THE EFFECTS OF SODIUM CHLORIDE ON THE DRYING CHARACTERISTICS OF A REFRACTORY HARDWOOD

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ABSTRACT

THE EFFECTS OF SODIUM CHLORIDE ON THE DRYING CHARACTERISTICS OF A REFRACTORY HARDWOOD

By John G. Haygreen

Chemical seasoning has been used for a number of years to reduce the amount of seasoning degrade which often occurs in thick refractory hardwoods. The reduction of surface-checking which results from such treatments is due to a change in the sorption characteristics of the surface layers of the lumber and to the antishrinkage effect of the chemical. These characteristics also make possible kiln-drying under humidity conditions which would be too severe for untreated material.

In this study, the kiln-drying of green chemically-treated lumber was investigated to determine what effect the presence of a salt has on the factors which limit the optimum drying conditions. A commercial sodium chloride preparation applied to northern red oak was used throughout this study. The behavior of elastic strain, of moisture, and of irrecoverable creep during drying under different humidity schedules was studied. The salt concentration gradient and the effect which drying conditions have on this gradient were also investigated.

When treated oak was dried under a normal kiln schedule designed for untreated material, the stresses developed were lower than those of untreated stock and decreased with increasing amounts of salt. A correspondingly lower degree of tension set was produced prior to stress-reversal. The rate of stress relief during conditioning was the same for treated and untreated stock. In subsequent tests, the

initial relative humidity was decreased developing maximum tensile stresses as indicated by set, checks, and tensile strain. The diffusion of salt toward the center of the samples was greatly reduced by decreasing the initial relative humidity. The development of set was more rapid under the lower initial relative humidity conditions, but the total magnitude of set produced was not changed.

A more severe sequence of drying conditions was designed on the basis of the first tests. The treated stock which was dried under this sequence developed a stress pattern similar to that occurring in untreated stock. This indicates that the optimum schedule was approached. This stock was dried without degrade in 55 percent of the time required under the normal schedule. The salt concentration in the center portion of the boards dried under the normal schedule was found to be about one-third as high as the concentration on the surface. The movement of salt to the center of the boards was greatly reduced by using the more severe schedule.

If the relative humidity conditions are properly chosen, the behavior of stress, moisture, and set in sodium chloride-treated lumber will be very similar to that normally encountered in untreated lumber. The proper initial relative humidity can be predicted on the basis of the shrinkage-relative humidity relationship, if known.

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By

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INTRODUCTION

Chemicals may be applied to lumber to improve its seasoning characteristics, or to reduce its susceptibility to fire or decay. Some chemicals also improve the dimensional stability of wood, but little commercial use has been made of this fact. Regardless of the purpose for which a chemical is added to wood, the drying characteristics may be altered depending on the nature of the particular salt used.

Chemical Seasoning

Chemical seasoning refers to the process of treating green wood with a hygroscopic chemical and then air-drying or kiln-drying this material in the conventional manner. The primary reason for using such a process is to reduce the amount of seasoning degrade, mainly surface-checking. A water soluble chemical is used which penetrates the surface layer of the lumber, reducing the vapor pressure in this layer. By reducing the vapor pressure the surface is maintained at a higher moisture content than is normal. The antishrink effect[1] of the chemical in conjunction with the higher moisture content tends to reduce or eliminate checking.

In the last several years the most widely used commercial product for chemical seasoning has been a sodium chloride preparation.

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[1]Antishrink effect refers to the reduction in the shrinkage caused by the bulking volume of the chemical within the cell wall structure.

This preparation has found considerable application in the southern hardwood region where it is used on 6/4 and thicker oak, pecan, and beech. A survey conducted among the larger hardwood mills in the south in 1958 indicated that about 35 percent of the mills surveyed used some "salt" for treating their thick refractory hardwoods.

