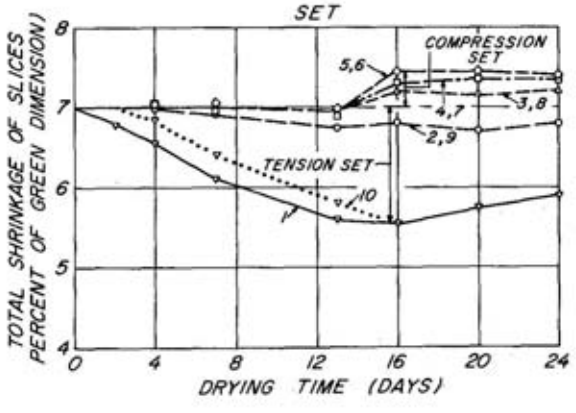


Figure 24. -- Immediately recovered strains and permanent sets in the 80° F. specimen. (M 131 999)

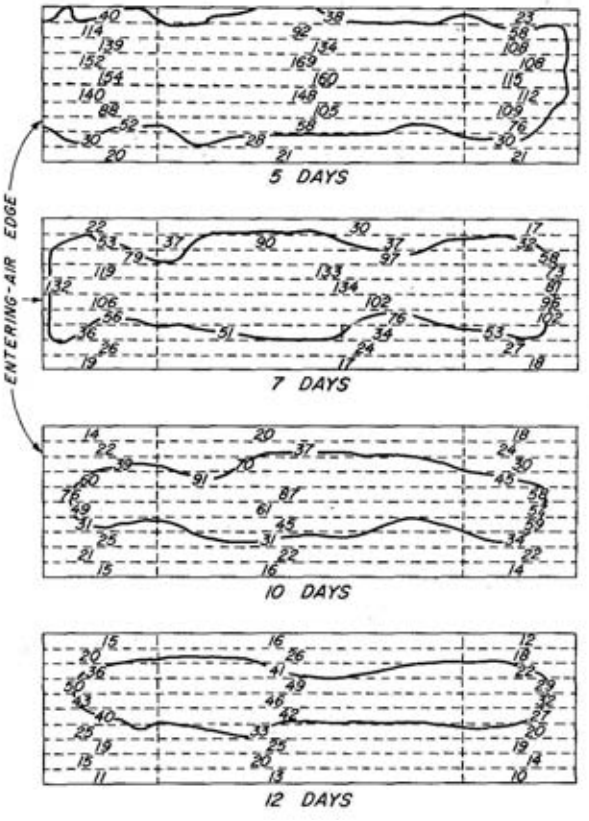


Figure 25.--Moisture distribution in the 110° F. specimen after 5, 7, 10, and 12 days of drying. (M 131 973)

110° F. Specimen

After 3 days of drying, three small zones of slice 1 and the entire slice 10 appeared dry. Subsequent moisture distributions (fig. 25) indicated some tendency for capillary pull toward the entering-air edge during the first seven days. Moisture distributions thereafter were balanced about the wettest zones in slices 4 and 5, and there were moisture gradients withinthe wet zone. During the first three days, slices 2, 3, 4, and 5 remained neutral (fig. 26) while slices 6, 7, 8, and 9 developed compressive strain in unusual pairs. With the largest maximum strain being only 0.0036 inch per inch, no checking occurred. Slice 9 developed major tensile strain after seven days, and unusual pairing of strains persisted. At 12 days, average moisture content was 33 percent, stresses had not reversed, and no compression set had developed.

140° F. Specimen

The entire section appeared wet the first two days (fig. 27), but some tendency toward normal moisture gradients existed. Any capillary pull

