THE EFFECTS OF PART-TIME KILN OPERATION ON THE DRYING CHARACTERISTICS OF A REFRACTORY HARDWOOD

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ABSTRACT

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By William E. Cobler

Kiln schedules recommended by the U. S. Forest Products Laboratory are merely guides for the kiln operator to use in developing the best schedules for his individual case. Many kilns are operated by following these schedules completely and therefore are not being operated at maximum efficiency and are producing lumber of lower quality. Moreover many kilns that are being operated on a part-time basis are utilizing the schedules developed for full-time drying.

In this study, part-time kiln drying of a given refractory hardwood was investigated to determine the effects of part-time drying on the drying characteristics. Beech (Fagus grandifolia) was utilized throughout this study. The behavior of elastic strain, of moisture content, and of kiln conditions during full-time and part-time kiln drying was studied.

When part-time kiln drying (12 hours off, 12 hours on) was utilized following the U. S. Forest Products Laboratory recommended kiln schedule for beech, the stresses developed were greater in the latter part of the drying cycle than in full-time drying. In part-time drying the stresses developed exceeded the stress at proportional limit almost throughout the drying cycle. Consequently severe surface checks developed which would degrade the lumber.

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Part-time and full-time drying exhibit approximately the same stress pattern that has been found to exist for most hardwoods. Part-time drying however increases drying time. From the results of this study a more severe schedule can not be used to shorten drying time. It is indicated that a less severe schedule is necessary to reduce drying defects.

During part-time drying kiln conditions changed during each off-period by a drop in temperature and a decrease in wet-bulb depression. The drying conditions therefore became increasingly less severe throughout the off-period.

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INTRODUCTION

The kiln schedules recommended by the U. S. Forest Products Laboratory are designed for drying wood when utilizing full-time operation of the kiln. The recommended schedules however are presented as guides for developing kiln schedules best suited to a given operation and are not to be considered ideal, because of the many variables present. The type and condition of the kiln, quality required, overall drying costs, character of the wood, and whether the kiln is operated full-time or part-time presents variables that may not be accounted for in the design of U. S. Forest Products Laboratory recommended schedules.

As lumber dries, stresses develop within the wood. The period in which these stresses occur and their magnitude can be the most important causes of defects that decrease the value of the lumber. Extensive research has shown that most refractory hardwoods exhibit generally the same drying stress patterns during full-time operation. Part-time operation of the kiln may produce stresses that differ greatly from those developed during full-time operation.

Part-time Kiln Drying

The seasoning of lumber by part-time operation refers to those kiln operations where some part of the kiln, either the heat or fans or both are not being operated during some portion of the drying period. In many small industries a continuous supply of steam for heating is not available due to work schedules which require shutting down the boilers overnight. One of the most common part-time schedules is one in which normal operation is utilized during working hours and a fan-only operation during the remaining time. Regardless of the reasons for part-time kiln drying and the periods involved, the drying conditions within the kiln change when the heat is not being applied.

Drying Stresses

It is desirable to use the optimum schedule to dry lumber which will minimize drying time and drying defects and at the same time maximize economic returns. Both drying time and drying defects are related to stresses that develop as the lumber dries. If stresses during drying are maintained at too high a level, drying time will be short but defects will develop. Conversely, if stresses during drying are maintained at too low a level, drying time will be increased with no defects developing.

Research has shown that the stresses developing during drying of refractory hardwoods follow the same pattern (1)(4)(6). As green wood is dried, the surface begins to dry first and upon reaching the fiber saturation point begins to shrink. The core which has not yet begun to dry resists the shrinkage of the surface layers. As a result, tension stresses develop at the surface and compression stresses develop in the core. When stresses develop in wood, the wood becomes distorted or strained. Strain that is produced by short-time stress below a certain limit (called the proportional limit) substantially disappears when the load is released. This strain is called elastic strain. Stress beyond the proportional limit, or stress below the proportional limit applied for long periods of time, produces strain that does not disappear upon release of the load. This permanent strain is called set. As drying progresses, tension set occurs at the surface and compression set occurs in the core. The core begins to dry and consequently shrink. As this shrinkage takes place, stress reversal occurs and the core is in tension with the surface in compression. After stress reversal, the core develops a maximum tension stress and the surface a maximum compression stress. Casehardening is the term applied to this condition, which can be relieved by conditioning techniques.

If drying stresses are not kept under control, ill effects will be produced. Keeping stresses at a minimum does not solve the problem as the drying time will be lengthened out of proportion. Splitting, checking, warping, collapse, and honeycombing are all directly related to excessive drying stresses. It is therefore necessary, in kiln drying wood regardless of the method used, to obtain a knowledge of drying stresses to aid in the development of better drying techniques.

Through research, kiln schedules have been developed that give the kiln operator a guide for developing schedules best suited for his operations. However, many operators depend entirely on the schedules recommended by the Forest Products Laboratory and operate their kiln on a part-time basis without considering how part-time operation effects the conditions in the kiln or the stresses that develop in the material. Kiln conditions that develop and the behavior of moisture gradient and drying stresses are well understood when wood is dried under normal conditions. Therefore to develop a part-time kiln schedule, which will minimize defects and drying time and maximize profits, it is necessary to know how the kiln conditions, moisture gradient, and drying stresses react to part-time kiln operation.

Statement of Problem

The three factors that effect the rate at which moisture moves in wood are: (a) the relative humidity of the surrounding air, (b) the temperature of the wood, and (c) the steepness of the moisture gradient. When relative humidity is lowered, there is a corresponding increase in capillary action and diffusion. Capillary action is increased by the evaporation of the water from the surface into the surrounding air. Diffusion is increased when the moisture content at the surface is decreased, thereby steepening the moisture gradient. When the temperature is increased the moisture will move faster from the wetter interior to the drier surface.

If the kiln is operated on a part-time kiln schedule*, the drying conditions in the kiln alternately change from normal conditions to less severe conditions. When the steam heat is shut off the kiln begins to cool and the dry-bulb temperature begins to drop; at the same time the wet-bulb temperature also drops but not as rapidly. Therefore the equilibrium moisture content is increased throughout the period when the steam heat is shut off. These changes in conditions raise the relative humidity of the surrounding air, lower the temperature of the wood, and flatten out the moisture gradient. All of the changes effect the rate at which wood dries. Therefore during the periods when the steam heat is shut off the drying rate will be reduced and overall drying time will be increased.

The drying stresses that develop in refractory hardwoods under normal full-time drying conditions are fairly well known and tend to exhibit the same general stress pattern. In part-time drying the drying stresses may not develop the same pattern. Stresses may increase

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*In this study the part-time kiln schedule utilized required continuous operation of the circulating fans and part-time operation of the steam heat.

or decrease during the periods when the steam heat is shut off. The stresses are directly related to the moisture content and temperature of the wood. The changes in drying conditions therefore have some effect on the magnitude as well as the period in which the maximum stress develops.

It is the purpose of this study to investigate the effects that part-time kiln drying has on the conditions existing in the kiln and the effects the condition changes have on drying stresses, moisture content, and overall drying time.

REVIEW OF LITERATURE

Kiln Drying and Drying Stresses

Even though history records instances of artificial drying of wood nearly 3000 years ago, the beginning of kiln drying and the origin of wood drying theory are uncertain. An ancient practice was to subject lumber to the fumes of burning slash in inclosed rooms. Many other methods of artificial drying have been tried but basically most of the kiln drying is done through application of heat by some means and evaporation of the water from the surface of the wood. The modern forced-draft and humidity-controlled kilns were developed as the drying process became better understood. The works of Tiemann (15), Stamm (14), Spalt (13), and Higgins (5) have been helpful in explaining the manner in which water moves in wood during drying. Fernow (2), Roth (12), Peck (9), and many others have offered explanations for defects that develop in many woods as they are dried artificially.

Optimum kiln schedules were developed for given species which minimized drying defects and drying time and maximized profits. These schedules were developed by trying different combinations of drying conditions from which a selection was made that produces the least amount of defect. The extent and time of the changes that were made in the kiln conditions during the drying cycle were also based on the occurrence or absence of drying defects. Further development of optimum kiln schedules was hampered due to limitations of kiln design which produced poor heat distribution and air circulation, and the absence of a criteria for determining the causes and development of drying defects.

During World War I a growing demand for greater quantities of dried lumber gave impetus to the theory and practice of lumber drying. A relatively short time later the U. S. Forest Products Laboratory, seeing a growing need for further examination of the stresses that develop during drying, began a series of studies on this problem.