Drying Stresses and the Optimum Kiln-Schedule

The expense of kiln-drying green hardwood lumber can run up to $50 per MBF for thick stock. Although this expense is a function of a number of factors, it is closely related to the drying time. The total cost of drying, however, also includes the loss in measurement and grade during drying. The optimum kiln-schedule could be defined as one which minimizes the total cost of drying. Although this cost is a function of shrinkage, seasoning degrade, and drying time, the most important factor in minimizing this cost is drying time. This is because the other two factors must be held nearly constant. Shrinkage can only be varied a very small amount, and seasoning degrade must be held as near zero as possible due to the high cost resulting from its occurrence. Therefore, the use of a seasoning agent would reduce the drying cost if the drying time were reduced appreciably while not increasing the shrinkage or degrade.

It is very difficult to determine the optimum kiln-schedule which minimizes drying time while eliminating defects. Ideally, schedules should be based upon the internal stresses which develop in the lumber as a result of the moisture gradient. In refractory hardwoods stress development follows the pattern outline below.

1. When drying is begun the surface of the board tends to dry

to the EMC in the kiln. A steep moisture gradient thus develops in green lumber. Since the outer portion of the board is below the FSP this portion tends to shrink.

2. The outer portion can shrink only a very small amount due to the reaction of the inner portion of the board. Tension stresses in the shell and compression stresses in the core result. The stress produced at this time is a function of the difference between the normal unrestrained dimension and the actual dimension of the layer.

3. Set occurs as a result of creep below the proportional limit and stress above the proportional limit. It occurs both in the shell and in the core, but is more severe in the shell due to the higher stress. Set produces a change in the normal unrestrained dimension and thus in the stress.

4. As drying continues the interior of the board drops below the FSP and tends to shrink. As a result of surface tension set and core compression set the core exhibits a higher coefficient of shrinkage than the shell. Therefore, as the core continues to shrink the surface layers go into compression and the core into tension. The initial stresses are thus reversed.

5. The moisture gradient flattens during the final portion of the run producing still higher core tension stresses and shell compression stresses. At the completion of the drying cycle this stress condition is called casehardening.

The initial drying stresses are a result of the moisture gradient. Set begins to develop almost immediately, affecting the stresses both in the shell and in the core. Stresses during most of the run are thus a function of both the moisture gradient and set. At the end of the drying process when the moisture gradient is flat the residual stresses are a function of set.

The relationship between drying stresses and drying defects is important in the design of the optimum kiln-schedule. Surface-checking results from surface stresses which exceed the maximum strength. Checking is thus a direct result of drying stresses. Collapse can result from either drying stresses or from hydrostatic tension. It is believed that hydrostatic tension is the more common cause of collapse. When collapse is caused by drying stresses it could be considered excessive compression set. Honeycomb usually is a result of surface-checks which are extended into the center of the board as the drying progresses. It may also be produced by tension failures in the center portion of the board. This often is the case in portions which have previously collapsed.

There are three critical points around which the truly optimum kiln-schedule must be based. These points are: (1) the initial tensile stress on the surface which must be controlled so that surface-checking does not occur, (2) the temperature and relative humidity early in the schedule which must be controlled such that hydrostatic tension does not cause collapse, (3) the temperature and the stress level prior to stress reversal must be controlled so that excessive set in shell and core does not occur, which would result in severe stresses after stress reversal. Such stresses could result in tension-failure type honeycombing.

It can be seen that the first portion of the kiln run is the most important in the design of the optimum schedule for a refractory hardwood. The stress development which takes place after stress-reversal is determined by the set which is produced prior to stress-reversal. After stress reversal, the relative humidity in the kiln is, therefore, not of primary importance. The temperature must be controlled after reversal, however, to avoid lowering the tensile strength below the level of the tensile stresses. If this occurred honeycomb would develop.

If the strength, elastic, moisture, and diffusion characteristics of a wood were known a theoretical, rather than an experimental, approach could be used to determine the optimum schedule. Theoretically, derived moisture distribution-time values could be used to ascertain the initial stresses which would develop under proposed initial drying conditions. From the stress-strain-creep relationship the amount of set which would be produced could be estimated. In order to minimize drying time the maximum strength and set values would be approached, but to minimize drying defects these maximum values should not be exceeded. Due to the variable nature of wood a statistical approach would be necessary, and an acceptable limit for seasoning defects would have to be chosen.