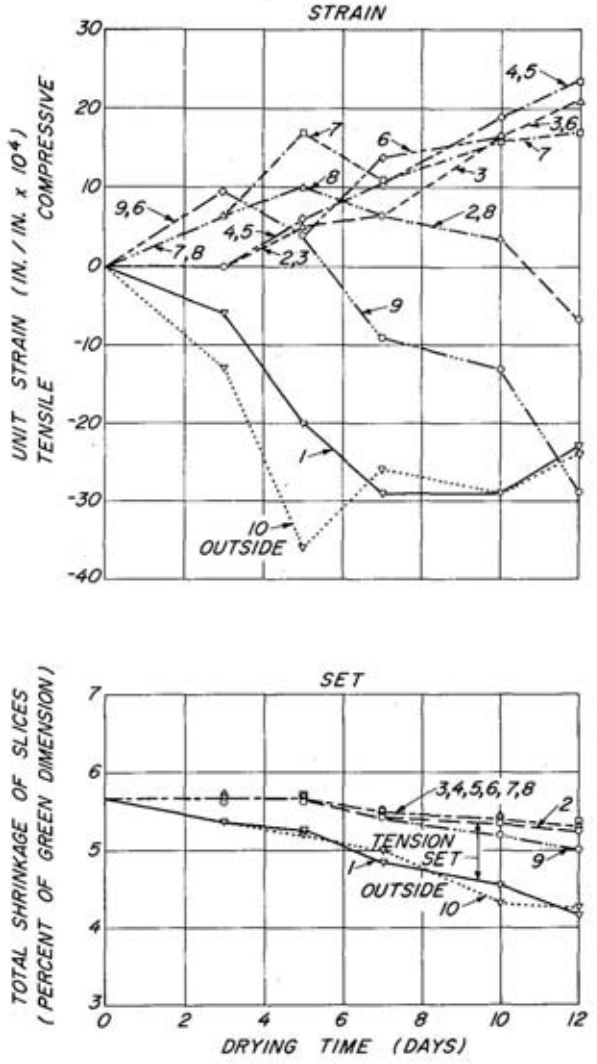


Figure 26.--Immediately recovered strains and permanent sets in the 110° F. specimen. (M 131 996)

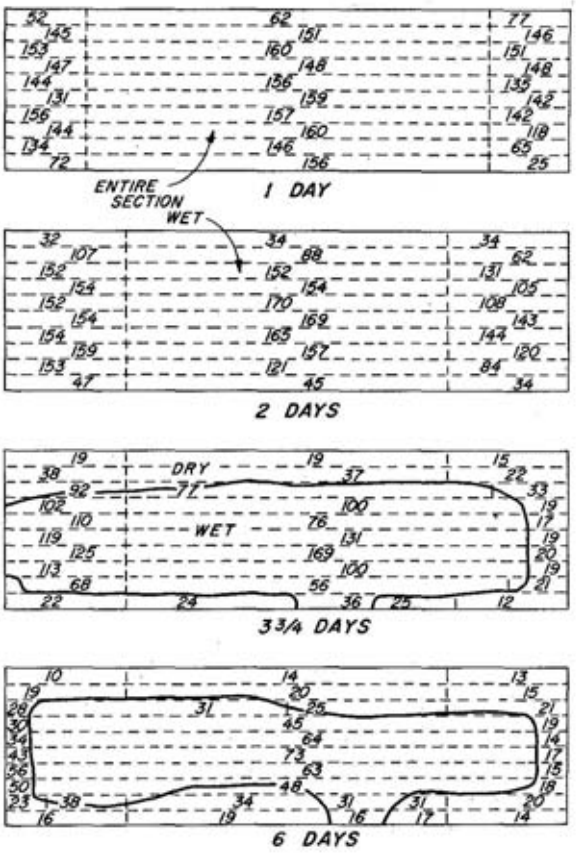


Figure 27.--Moisture distribution in the 140° F. specimen after 1, 2, 3-3/4, and 6 days of drying. (M 131 974)

towards the entering-air edge and the bottom appears to have been weak. Moisture gradients seem to balance around slice 7. Some of slice 10 was below fiber saturation point at one day, so tensile strain developed (fig. 28). By the second day, slice 1 was drier, and developed the most strain. The maximum of 0.0053 inch per inch did not cause checking at the time, but some did occur by the sixth day. No compression set developed by the time the experiment had to be terminated because of shortness of specimen. There was considerable tension set in slices 1 and 10 and some in slices 2 and 9, however.