In 1940, Peck (9) made a complete study of the development of stresses in the drying board. His method, now known as the "slicing or strip technique", gives an indication of the stress conditions. The strip technique, a further development of Tiemann's (15) slotted section method, utilizes the measurement of the elastic strain as an indication of the stresses present. Peck measured the length of previously marked off strips which extended across the width of the board while intact. The strips were then cut from the board and remeasured. The change in dimension was taken as an indication of the drying stress. Tensile stress was indicated by a decrease in length and compression stress by an increase in length.

In 1954, Ellwood (1), working on one-inch thick beech, made extensive investigations on the properties of the species in relation to tension and compression perpendicular-to-the-grain and their relation to drying. By rigid control of conditions during testing, he was able to determine the effect of temperature and moisture content on tension and compression stresses perpendicular-to-grain. Ellwood's work confirmed that the modulus of elasticity increased with a decrease in moisture and decreased with an increase in temperature. He concluded, however, that the effect of moisture content was much greater than that of temperature (Figure 8).

Similar studies have been made by Loughborough and Smith (18) in 1946, Rietz (11) in 1950, Torgeson (16) in 1951, McMillen (6,7) in 1955 and 1958, and Haygreen (4) in 1961. Figure 1 shows the stress development obtained by the strip technique of stress analysis of a two-inch thick red oak board during kiln drying (7). Examination of these curves shows that the surface layers immediately develop tension stresses which increase until a maximum is reached then decrease until the stresses are reversed and these layers are under compression. The other layers, during the initial drying stages, are under compression until a maximum is reached and then stresses begin to subside until they reverse and these layers are then under tension. This is generally the stress pattern observed in investigations of the stresses during drying of refractory hardwoods when utilizing the strip technique.

The purposes of these studies have been to develop optimum kiln schedules to be utilized under normal drying conditions, i. e., full-time operation. If part-time kiln operation is used the short drying time that has been stdived for is sacrificed. It is necessary therefore to investigate the stresses that develop in part-time drying. Part-time drying stresses may differ from those developing in full-time drying. Therefore, it may be possible to adjust the kiln schedule recommended for normal kiln operation so that overall drying time in part-time drying may be reduced. Rasmussen and Avanzado (10) recommend that a more severe drying schedule could be used to reduce drying time. Wolfe (19) suggests an increase in temperature at the end of the period after the kiln has been in full operation to increase the evaporation of moisture during the shut-down period.

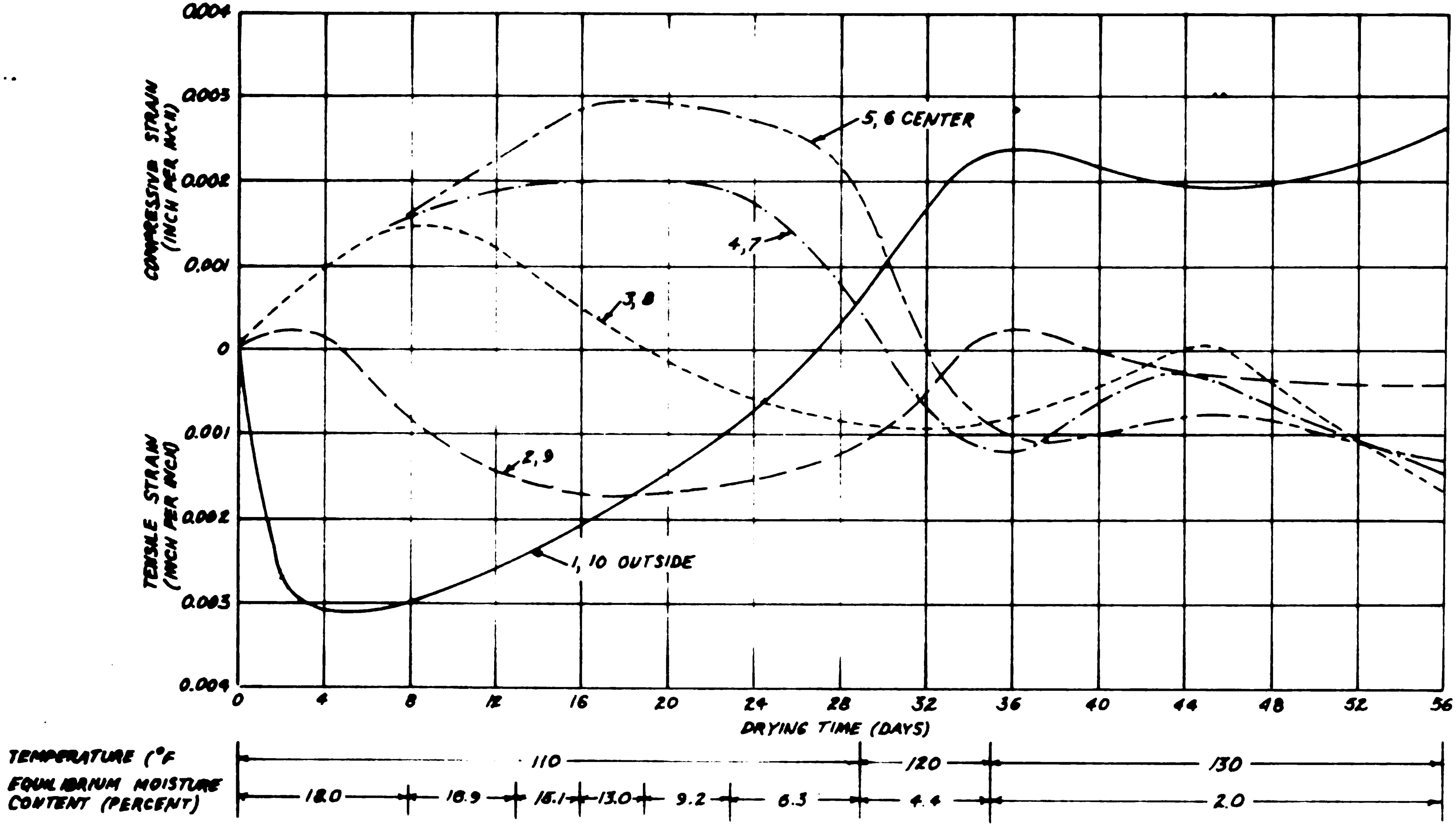


Figure 1. Stress development curves for 2- by 7-inch red oak board.

Investigations by Nohara (8) in 1960, and Rasmussen and Avanzado (10) in 1961, on the economics of part-time kiln drying have indicated a need for shortening the overall drying time in part-time operation. The influence of the strip technique approach in developing new and better kiln schedules is apparent in the kiln schedules recommended by the U. S. Forest Products Laboratory published in 1951. Although the strip technique has not been utilized in studies of all refractory hardwoods, it is, however, fairly well accepted as a method of stress measurement. In the present study the strip technique was utilized.

To investigate more fully the conditions in part-time drying with respect to drying defects, particularly surface checking, the following study was undertaken to explore the effects of this method of drying on kiln conditions, stresses, moisture content, and drying time.

EXPERIMENTAL PROCEDURE

Material Tested and Equipment Used

Ten beech (Fagus grandifolia) logs ranging in diameter from 18 to 30 inches were obtained from the same site in lower Michigan and processed at the Michigan State University sawmill. The rough boards, nominal 1 inch by 6½ inches were produced with thicknesses ranging from 1.05 to 1.13 inches. Test boards eight feet long were utilized in kiln run No. 1. Boards four feet long were used in the other two runs to facilitate the use of a small drying chamber. All test boards were selected as being flat-sawn, all heartwood, with no apparent defects. The test boards were paired for testing by taking them from the same piece or from pieces that had adjacent faces in the log. Elapsed time between cutting and placing in the kiln was about two hours. The growth rate of the test boards averaged 12 rings per inch but varied from 8 to 19 rings per inch. The average oven-dry specific gravity of the test boards was 0.67, ranging from 0.64 to 0.70. No significant difference in the specific gravity between samples was found to exist, therefore, it appears that the sample can be assumed homogeneous. All test boards were end coated with a mixture of two pounds of No. 320 aluminum powder per gallon of spar varnish as recommended by Haygreen (4).

All drying was carried out in an internal-fan, cross-circulation kiln. During kiln run No. 1 which utilized a part-time schedule, the kiln was loaded to approximately 60 percent capacity. During the second and third runs, a 72 cubic feet drying chamber constructed inside the internal-fan, cross-circulation kiln was used.

During run No. 1, air-flow through the stack was maintained at 250 to 325 feet per minute. During the two successive runs, by operating only one fan and opening vents in the otherwise closed baffles, the air-flow was maintained at or near the velocity that was found to exist in the fully loaded kiln. Reversal of the air-flow was performed every twelve hours at 2:00 P.M. and 2:00 A.M. The recorder controller and a hygrometer were used throughout all kiln runs to obtain and check the required kiln conditions. The dry-bulb temperature disagreed as much as 4°F., but the more important wet-bulb depression remained within 1°F.