Statement of the Problem

The length of time required to dry lumber which has been treated with salt may differ from that for untreated material. Several investigations have indicated that woods dry faster when treated with sodium chloride, while others indicate the opposite effect. These comparisons were noted when both the treated and the untreated lumber were dried under similar conditions, as would necessarily be the case in air-drying. In kiln-drying, however, the drying conditions can be adjusted to the drying characteristics of the wood being dried. Lumber treated with a chemical seasoning agent generally has a flatter moisture content gradient and thus a less severe stress distribution than has untreated lumber being dried under the same conditions. For this reason, the drying conditions could be made more severe during the drying of treated lumber, possibly resulting in a significantly shorter drying time and correspondingly a lower drying cost.

It is apparent that a better understanding of the effects of salt is necessary if the efficiency of drying salt-treated wood is to be improved. The purpose of this investigation was to evaluate the primary factors which determine the optimum kiln-drying conditions for salt-treated lumber. As with untreated lumber the internal or drying stresses, which are developed by the sequence of drying conditions, are the most important factors.

REVIEW OF LITERATURE

Drying Stresses

The presence of drying stresses and their significance in the proper drying of lumber were probably first recognized by H. D. Tiemann in 1915. At that time he developed the familiar prong test commonly used to determine the presence of casehardening.

The first complete study of drying stresses was carried on by Peck (36) around 1940. He investigated drying stresses in two-inch thick blackgum. Peck used what is now known as the "slicing or strip technique" to estimate the stress condition. Peck cut strips from the face of a section cut from the board. He measured the length of the strips both before and after cutting. The change in the length of the strip was taken as a measure of the stress present. Thus, if a strip were longer after cutting, a compression stress was indicated, and if it were shorter after cutting, then a tensile stress was indicated. Peck assumed that the magnitude of the change in length of the strips was an indication of the magnitude of the internal stress. Although this assumption was later (12) (28) (29) shown to be an oversimplification of the case, the information obtained in his study made possible the design of a fast drying schedule for this species.

In 1946 Loughborough and Smith (49) published the results of a more comprehensive study of the same type as that of Peck. They, however, investigated sweetgum. The general finding of both of these early studies was that the tension strains on the surface build up rapidly after drying begins, and that after a few days this strain begins to lessen. It is then possible to reduce slightly the relative humidity in the kiln without risking further surface-checking. An empirical formula was derived for determining when the original relative humidity in a kiln can be safely reduced. It was found that when E from the relationship

$$E = \frac{\text{present MC} - \text{kiln EMC}}{\text{original MC} - \text{kiln EMC}},$$

reaches 0.7 then it was safe to reduce the humidity. MC is used as a symbol for moisture content and EMC for equilibrium moisture content. From the knowledge of the behavior of drying stresses gained in these studies the U.S. Forest Products Laboratory published in 1951 a new set of kiln schedules for American woods. The design of these schedules is thoroughly discussed by Rietz (39). These schedules resulted in more rapid drying and reportedly did not increase the occurrence of degrade as compared to the schedules which they replaced.

More recently McMillen (27) (28) (29) has employed the strip technique to study the drying of northern red oak. His extensive studies covered the effects of temperature and relative humidity on both the strain and the set. He estimated the set by noting the change in the total shrinkage of the strips. He found that the magnitude of the set was closely related to the severity of the relative humidity, but was not apparently affected by the temperature.

A method similar to the strip technique has been used to determing uniaxial residual stresses in steel rails (3). Other methods, employing strain gages, used to determine residual stresses in metals do not appear applicable to the determination of drying stresses. The severe moisture conditions, high temperature, and long-time loading involved would make strain gage analysis unreliable. Improvement of strain gage techniques may eventually make such analyses possible.

Kuebler (23) recently used a different technique to estimate the drying stresses in veneer. He sliced very thin sections from veneer and calculated the stresses from the curvature of the sliced sections. It appears that he assumed that Young's modulus is constant through the veneer. This technique might also be applicable to a study of stresses at the surface of lumber, but has not been so used as far as the writer has been able to determine.