170" F. Specimen

Moisture distributions and strain and set diagrams are shown in figures 29 and 30. The moisture distribution at 1-3/4 days was very similar to that at 2-3/4 days. Although there appears to have been some tendency for capillary flow towards the two edges and bottom near the leaving-air edge, the moisture distributions were essentially balanced thicknesswise, and drying was not especially rapid. When tensile strain in slice 10 increased greatly after 3-3/4 days, severe checking occurred. Because of breakage, the exact

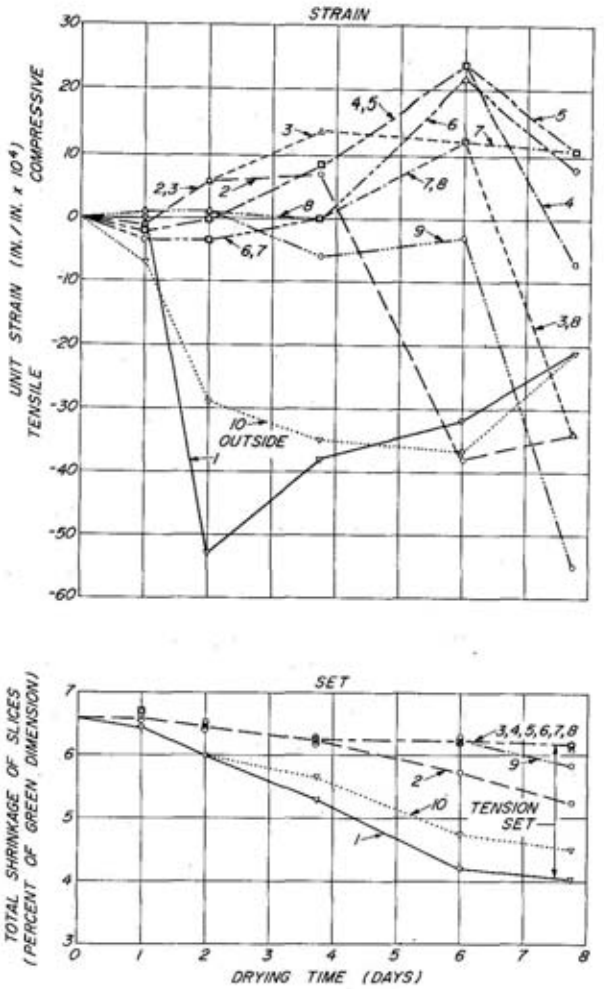


Figure 28.-- Immediately recovered strains and permanent sets in the 140° F. specimen. (M 132 005)

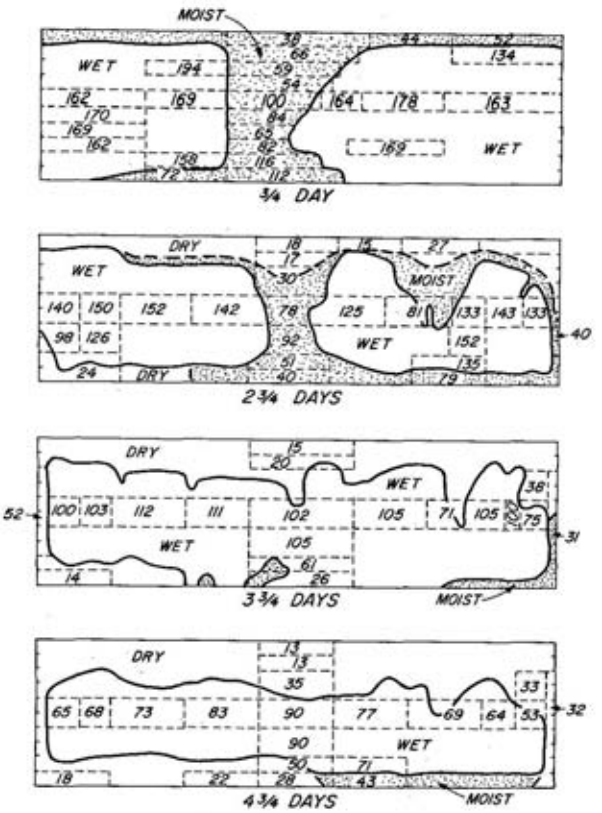


Figure 29.--Moisture distribution in the 170° F. specimen after 3/4, 2–3/4, 3–3/4, and 4–3/4 days of drying. (M 131 972)