Experimental Design

Evaluation of the effect of part-time drying on the drying characteristics of beech is the objective of this study. Drying stresses, moisture content, and drying time are the characteristics to be considered.

To compare the drying characteristics of beech under full-time kiln drying to the characteristics under part-time drying, two initial kiln runs were made. The first was a part-time drying schedule applying heat for a 12-hour period then a successive 12-hour period when no heat was applied. The second was a full-time or normal drying schedule. In all kiln runs the kiln schedule followed was the moisture content schedule T8 C2 recommended by the U. S. Forest Products Laboratory (16). A third kiln run was made as a control. A part-time schedule was utilized with the samples in the drying chamber to give a comparison between the use of the chamber and the fully loaded kiln. It was thought that the equilibrium moisture content might differ significantly due to the moisture content given off by the full kiln load of lumber. There was no significant difference in the change of equilibrium moisture content between run No. 1 and run No. 3 (see Table 1). Therefore, it appears that the fully loaded kiln has no effect on condition changes under part-time operation. Throughout the study, two samples were taken at each 12-hour interval.

Strain and moisture content values were determined at ten points through each sample. It is shown in Table 2 and by Haygreen (4) that no significant difference in strain exists between the top and bottom surfaces, i. e., strips 1 and 10. Combining the two values at the same level in the sample gave four values from which the mean strain or moisture content could be determined for a given depth in the board. All graphs therefore show data points that represent the mean of four measurements.

Determination of Strain

Determination of strain and moisture content was by the use of the strip method. Similar tests have been made by McMillen (6) and Haygreen (4). Basically, the strip method is the measurement of the elastic strain as an indication of the stresses. Three-eighths-inch thick sections were cut two inches from the end of the kiln sample board. From this section, a four-inch long piece was cut (see Figure 2). This method of obtaining the sample was aimed at reducing the effect of the stresses and moisture gradient that develop at the edge of the board. The piece was then marked off in ten divisions, beginning at the convex side of the rings; the outer four were 1/16-inch thick, and the inner

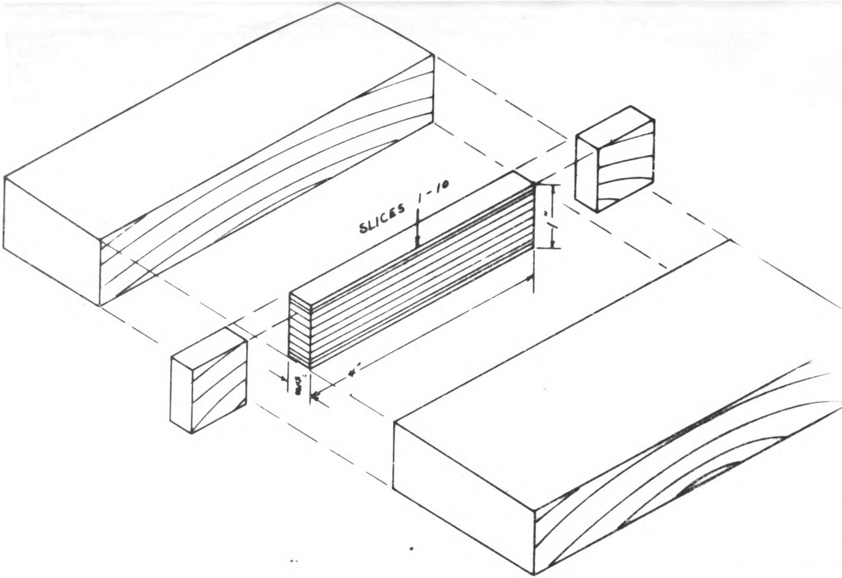


Figure 2. Location of ten test strips in a drying sample.

six 1/8-inch thick. It was thought that the thinner outer layers would give a better indication of the steep moisture gradient at the surface as well as a better indication of the drying stresses. The piece was then measured from one end to the other using a dial gauge jig. Each division was then sliced from the piece by means of a large, thin, steel blade. This method eliminated the loss of material that would occur if sawing had been employed. After slicing, the strips were again measured to obtain the elastic strain. The same strips used for stress determination were also used for moisture content tests.

Due to loss of moisture and heat from the strip during the time between cutting and measuring, errors in measurement may become serious. Ugolev (17) suggests a linear relationship exists between the magnitude of shrinkage and time of drying. His proposed method for eliminating this variation was to use a stop watch and measure each strip after the same interval of time had elapsed after slicing. However, Ugolev considered 15 to 20 minutes a very short period of time between the determination of the initial and the final length of the layer. In the present study, this elapsed time was never longer than five minutes, with an average time of three minutes. The elapsed time between cutting and measuring was three to five seconds. Therefore, it was deemed unnecessary to require such exact timing in taking measurements. Haygreen (4) devised a correction procedure which improves the accuracy of the strain determinations without the exact timing of measurements.

Where:

S = stress in the tangential direction

E = Modulus of elasticity in the tangential direction

e = true elastic strain

e' = measured elastic strain

Since the two surface layers, 1 and 2, are half the thickness of the other three layers:

$$\frac{S_1}{2} + \frac{S_2}{2} + S_3 + S_4 + S_5 = 0$$

Therefore, since S = Ee,

$$\frac{E_1e_1}{2} + \frac{E_2e_2}{2} + E_3e_3 + E_4e_4 + E_5e_5 = 0$$

If the assumption is made that the error in all strips is the same, then the differences between the elastic strain readings will not change during the measuring process, or:

$$e'_1 - e'_2 = D_1 = e_1 - e_2$$

$$e'_2 - e'_3 = D_2 = e_2 - e_3$$

$$e'_3 - e'_4 = D_3 = e_3 - e_4$$

$$e'_4 - e'_5 = D_4 = e_4 - e_5$$

The values of D are then the differences between strains which are actually measured. An expression for e_1 can be obtained from these last four independent equations:

$$e_1 = \frac{D_1(E_2 + E_3 + E_4 + E_5) + D_2(E_3 + E_4 + E_5) + D_3(E_4 + E_5) + D_4E_5}{\frac{E_1}{2} + \frac{E_2}{2} + E_3 + E_4 + E_5}$$

Other true strains can be obtained since:

$$e_2 = D_2 + e_3 \qquad e_4 = D_4 + e_5$$

$$e_3 = D_3 + e_4 \qquad e_5 = e_4 - D_4$$

The assumptions that must be made when using this correction procedure are: (1) a uniaxial stress situation exists, and (2) the errors due to temperature and moisture content changes are the same for all strips. The modulus of elasticity values used in this correction were obtained from the works of Ellwood (1).

There are three difficulties in determining the drying stresses by this method. One is that the stresses computed from the elastic strain are the average stresses in the strip. During the early part of the drying cycle, the moisture and stress gradients are very steep near the surface of the board. Therefore the computed stresses may be considerably smaller than those actually existing at the surface. The second difficulty is that a three-dimensional stress exists in the wood and not the uniaxial one assumed. The effect of the first difficulty was reduced somewhat by cutting the slices 1, 2, 9, and 10 as thin as possible or 1/16-inch thick. The effect of the second difficulty was minimized by cutting the piece from the test board as illustrated in Figure 2. By taking the piece of wood from the center of the board, the effects of the stresses existing on the edge of the board were reduced. The third difficulty, although probably not as important as those previously mentioned, should be considered even though no attempt was made to reduce its effect. Ellwood (1) suggests that indicated strains should not be used as an indication of stress unless the development of set is taken into consideration. He found that maximum stresses occur some time prior to maximum set and concluded that it is not apparent how the maximum compression set could occur while the layer was indicating tensile stress. Therefore, there may be some error in interpreting strain readings obtained in the slice technique as representing the actual stresses that develop.

Determination of Moisture Content

As soon as the elastic strain had been measured, the strip was weighed on a direct-reading automatic balance. The average time for cutting, measuring, and weighing was three minutes for all ten slices. The slices were then dried to an oven-dry condition. The moisture content was determined after weighing the oven-dry slices.

RESULTS

Kiln Conditions

In all cases, at the end of each 12-hour cycle, the dry-bulb temperature and the wet-bulb depression decreased. Both the wet-bulb temperature and the dry-bulb temperature decreased during each period in which the heat was shut off. However, the wet-bulb temperature did not decrease as much as the dry-bulb temperature, resulting in a gradual increase of the equilibrium moisture content within the kiln. Examination of the charts produced by the automatic controller-recorder revealed that the equilibrium moisture content change was linear throughout the "heat-off" half of the cycle. Figure 3 shows the changes in wet-bulb and dry-bulb temperatures as well as the equilibrium moisture content changes throughout the total drying cycle.