In the "stress" measurement techniques discussed above it is the elastic strain of a section cut from a drying specimen which is measured. If these strains are to be related to the corresponding stresses a complete understanding of the elastic and plastic properties of wood perpendicular-to-the-grain are required. Since most failure theories are discussed in terms of stress rather than strain it would be very helpful, though not necessary, to convert from strain to stress. Several investigators have worked on this problem in the last six years. Ellwood (12) investigated the effects of temperature and moisture content on the perpendicular-to-grain tensile and compressive properties of beech. He found that tensile and compressive properties were both affected to the same extent by temperature and moisture.

Youngs (50) studied exhaustively the mechanical properties of red oak perpendicular-to-the-grain. His work included tension and compression characteristics under various temperatures and moisture contents. He also investigated the effects of the duration of heating, creep and recovery, and stress relaxation. This study is a significant step toward the determination of drying stresses. However, even with this information the state of stress at a point cannot be directly determined, but only the average stress in the strip. Since the stress gradient is presumably very steep near the surface of a board, at the beginning of the run, the stress at the surface is much higher than the average stress in the slice.

In order to overcome this difficulty Youngs and Norris (51) developed a mathematical method of estimating the perpendicular-to-grain normal and shear stresses which occur at any point in the cross section of a drying board. For this solution the following are required: (1) elastic strain measurements such as those of McMillen, (2) the moisture content and temperature of the slices at the time they are cut, (3) data on perpendicular-to-grain elastic properties under the temperature and moisture content conditions of the slice. This method uses a stress function which is evaluated by the use of simultaneous equations and the principle of least work. It presents rather imposing problems in carrying out the mathematics involved. At the present time Youngs and Norris are trying to program it to a computer.

A different subject in the area of drying stresses which has received considerable attention in the last several years is that of collapse. Kauman (20) investigated tension and compression set in eucalyptus and related his findings to the extent of collapse and to the overall shrinkage of the specimens. He concluded that drying stresses are not the most important collapse-inducing force, but that the concept of hydrostatic tensions is a more likely explanation. Kemp (21) working with aspen found that the drying time prior to collapse decreased with an increase in temperature and increased with an increase in relative humidity.

The most recent and thorough study of collapse is that of Ellwood, Eckland, and Zavarin (12). Their conclusions are in general agreement with those of Kauman. The reduction in collapse which they found in samples in which water had been replaced by an organic liquid was consistent with predictions from liquid-tension theory.

It is interesting to note that a void is present in the literature in the area of surface-checking as related to surface stresses. This particularly is significant since surface-checking is one of the most common seasoning defects. The difficulties involved in determining such stresses are, presumably, responsible for this void.

Properties of Salt-Treated Wood

There are two properties of salt-treated wood that are particularly important in regard to the development of drying stresses. These properties are: (1) the sorption characteristics, (2) the shrinkage characteristics.

Paten (34) found that in Scots pine containing three percent sodium chloride the entire sorption and desorption curves lay above those of untreated material. (See Fig. 1.) At about 92 percent relative humidity these curves approached the vertical. He compared these results with a calculated adsorption curve and found that the experimental curve lay above the calculated curve from 0 to 75 percent relative humidity. From 75 to 92 percent the curves agreed quite closely.

A study which included proprietary fire retardants and preservatives, as well as common salt, was carried on by Kollmann (22). Spruce which was impregnated with a saturated sodium chloride solution exhibited somewhat different sorption characteristics than the pine in Paten's experiment. (See Fig. 1.) One reason for this difference may