strain value at 4-3/4 days is doubtful. The largest amount of compressive strain developed in slice 3. Slices 5 and 6 also developed significant compressive strain, but other interior slices remained essentially neutral until after stress reversal, completed at 20 percent average moisture content. During the last day there was no major change in tension set of the outer slices. The amount of compression set of the interior slices at 5-3/4 days was the greatest observed in any specimen. There was some decrease of this set between 5-3/4 and 7-3/4 days, This may have contributed to decreased tensile strains in the outer slices during the last day, but low moisture content appears to be the most probable cause. Slice 10 developed less-than-normal tension set. Perhaps its strains tended to remain elastic.

Board Shrinkage

All boards began to shrink at moisture contents above 30 percent (fig. 31) and, before reaching this level, the 80° and 170° F. specimens shrank more than 1 percent. The shrinkage of the 170° F. specimen at 10 percent moisture content was 1 percent greater than the shrinkage of specimen A from "Effects of Type of Wood" at 110° F. It is reasonable to assume that shrinkage of the 170° F. specimen was at least 3,8 percent at

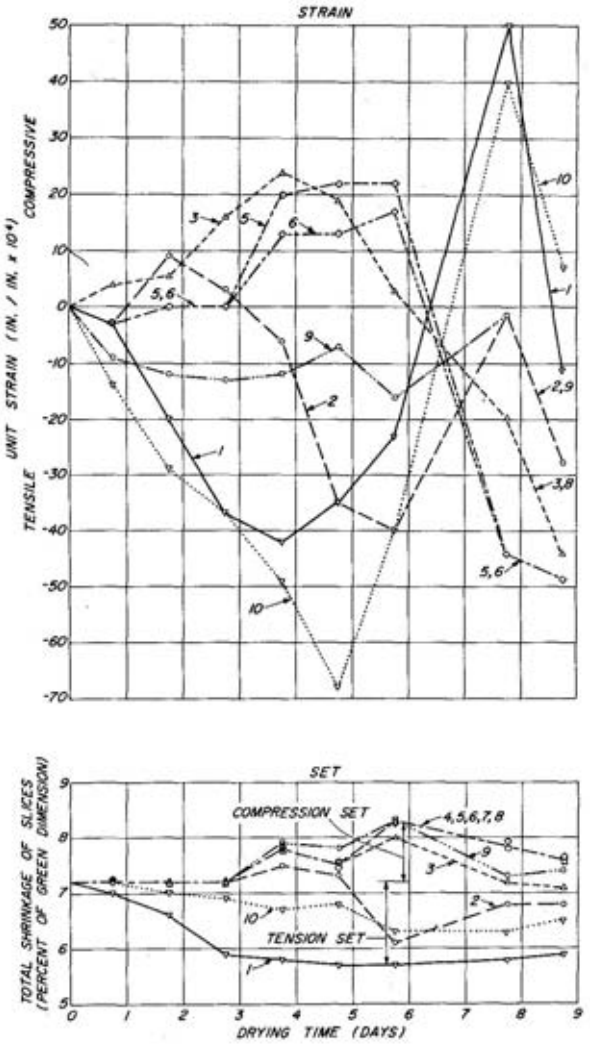


Figure 30.--Immediately recovered strains and permanent sets in the 170° F. specimen. (M 131 998)

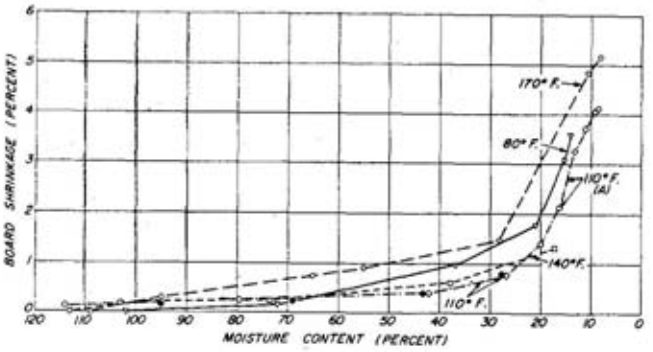


Figure 31.--Board shrinkage as a function of average moisture content for the temperature study specimens and the comparable specimen A. (M 131 352)