At the beginning of each "heat-on" half of the cycle, the time required to reach the desired dry-bulb temperature was directly related to the maximum temperature required. That is, it required more time to reach the maximum temperature as the maximum temperature was increased from 130°F. to 180°F. During all "heat-on" periods, the maximum time required to reach the desired temperature was never more than one hour when the kiln was operating at full capacity. However, due to the alternate heating and cooling, an excess of condensation in the steam pipes was developed and at times, the traps could not handle the excess. When this occurred, the heating coils did not operate efficiently and the time required to reach the maximum temperature was increased. In

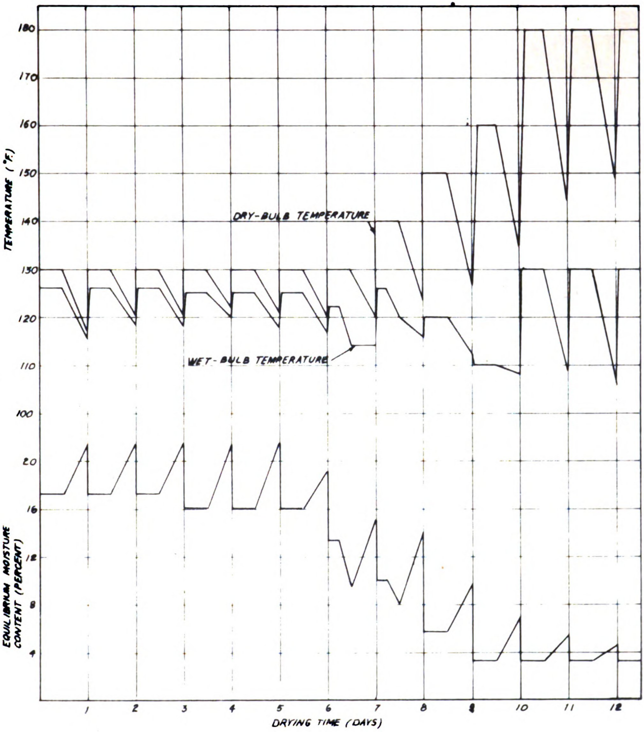


Figure 3. Kiln conditions as determined at the end of each 12-hour period during part-time drying.

an efficient kiln, the time required to reach the desired temperature should not be excessive.

Malfunction of the dampers during the heat-on periods of the seventh and eighth days produced drying conditions that were more severe than was desirable. During the period when the fans were reversing, the dampers would open then fail to close. When the moisture-laden air was allowed to escape, the equilibrium moisture content was consequently lowered. The dry-bulb temperature however remained at the desired setting. An increase in the severity of the drying conditions over a period of six hours may have had an effect on the test results. Examination of the strain curves (Figures 5 and 6) indicate an increase in measured strain is normal for this period of the drying cycle and therefore the effect on the test results may not be significant. Therefore, no attempt was made to adjust the data or to correct for the severity of the conditions.

The third kiln run, a part-time schedule, was made to check the effects of using the chamber on the conditions that developed in the kiln. It was necessary to use the small drying chamber because of a limited supply of green beech. It is shown in Table 2 that there was no significant difference between the conditions that developed while using the chamber and the conditions that developed when the kiln was fully loaded. The period required to reach the desired conditions was the same in both the chamber and the fully loaded kiln. Therefore, any difference in the results from the two runs should not be due to the use of the chamber.

Moisture Content and Moisture Gradient

The moisture gradient remained steep until about the seventh day of part-time drying. The surface strains began to drop off rapidly soon after the moisture gradient began to level off. During the full-time drying, there was a corresponding decrease in surface tension at about the fifth day of the drying cycle. These results follow closely those found by McMillen (6). The steep moisture gradient during the first portion of the drying cycle, because of the high surface tension that corresponds with this condition, causes this period to be the most critical for the development of surface checks when full-time drying is utilized. However, this steep moisture gradient in part-time drying may not produce the same stress results. This is discussed in more detail in the section dealing with stresses.

It was attempted and would have been desirable if a correlation or relationship could have been made or shown to exist between the moisture content of each level and the strain at that level. The difficulties encountered in determining the moisture content of each slice and comparing the moisture content values from consecutive slices prevented this from being done. At the beginning of the drying cycle when the moisture gradient is the steepest, a slight variation in the thickness of the slice may cause an increase or decrease to be indicated when the opposite is true. The moisture content determined for each strip is the average moisture content and will be effected by the thickness of the strip. Due to the method of measurement, marking, and cutting of each strip, the thickness was not controlled to any predetermined degree of accuracy. The variation in moisture content due to the variation in thickness of the slice may not be large yet this error may add to the error caused by moisture pockets within the test board. When comparing moisture content of slices from two different sample pieces,

a gain of moisture may be indicated when in reality a loss occurred. There is no way of knowing what the moisture content of the present sample was when the previous sample was taken. Therefore, if a moisture pocket existed in the present sample and not in the previous sample, an increase in moisture may be indicated.

During this study the above situation was found to exist. In most cases all levels throughout the sample piece indicate either a loss or gain of moisture for a given period. At an equilibrium moisture content well below the moisture content of the surface layer, many sample pieces indicated a gain in moisture throughout all five layers. Therefore, no correlation could be made from this study between the stresses of each layer and the changes in moisture content of each layer.

The moisture content of a given slice is however related to the strains that develop in that slice. The relationship between these characteristics was therefore investigated and will be discussed in the section dealing with stresses.

A comparison of the drying patterns developed by the kiln samples of both part-time and full-time drying, as illustrated in Figure 4, show that both methods of drying develop generally the same pattern. The only significant difference is the variation of individual values and the overall drying time. In part-time operation of the kiln, the wood continued to lose moisture even during the periods when the heat was off. The moisture was, however, lost at a slower rate. Therefore, because of this slower rate of moisture loss, the overall drying time was increased from 7 days in full-time drying to 12.5 days in part-time drying.

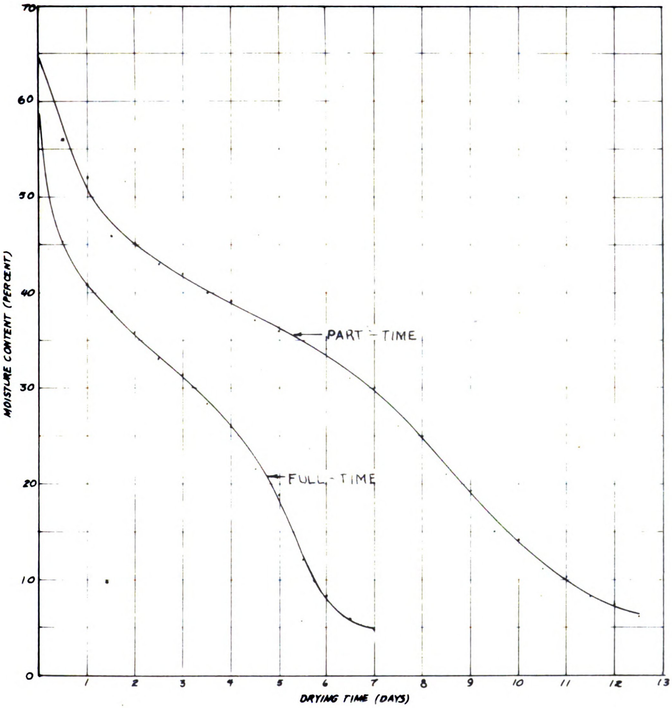


Figure 4. Drying rate of beech during part-time and full-time drying.

Strain in Tension and Compression

The unit strains perpendicular-to-grain observed in run No. 1 are shown in Figure 5. Tension strain increased gradually in strips 1 and 10 until the end of 1.5 days. The surface strain at the end of 1.5 days indicates an increase at a decreasing rate for a period when the kiln had heat applied. The strain however could have reached a maximum sometime prior to measurement and could have begun to decrease. Until stress reversal occurred at 9.5 days, the surface strain exhibited the pattern that had been expected, i. e., the more severe conditions when the heat was on, increased the surface tension and the less severe conditions when the heat was off, decreased the surface tension. After stress reversal and during the time when drying conditions were more severe, very little change in strain occurred between alternate periods. The surface layers during this latter period were losing and gaining moisture less rapidly than during the early portion of the drying cycle. Therefore, the changes in stresses would be less detectable and would exhibit a nearly continuous increase in compression strain.

A malfunction of the dampers in the kiln during the operating periods of run 1 prior to sampling at the end of 6.5 and 7.5 days caused severe conditions to develop. Surface tension strain increased at 6.5 days to almost the maximum strain reached earlier in the drying cycle. The increase in strain at this point may not be as significant as it appears to be. A corresponding increase, though not as great, occurred in the latter portions of all three kiln runs.

The maximum tension strain to develop in both run 1 and run 2 was approximately the same (Figures 5 and 6). In run 1, the maximum tension strain was 0.00509 inch per inch; in run 2, it was 0.00485 inch per inch.