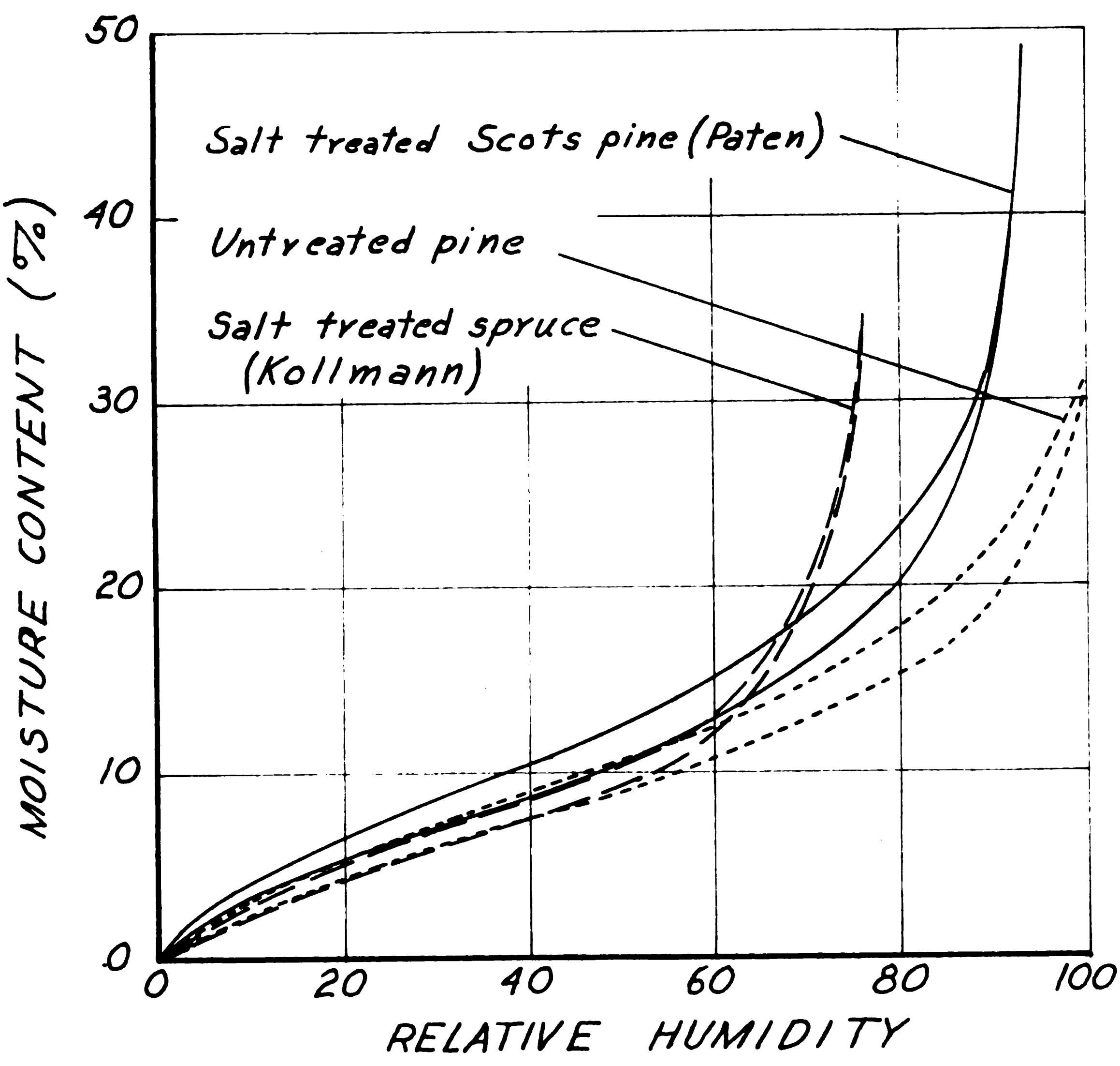