15 percent moisture content. This is about 0.8 percent greater than the shrinkage of all other specimens in the experiment at this moisture level,

A combination of large early shrinkage and considerable compression set at 5-3/4 days could be the reason for the greater total shrinkage of the 170° F. specimen, There is no apparent reason, other than inherent characteristics, for the large shrinkage of the 80° F. specimen. This specimen had considerable tension set in slices 1 and 10, some tension set in slices 2 and 9, and a moderate amount of compression set in the interior slices. All of these factors should contribute to low shrinkage at moisture levels below 20 percent.

Total shrinkage from the green to ovendry condition was 7.0 percent for the 80° F. specimen and 7.2 percent for the 170° F. specimen, compared with 7.0 percent for 110° F. specimen A and apparent total shrinkage (shrinkage of interior slices, figs. 26 and 28) of 5.3 and 6.2 percent, respectively, for the 110° and 140° F. specimens.

GENERAL DISCUSSION

Strain and Set

Ponderosa pine in this experiment developed tensile and compressive strain patterns analogous to those of oak (4, 5). In detail, they were considerably more complex than the oak patterns and also differed from each other. Major differences were attributable to type of wood (heartwood, sapwood). Among sapwood specimens, the most important factor was irregular moisture movement in apparent response to an interaction of drying environment and inherent wood property differences, through which balanced or unbalanced moisture distributions developed. Tensile Strain maximums and consequent checking were controlled by manipulation of EMC reductions. Under a delayed EMC reduction pattern, varying temperature up to 140° F. appeared to have no major influence on strain and set. The results from the one specimen dried at 170° F., however, indicated that this temperature could cause more compression set,

Except for heartwood, both tensile and compressive strain development was delayed until the second day, or until appreciable portions of the outer slices were below 30 percent moisture content.

Tensile stress in slices 1 and 10 wasgenerally sufficient to develop considerable tension set in both slices. The amount of set in these slices was nearly identical at the end of drying, after quite frequent individual behavior early in drying. The 170° F. specimen provided an exception, with both interim and terminal set in slice 10 being quite small. Perhaps in this slice a high capacity for elastic strain resulted in a low requirement for tension set. In contrast to the oak, there generally was some tension set in slices 2 and 9. Compression strain and set were, as a rule, relatively small.

Stress reversal, brought about by tension set with some effect of compression set, generally occurred between 20 and 15 percent average moisture content, with the value being closer to 15 percent in most cases. At 170° F., reversal occurred very close to 20 percent.

Computation of Drying Stresses

Irregular moisture distributions and the development of surface checking in some specimens discourages any attempt to analyze all of the specimens for actual drying stresses by the method of Youngs et al (21, 22). It would be interesting to analyze the heartwood specimen and the slower drying sapwood specimen under "Effects of Type of Wood" and the 80° F. specimen which developed essentially balanced strain patterns. It also would be interesting to study the complete data of some of the specimens with unbalanced patterns, such as the sapwood-heartwood specimen, the faster drying sapwood specimen (A) and the 170° F. specimen to see if the method could be modified to apply to them also. Consideration would also need to be given to modifying the method for the specimens with unbalanced moisture distributions where only small portions of the surface zones were dry enough to generate tensile stresses in the early stages of drying. The amount of perpendicular-to-grain mechanical property data available on ponderosa pine for such stress analysis is limited. It is not as regular as that obtained for oak by Youngs (20) and needs to be reviewed to determine its suitability.

Tensile Strain and Checking

The times at which significant tensile strains and checking occurred are given in table 4. Strain was not measured continuously; there is no certainty that the actual maximums were observed nor full indication of total time of high strain. Also, at a given time, some differences of actual strain occurred along the length of the specimen. The specimen containing both heartwood and sapwood is an example. Consistent strain patterns were the general rule, however.

A strain of 0.0050 inch per inch or over almost invariably resulted in immediate checking (table 4). At 140° F., checking did not occur until 4 days after the maximum of 0.0053 inch per inch. Generally, a strain of 0.0040 inch per inch or less did not cause checking. Holding of a strain between 0.0040 and 0.0050 inch per inch for some time also caused checking in some cases.