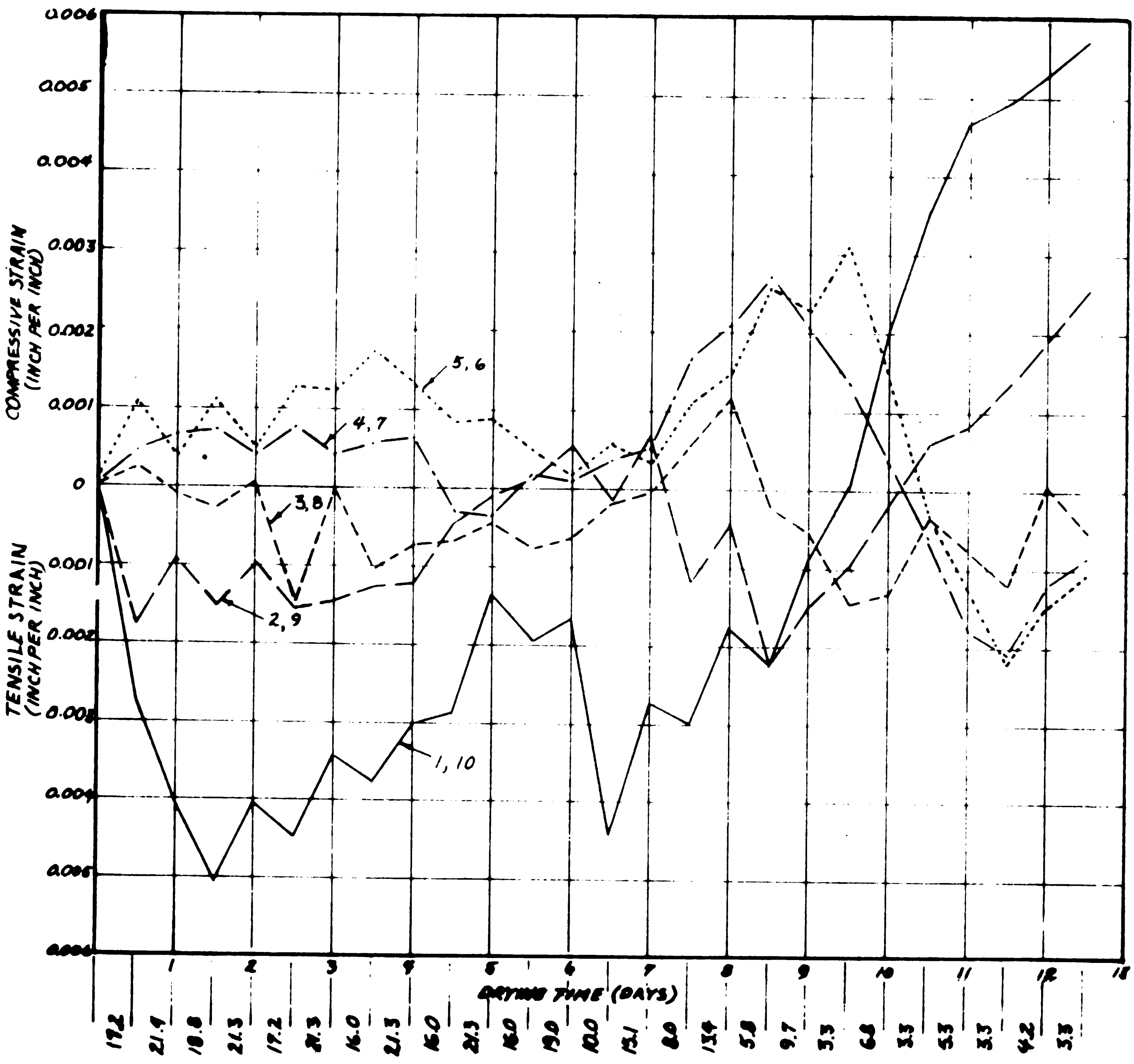


Figure 5. Indicated strain curves for 1- by 6-inch beech board during part-time drying.

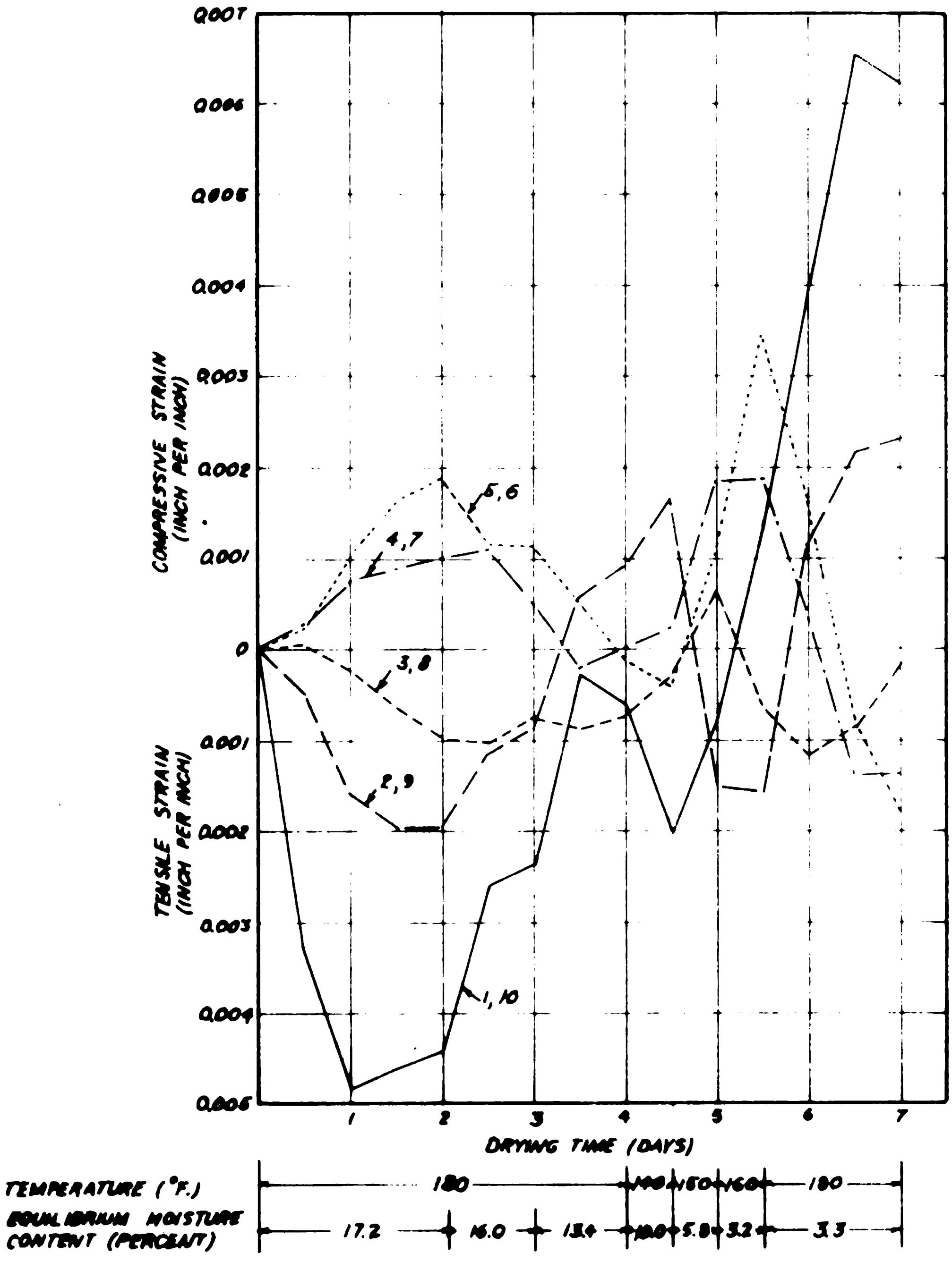


Figure 6. Indicated strain curves for 1- by 6-inch beech board during full-time drying.

The maximum compression strain in run 1 was 0.00288 inch per inch; in run 2, it was 0.00345 inch per inch. Part-time kiln operation therefore does not produce indicated strains that are significantly different in magnitude from the maximum strains produced under normal drying conditions.

Even though maximum strains that developed under different drying methods differed very little, there was indication that the surface layers of the wood were reacting differently. During full-time operation only a few small surface checks developed at the beginning of the drying cycle. During both part-time runs a visual check was made each period to determine the reaction of the surface checks during each drying interval. The surface checks in runs 1 and 3 became larger and more numerous than is desirable and alternately decreased in magnitude during the off-period and increased in magnitude during the on-period. This reaction to the changes in conditions indicated that the strains developed at the surface were greater than the measured strains indicated.