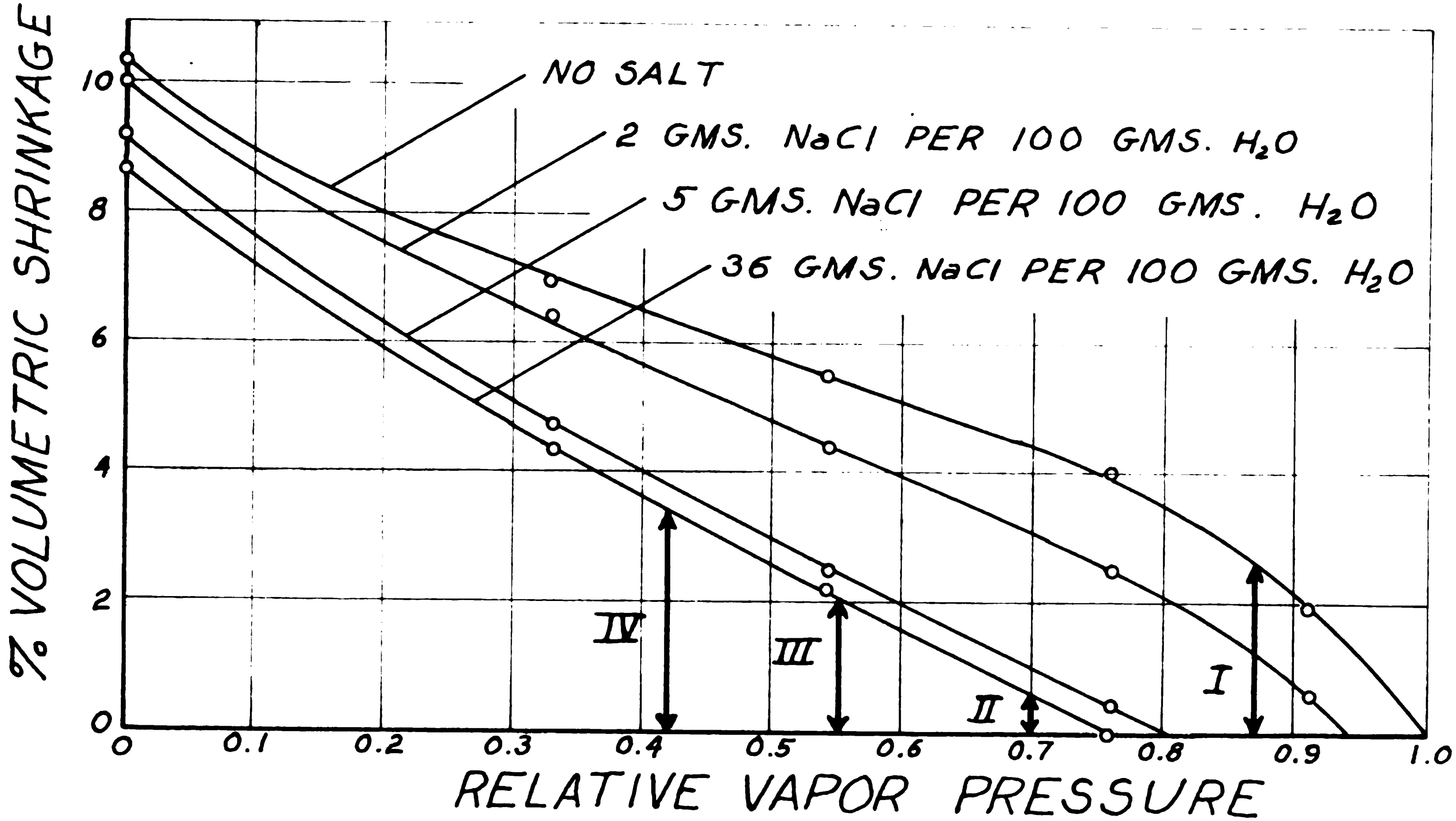