Values greater than 0.0054 inch per inch in table 4 should not be considered actual strains because the sections from which these were obtained were badly checked. Exact strain at time of checking is not known.

Board Shrinkage and Set

In the drying of oak, compression set was shown to have a major effect on board shrinkage (5) while tension set was about the same in all specimens. In the pine, considerable tension set developed in slices 1 and 10 of almost all specimens and in slices 2 and 9 of many. Major compression set occurred only in the heartwood, the faster drying sapwood specimen (A), and the 170° F. specimen, There seems to be no major influence of set on board shrinkage at 15 percent average moisture content except at 140° and 170° F. At 140°F. a great deal of tension set developed without any compression set. Board shrinkage at 15 percent average moisture content is strongly related to total shrinkage from the green to the ovendry condition. The relationship appears to be improved somewhat by adding one-tenth of the sum of the compression sets of thevarious slices to the total shrinkage and subtracting one-tenth of the sum of the tension sets. As there are uncertainties in the set values, mainly due to inherent shrinkage changes along the length of the specimens, these relationships have not been analyzed mathematically.

Table 4.--Significant tensile strains in outer slices and surface checking of specimen

Specimen	Time of drying	Tensile strain		Surface checking	
		Slice 1	Slice 10	Top	Bottom
	Day	In. per in. by 10^4	In. per in. by 10^4		
TYPE OF WOOD					
Heartwood	1	...[1]36...		None	None
Both	1	---	32	---	None
(section 5)	2	52	---	Checked	---
(section 8)	2	37	---	None	---
Sapwood					
Specimen A	3	40	---	None	---
	4	---	49	---	None
	5	---	43	---	Checked
Specimen B	4-4/5	...[1]40...		None	None
EMC REDUCTION PATTERN					
Fast gradual	3	27	---	---	---
	4	10	50	Minor	Checked
Delayed	3	39	38	Checked	Checked
	4	---	62	---	Checked
Backup	5	42	41	Minor	---
	6	35	35	None	None
	7	65	12	Checked	---
TEMPERATURE					
80° F.	7	39	54	None	Checked
110° F.	5	---	37	---	None
	7	29	26	None	---
	10	29	29	---	---
140° F.	2	53	29	None	---
	3-3/4	38	37	---	None
	6	32	37	Checked	---
170° F.	3-3/4	42	49	None	None
	4-3/4	36	68	---	Checked

[1]Slices 1 and 10 analyzed as a pair.

Capillary Moisture Flow

The sapwood specimens in all three phases of the study gave strong indication that massive moisture flow may occur as a result of capillary forces, causing unbalanced moisture distributions to develop. This occurred with the two sapwood specimens under "Type of wood" and the fast-gradual and delayed specimens in the EMC reduction pattern phase of the study. The backup specimen changed from a balanced to an unbalanced distribution as drying progressed and maintained

a good drying rate. The section cut at 3-1/4 days also indicated a strong possibility for a longitudinal component of massive flow to be a major factor in rapid drying. All of the temperature study specimens developed balanced moisture distributions and consequently dried slower than otherwise would be expected. The effects of massive moisture flow generally are of greatest importance from the green condition down to about 75 percent average moisture content.

APPLICATION TO COMMERCIAL OPERATIONS

Ponderosa pine generally is kiln dried rapidly in commercial kilns without major checking problems. This probably results from partial drying on green storage tracks, relatively moderate air circulation through the load, and frequent fan reversals. Several other softwoods dry as readily. Where checking is no problem, the results of this study have no direct bearing on the drying operation. Where checking is a problem, such as for the denser pieces of ponderosa pine and Douglas-fir, the backup and delayed EMC reduction pattern merits consideration. A combination of conditions that will avoid checking should be attainable. An initial 24-hour period with a wet-bulb depression slightly larger than can be tolerated in the second and third days of drying should result in faster drying, especially for stock that is very wet. A slow gradual reduction of EMC may be required for the more refractory items. No evidence was found that EMC could be drastically reduced before 15 percent average moisture content was reached.