The measured strain is an average of the strains throughout the thickness of the strip, and are therefore not indicative of the strain that exists at the very surface of the board. To determine a better measure of the surface tension, curves were fitted to measured strain data by the method of least squares. Figure 7 shows several curves, as determined through the use of a computer, as being the best fit. Even though there is some danger in assuming that the curves continue the same trend beyond the data, extrapolation was utilized in determining the strains that develop at the surface.

The moisture content of a strip at the time of measurement is not effected by the overall drying time and is preferred as a basis for

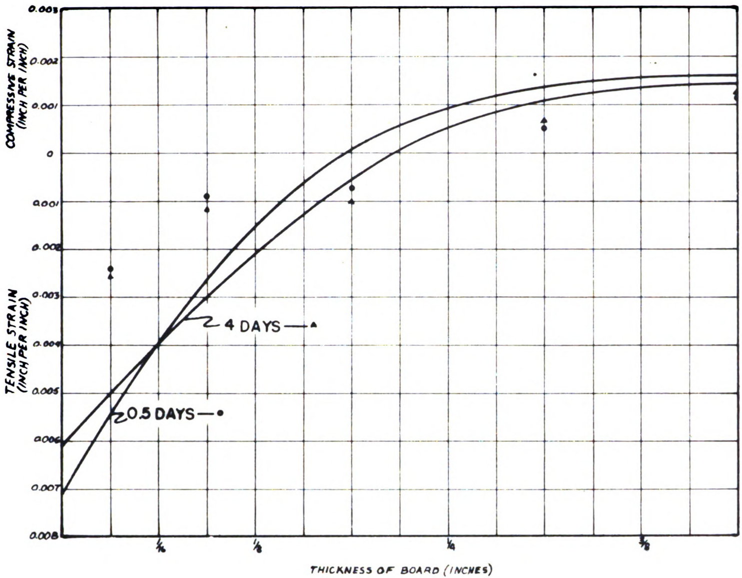


Figure 7. Representative samples of curves fitted to strain data through use of computer and least squares method.

comparison of part-time and full-time drying. The strains taken from curves, such as those shown in Figure 7, were plotted over the moisture content at which they occurred. In this manner, a curve showing the average strain occurring at a given moisture content was obtained (Figure 8). To indicate the range over which these strain measurements varied during part-time drying, two curves were fitted; one curve was fitted to data obtained at the end of the on-period, the other to data obtained at the end of the off-period.

In part-time drying, surface tension strain, during the latter part of the drying cycle was maintained at a higher level than in part-time drying. During the off-periods of part-time drying the tension strain was greater at a given moisture content than that found to exist in full-time drying. During the latter portion of the drying cycle, after the surface layer has dried below the fiber saturation point, the modulus of elasticity begins to increase as the wood dries. At the same time, the temperature is being increased which lowers the modulus of elasticity. The temperature, however, has far less effect on the modulus of elasticity than the moisture content. It has been shown by Ellwood (1) that an increase in modulus of elasticity of about 25,000 p.s.i. would occur under the maximum temperature of 130°F. (temperature at which the maximum strain occurred during the latter portion of the drying cycle) with a corresponding decrease in moisture content from 30 to 15 percent (Figure 9). Therefore, at the time when the moisture content was 15 percent and the temperature no greater than it was at the beginning of the cycle, the same strain would actually be an indication of about twice as much stress, i. e., it would take about twice as much strain to produce an equal elastic strain.

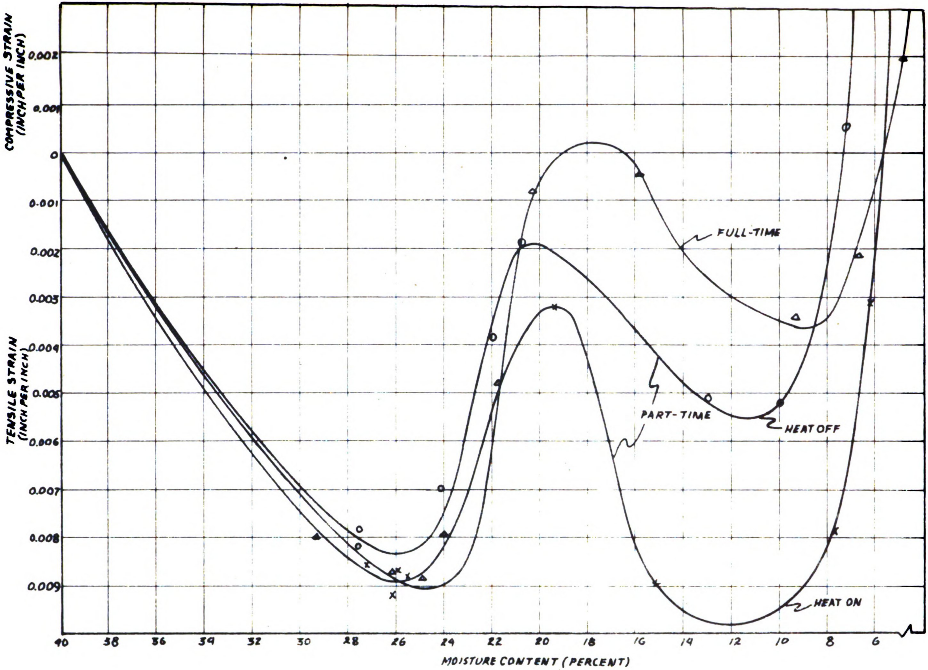
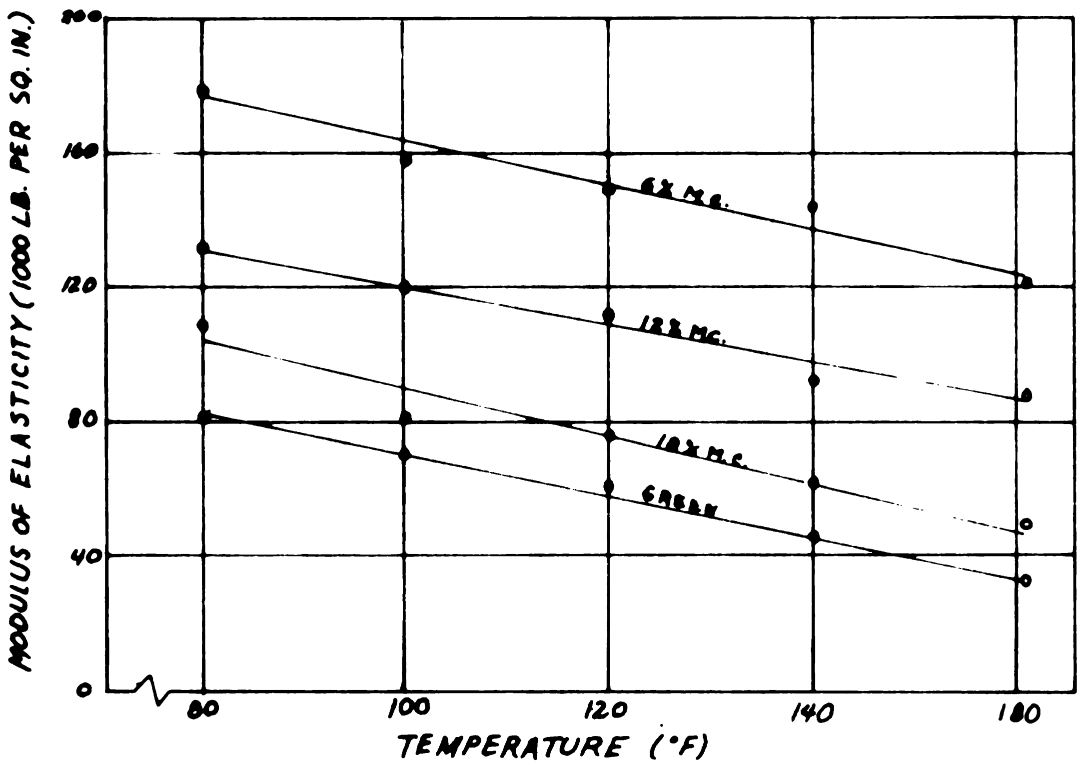


Figure 8. Indicated strain development curves for 1- by 6-inch beech board. Corrected to indicate the **strain at the surface.**