Fig. 1. Sorption and desorption curves for sodium chloride-treated and untreated spruce and pine.

be a higher salt concentration in the spruce. Kollmann did not determine the salt content of the dry samples. It should be noted that Kollmann found that the sorption curve for the treated material was in close agreement with that of untreated material below 60 percent relative humidity. It has been widely assumed that the entire sorption curve for treated wood is above that for untreated stock. The sorption curves of Minolith and Basilit-3 treated wood were found to be similar to that of sodium chloride-treated material.

Peck (35) determined the antishrink effects of various chemicals and the relative humidity in equilibrium with different percentages of saturation of aqueous solutions. The antishrink effect of salt was found to be 12.7 percent compared to 44.7 percent for urea. This percentage is based on the reduction in green to oven-dry shrinkage. He found that the relative humidity in equilibrium with a saturated common salt solution was 78 percent; that for a 20 percent saturated solution was 96 percent.

A study which is more directly applicable to an analysis of drying stresses in treated lumber was directed by Stamm (44). One portion of his study dealt with the relationship among shrinkage, relative humidity, and salt concentration in white pine. (See Fig. 2.) The vertical lines labeled I through IV in Fig. 2 indicate the initial relative humidity conditions of the tests in this study as will be discussed later. It should be noted that the curve for the pine treated with a completely saturated salt solution is not greatly different from the curve for pine treated with a 14 percent saturated solution. It can be seen from this curve that pine treated with the 2-gram solution would start to shrink when the relative humidity



(From Stamm)

Fig. 2. Shrinkage-vapor pressure curve for sodium chloride-treated white pine.

dropped below about 94 percent. Pine treated with a saturated solution would not start to shrink until the relative humidity dropped below 76 percent.

In order to investigate the shrinkage-relative humidity relationship further, data from Kollmann, Paten, and Stamm were combined in Fig. 3. Strictly speaking, it is not entirely correct to combine this information since different species and testing procedures were involved. It is interesting to note, nevertheless, that the curves from Kollmann and from Paten are quite similar except between 0.7 and 0.8 relative vapor pressure.

Chemical Seasoning

The use of chemicals to aid in the seasoning of lumber is not new. In the early 1900's in Australia, lumber was treated with cane sugar to reduce checking. This was then known as the Powell Process. Other low grade sugars were used as seasoning agents in this country about that same time. In parts of Europe during the 1800's timbers were sometimes soaked in sea water to reduce splitting. In the last twenty years a number of chemicals have been suggested and investigated as possible seasoning agents. These include common salt, urea, invert sugar, molasses, diethylene glycol, and urea aldehyde. Of these, sodium chloride preparations and urea preparations have been used on a wide commercial basis. The others have been rejected because of cost, difficulty in application, change in the color of wood, or other difficulties. Personnel of the U.S. Forest Products Laboratory have conducted a number of investigations (35) (37) (48) into the use of chemical seasoning agents.

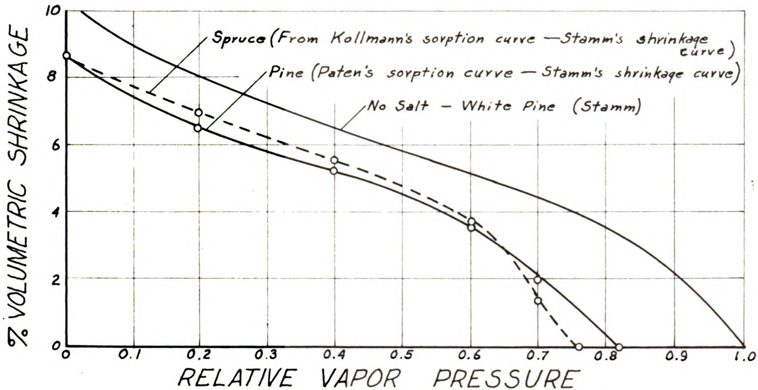


Fig. 3. Shrinkage-vapor pressure curve for sodium chloride-treated pine and spruce.

There are several possible methods of applying the chemical to the lumber: spray, dip, soak, and dry spreading. The spray or dip methods are preferable from the standpoint of labor costs involved. However, they have not proven very successful (13) (24) due to the fact that only a small amount of the chemical is retained in the lumber. Starch has been added to the spray or dip solution in an attempt to increase the retention of the chemical, but only very small benefits have resulted from this procedure. The soak method is prohibitively expensive due to the time and equipment involved. Dry spreading is the primary method of application used commercially today. The dry salt is usually spread with a large "shaker-box" which holds 15-20 pounds of salt. The lumber is then bulk-piled until the salt has disappeared.

There are several disadvantages to the use of a sodium chloride preparation. The major objections from the standpoint of furniture or millwork manufacture are difficulties which occur in the hi-frequency gluing and in the finishing of "salted" lumber. Reduction in strength a tendency to "sweat" under conditions of high humidity, and a change in the sorption characteristics of the lumber are also results of such treatment. There would seem to be no solution to the problem of the hi-frequency gluing of salt-treated lumber. As far as the writer has been able to determine very little work has been done (18) regarding the finishing of such lumber. A few small scale studies in Australia and in the United States (5) do not indicate finishing difficulties result from salt treatment, but furniture manufacturers report such difficulties. It is possible that below a certain salt-concentration level finishing problems would not occur. Since the mechanism of finishing failures due to salt is not understood, this is only speculation.