The general effectiveness of a 6-hour conditioning treatment at 160° F. with a 10° F. wet-bulb depression in relieving set and stress at the end of drying was indicated by the results under "Effects of Type of Wood." No conditioning treatment was given to specimens in the other phases. Although the comparatively high temperature of 170° F. appeared to have relieved some of the compression set during the last 3 days of this run, neither compression nor tension set were completely relieved and use of this temperature alone at a low EMC cannot be considered an adequate conditioning treatment. The need for equalizing treatments to bring all boards to a reasonable uniformity of moisture content and the techniques by which adequately desuperheated steam can be produced so as to insure adequacy of conditioning in commercial kiln operations are described elsewhere (6, 10, 19).

* * *

CONCLUSIONS

1. Strains and sets in ponderosa pine heartwood are comparatively simple and similar to those of oak. They are more complex in specimens containing sapwood, Type of wood did not greatly affect maximum tensile strain in outside slices, but maximum compressive strain of interior slices in sapwood specimens was generally lower than in the heartwood specimen, and in some cases was very low. Tension set developed in the outside and first pair of subsurface slices and was greater in the sapwood specimens. Maximum compression set of the interior slices at 110° F. was not greatly affected by type of wood.

2. Tensile and compressive strains arose in complex patterns in sapwood specimens dried under different EMC reduction (at 110° F.) and at different temperatures (under delayed EMC reduction patterns). Tensile strains and tension sets of outer slices generally were comparatively large. Compressive strains and compression sets of interior slices generally were small at temperatures from 70° to 140° F. At 170° F., compression set of the interior slices was large.

3. At the high air velocities used, theirregular moisture distributions obtained in sapwood specimens gave strong indication that massive flow by capillary action is a major factor in drying softwoods rapidly. Fast initial drying coincided with greatly unbalanced moisture distributions in the fast-gradual and delayed EMC reduction pattern specimens at 110° F. Slow initial drying coincided with generally balanced distributions in all temperature-study specimens. Off-center location of the wettest zones in generally balanced moisture patterns resulted in considerable irregularity of compressive strain development.

4. Rapid large changes in tensile strain resulting from irregular moisture distributions caused surface checking in sapwood. Severe checking developed in the sapwood portion of a board containing both heartwood and sapwood as a result of more severe tensile strain on the sapwood side.

5. Surface checking generally resulted immediately from tensile strains of 0.0050 inch per inch; however, in two instances, prolonged strain at a relatively high value was necessary when the strain was near 0.0050 inch. Strains of 0.0040 inch per inch or less did not generally cause checking.

6. Surface checking was prevented or greatly reduced by use of delayed and backup EMC reduction patterns. In the latter, after an initial 24-hour period with a moderate EMC, a high EMC followed by a delayed EMC reduction was used. This gave faster drying and as good control of checking as the delayed pattern starting with a high EMC.

7. In both heartwood and sapwood specimens, stress reversal did not occur until average moisture content was 20 percent or below, generally somewhat closer to 15 percent, This confirms late reversal of stresses in other softwoods of similar characteristics. Thus, in most softwood drying schedules, each lowering of EMC after the first period of high EMC must be moderate until 15 percent moisture content is reached,

8. Under all conditions, considerable board shrinkage occurs before 30 percent average moisture content is reached, but type of wood does not have a great effect on amount of shrinkage at the same moisture level between 20 and 10 percent moisture content. Board shrinkage at 15 percent moisture content was basically related to total shrinkage from green to ovendry, with the relationship apparently improved somewhat by correcting for the tension and compression set experienced by each specimen. Board shrinkage at 170° F. was an exception, in that it was considerably greater than expected from either relationship.

9. Tensile and compressive strain data from the heartwood, slower drying sapwood, and 80°F. specimens should be suitable for computation of actual drying stresses. Exploration of modification of the method of analysis to accommodate unbalanced strain development could be undertaken with the data from the sapwood-heartwood and faster-drying sapwood specimens under "type of wood," and the 170° F. specimen.

10. The need for improved study methods and more extensive sampling in further research is clear. Narrower segments of the overall problem should be considered in future research planning.

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