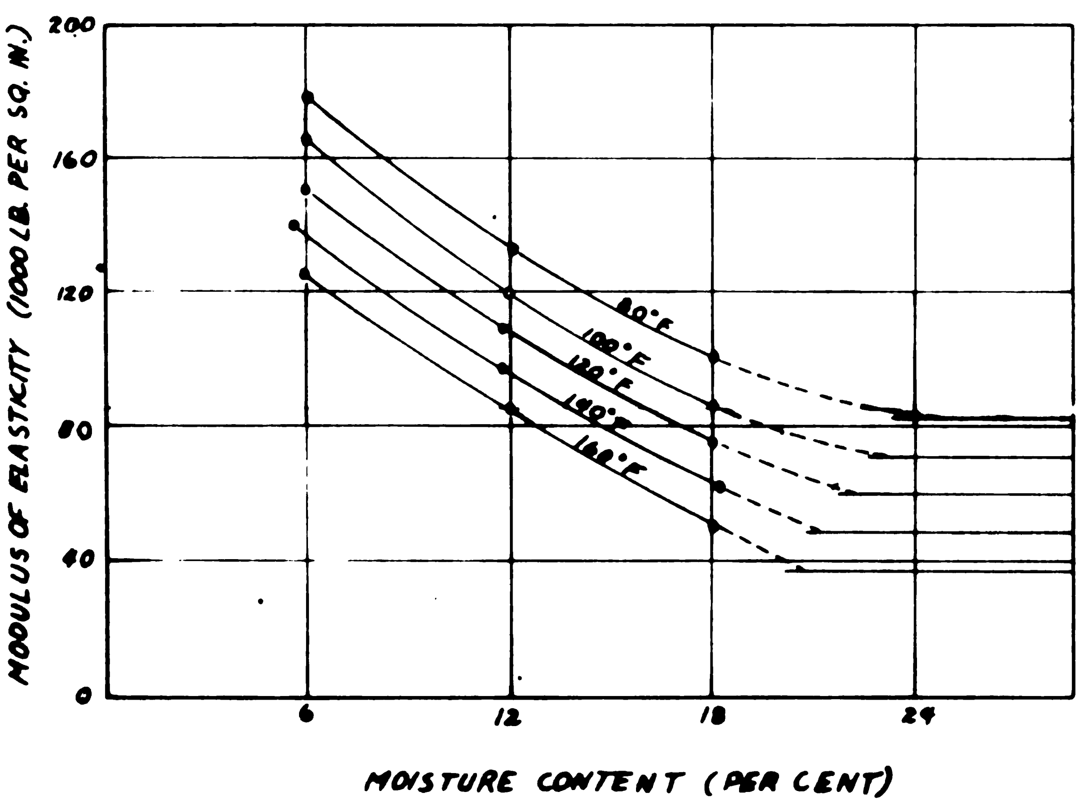


Figure 9. Effect of moisture content on modulus of elasticity of beech in tension perpendicular-to-grain (Ellwood (1)).

Maintaining the surface tension at a higher level over the same moisture content range may tend to produce more and larger surface checks. The differences in the strains produced in part-time drying from those produced in full-time drying may not seem significant however until these strain values are converted to stress values and corrected for an increase in modulus of elasticity as the wood dries. The average strain values at a given moisture content were taken from Figure 8 and since S = Ee where:

S = Stress

E = Modulus of Elasticity (taken from Ellwood (1))

e = Strain

the stress values may be obtained. Figure 10 shows stress values that occur at given moisture content levels. The actual stresses existing at the surface are much greater during the latter part of the part-time drying cycle than during the earlier portion.

The tension stress at proportional limit perpendicular-to-grain as determined by Ellwood (1) for beech is shown in Figure 10. The average tensile stress that developed during the early portion of the drying cycle in both part-time and full-time operation reached approximately the same level and exceeded the stress at proportional limit. During the latter part of the drying cycle the stress that developed in full-time drying did not reach the maximum stress developed earlier, and did not exceed the stress at proportional limit. In part-time drying the maximum stress as measured at the end of the on-period greatly exceeded the stress at proportional limit during the same period. The test results indicate that the stresses at the surface did reach and exceed the stress at proportional limit as determined by Ellwood.

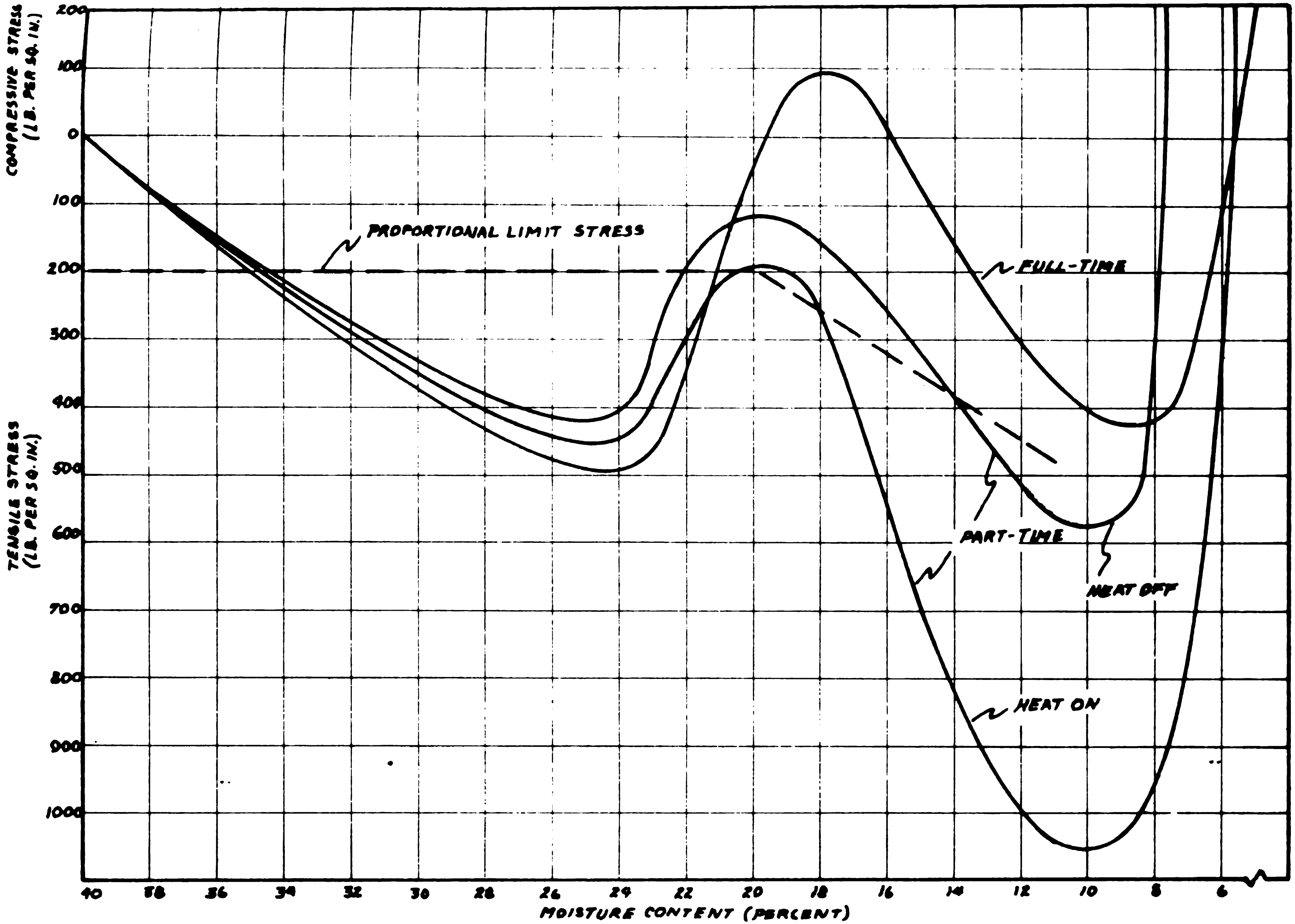


Figure 10. Stress development curves for 1- by 6-inch beech boards during part-time drying.

DISCUSSION

Drying Stresses

Elastic strain, an indication of drying stresses that develop in wood after the moisture content of the surface layer drops below the fiber saturation point, can be helpful in studying the relationship between stress behavior and drying conditions. The strip technique is used to measure the elastic strain. To utilize this method, it is necessary to assume conditions that do not actually exist. Therefore, it does not take into account all of the variables that may exist and is not an ideal method. It is an accepted method however and can be useful in studies of this type.

When kiln conditions are changed periodically throughout the drying cycle the strains that develop will also differ from those that would be expected to develop when utilizing full-time drying. When the heat in the kiln is turned off, the dry-bulb and wet-bulb temperatures decrease and converge, decreasing the wet-bulb depression. During this period the wood cools, the equilibrium moisture content is increased and consequently the drying rate is decreased. The heat is then turned on in the kiln, the wood is heated, the equilibrium moisture content drops and the drying rate is again increased. Corresponding with each increase and decrease in drying rate is an increase and decrease in elastic strain. When drying a refractory hardwood such as beech which is likely to surface check but is not troublesome in honeycombing, the important stresses to be considered are those that develop at the surface.

The results of this study indicate that the stresses at the surface in part-time drying are very similar to those in full-time drying during the first part of the drying cycle or until the moisture content of the wood drops below the fiber saturation point. Tension stresses at the surface drop off rapidly after the fiber saturation point is reached in full-time drying. In part-time drying there is a corresponding but smaller decrease in stress during the same period. Throughout the remainder of the drying cycle the maximum stresses that developed in part-time drying were greater than those that developed in full-time drying. In both methods of drying an increase in stress occurs at about the same moisture content that a corresponding increase in the stress at proportional limit occurs. The stress builds up in part-time drying to a new maximum which is above the stress at proportional limit. The stress in full-time drying does not reach a new maximum and remains well below the stress at proportional limit.

Comparing the stress patterns developed by both methods of drying indicate that the most critical period in part-time drying of beech may not be during the initial portion of the drying cycle but during the final stages. The suggestion to increase the severity of the drying conditions to shorten the overall drying time may result in a much higher percentage of degrade. Rasmussen and Avanzado (10), working with red oak, found that the quality of the lumber dried by both methods appeared to be the same. They also found that part-time kiln operation produced checks that occurred and began to close at a lower moisture content level but both methods produce about the same quantity of checks. This would indicate that the stress that developed was about the same in both methods for red oak. They may have produced completely

different stress conditions however by leaving the kiln off for as long as 48 hours at one time and 36 hours several times throughout the drying cycle after operating the kiln at full capacity for only 8 hours.

From the results of this study, it is recommended that the kiln schedule for beech T8 C2 should not be considered the ideal schedule to use when part-time operation of the kiln is to be utilized. A kiln schedule that would produce better results should be based on some criteria other than the moisture content of the kiln sample. The moisture content of the kiln samples does not indicate the surface stresses that are developed. The schedules recommended by the U. S. Forest Products Laboratory were devised by observing the strains that developed in full-time drying and these data were applied to recommended kiln sample moisture content schedules. A more realistic drying schedule for part-time drying could be developed by observing the stress development in many drying operations and applying the results to a kiln sample moisture content schedule for easier application. It is beyond the scope of this study to develop these schedules. The results of this study do, however, indicate that better kiln schedules should be developed for part-time drying.

Moisture Content

Determination of the moisture content by the strip method may produce erroneous results. It has been shown that the moisture gradient during the first portion of the drying period is very steep (1)(6), and that moisture pockets exist in the lumber during drying. The moisture pockets are probably most responsible for the difficulties encountered. A different piece of wood is measured for moisture each 12 hour period. A moisture pocket may lose moisture during that period but because it was at a high moisture content at the beginning of the period, it may indicate an increase when compared to the previous sample. The steep moisture gradient at the beginning of the drying cycle combined with the variable thickness of slices to be compared may also introduce some error in the results. The average moisture content of each strip is determined, therefore, if the thickness of the present test slice is greater than that of the previous slice, an increase in moisture may be indicated when in reality a loss of moisture occurred at that level.

The moisture content data gathered in this study was not utilized in making a comparison of the changes in stresses that occur with changes in moisture content as no correlation could be found.

Kiln Conditions

In full-time kiln drying, the efficiency of the kiln does not have as direct an effect on the conditions within the kiln as when using part-time drying. If in full-time drying the heating system does not build up heat in the kiln rapidly, this is not serious since heat is built up only at the beginning of the cycle and when changes in the schedule are made. In part-time drying this may become a problem when the heat in the kiln must be built up many times. If the efficiency of the heating system is very poor, it is possible that the maximum temperature desired will not be reached before it is time to turn the heat off again. If a kiln is not efficient in holding the heat within the kiln the effect in full-time drying would be an increase in drying costs. In part-time drying the loss of heat from the kiln, if it was excessive, would present the problem of the kiln cooling too rapidly with an increase in the temperature difference that would have to be built up each time the kiln was turned on. If the kiln was inefficient in heating and heat loss was high, the problems in part-time drying would be compounded. It would be highly undesirable therefore to use an inefficient kiln if part-time drying is to be utilized.

Overall Drying Time

The overall drying time in part-time drying of beech as compared to full-time drying when the schedule is based on the kiln sample moisture content is affected by three factors. These are:

(1) the inefficiency of the kiln which is multiplied in part-time drying,

(2) the time at which the schedule changes become necessary,

(3) the relative length of the on and off-periods.

In an inefficient kiln where heat retention is poor, the wood cools faster and decreases the drying rate more than in an efficient kiln. If a longer period is required to reach a desired temperature, the drying rate is decreased during this period which will also lengthen overall drying time. Determination of the moisture content of the kiln sample on a 12-hour basis, as was the case in this study, to determine the kiln schedule changes may cause the drying time to be longer. When the moisture content of the sample indicates that an increase in the severity of the conditions can be made, it may occur at the end of an on-period which in reality will be followed by a decrease in severity when the heat is shut off. The delay in making the change in kiln conditions would increase the overall drying time. In many instances where exhaust steam is used for kiln drying, an 8-hour operating period followed by a 16-hour off-period is a common practice.

The overall drying time would be greater in this case than where a 12-hour on and 12-hour off schedule is used.

Overall drying time in part-time drying of beech, from green to six percent moisture content, using the internal-fan, cross-circulation kiln utilized in this study, increased to approximately two times that of full-time drying.

CONCLUSIONS

1. The kiln schedules recommended by the U. S. Forest Products Laboratory should not be utilized to control the drying rate when intermittent operation of the kiln is used. The changes in these schedules are based on the moisture content of the kiln sample and no consideration is given to the differences in stresses that develop in part-time and full-time kiln drying.

2. The cyclic changing of kiln conditions in part-time drying tend to compound any inefficiencies of the kiln. The use of an inefficient kiln in part-time drying is therefore highly undesirable.

3. The results of this study indicate that the generally accepted theory, that a more severe drying schedule may be used to partially solve the extended drying time, is unfounded. As the results indicate, a less severe schedule may be necessary to prevent excessive degrade caused by surface checks.

RECOMMENDATIONS FOR FURTHER RESEARCH

It was considered, when this study was begun, to determine what correlation, if any, existed between the change in moisture content and the change in stress at different layers in the wood using a part-time drying schedule. Due to the limited number of kiln runs that were made and the small number of samples taken during each sampling period, the results were not conclusive. A complete study of the causes of variation when using the strip technique would be of value in future studies of this type. It is indicated in this study that the variation in the moisture content shows a relationship to the thickness of the slice, and moisture pockets in the board. The methods employed by Ellwood (1) may give a better indication of the correlation of stress and moisture content. Combining his method of measuring stress with the use of insulated pins on thermocouples and moisture meters to measure temperature and moisture content may make it possible to make consecutive measurements on the same piece of wood. This method could then be employed to measure the changes in stress and moisture content as the conditions in the kiln are cycled as in part-time drying.

Under both repetitive and constant loading above the proportional limit there is an apparent increase in modulus of elasticity (1). In this study there is an indication that the stresses measured were somewhat greater than those that actually existed. This may be due in part to the recovery of the wood from stress. A study is indicated on the characteristics of the recovery curves of both part-time and full-time kiln schedules.

In part-time drying, the duration of loading is increased but due to the cyclic nature of the drying conditions the development of set, creep, and relaxation may not be similar to what would be found in full-time drying. A study of the effects of part-time drying on these three characteristics is suggested. An increase in the duration of loading as is found in part-time drying will cause a reduction of strength. During the latter part of the drying cycle in part-time drying, a given stress value may produce more severe checks at a given moisture content due to the weakening of the wood. It would be of value in future studies to know what correlation exists between the duration of load and reduction in strength.

From this study, no recommendations can be made for developing new moisture content schedules, for use in part-time drying. A more complete study should include more kiln runs, including some with more and less severe conditions than recommended by the U. S. Forest Products Laboratory.

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APPENDIX

STATISTICAL TABLES

Table 1. Analysis of Variance of Equilibrium Moisture Content Changes in Chamber and Fully Loaded Kiln.

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F	$F_{.05}$
Treatments (A, B)	.6	1	.6	5.99*	.1635
Within	22.03	6	3.67		
Total	22.63	7			

*Indicates significance at the 5% level.

Treatments: A (Chamber) B (Fully Loaded Kiln)

Summary:

Treatments	Means
A	3.9% (E.M.C. Change)
B	3.5%

Table 2. Analysis of Variance of the Tension Strain in the Surface Strips During Kiln Run 2.

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F	$F_{.05}$
Surface (Top, Bottom)	.0102	1	.0102	7.71*	.3764
Within	.1086	4	.0272		
Total	.1188	5			

*Indicates significance at the 5% level.

Summary:

Surface	Mean
Top	2.96×10^{-3} in./in.
Bottom	3.51×10^{-3} in./in.

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