In the last twenty years most of the research concerned with chemical seasoning has dealt with either urea or sodium chloride preparations. Another possible chemical seasoning agent is polyethylene glycol-1000. The use of this chemical in the drying and stabilization of walnut gunstocks is discussed by Mitchell and Wahlgren (31). No information has been published on its use as a seasoning agent for lumber.

During World War II urea came into use in both the south and west to reduce surface-checking which was seriously degrading the stock in some areas. In the west, urea was used on Douglas fir (19) and in the south it was used on southern pine and cypress (4). About this same time in England (13) (14) the use of urea to reduce degrade in several refractory species was investigated.

Urea seasoning was largely discontinued after World War II. This was reportedly due to a number of factors. The most important of these was that the drying practices were improved so that it was no longer necessary to use urea to reduce checking. Also, of course, such treatment added to the costs and was not believed to be economically justified. Urea solutions are still used locally to reduce checking of green softwoods shipped to arid regions of the country. Urea treated lumber is required by many architects in the Phoenix, Arizona area (1).

The patent for the sodium chloride preparation now sold under the name "Lumber Cure" was issued in 1948. This preparation is composed of about 98 percent common salt and the remainder is composed of borax, disodium phosphate, and sodium sulphate. The additives are intended as corrosion inhibitors. Despite the difficulties which may be encountered from the use of this preparation, as already mentioned, it enjoys widespread use in the south.

A great many articles have appeared discussing the use of this sodium chloride preparation as a drying agent (7) (8) (25) (26) (29) (48). It has been shown that the use of salt on thick refractory species which are to be air-dried significantly reduces the amount of seasoning degrade. It is unusual for such species and thicknesses to be kiln-dried green from the saw due to the long drying time required. In the above mentioned studies the primary concern was for the reduction in seasoning degrade. It was also incidentally noted that the salt affected the air-drying rate slightly. However, in some cases the drying rate was apparently accelerated and in other cases it was retarded.

Preservative and Fire Retardant Salts

The resistance of wood to decay and fire is sometimes improved by impregnating the wood with a single or a combination of salts. Some salts, such as chromated zinc chloride, act as both preservatives and fire retardants. These water-borne preservatives are generally used for wood which is not to be exposed to leaching, and which must be clean, odorless, and paintable. The wood usually is treated by one of the pressure processes. In the case of fire retardants rather high retentions of 2 to 6 lbs. per cu. ft. are required so the full-cell process is often used. Considerable amount of water is thus forced into the wood. This water must be removed by kiln-drying if the wood is to be used for interior trim or construction.

A number of proprietary water-borne preservatives and fire retardants are used in this country and in Europe. Of these, it has been noted that Minolith, Flurasil, and Non-Com treated wood have different drying characteristics than untreated material. Kollmann (22) investigated the sorption properties of wood treated with a variety of proprietary salts used in Europe. No data have been published regarding the sorption characteristics of the recently developed fire retardant, Non-Com. Several people who have worked with this salt have noted, however, that the sorption properties of wood are affected.

Drying of Chemically-Treated Lumber

Seasoning chemicals change the drying characteristics of lumber thus reducing surface-checking; this change in drying properties might make possible the safe drying under severe drying conditions. Olinger (33) and French (15) have investigated this possibility in urea-treated oak. Olinger treated oak with about 100 pounds of urea per M bd. ft. and then dried the stock at a relative humidity of 85 percent and a temperature alternating between 160° F. and 120°F. Both the treated stock and the untreated controls were seriously damaged by checking and honeycombing. There was found to be only 4 percent less degrade in the treated material. In order to increase the chemical retention which Olinger obtained, French treated the lumber with dry urea crystals rather than a urea solution. French used a schedule similar to that of Olinger and found the amount of degrade was not appreciably reduced.

Lund and Taras (24) studied the accelerated drying of sodium chloride-treated lumber using elevated temperatures. They dried the treated lumber at a constant dry bulb of 180° F. The initial relative humidity was varied between 83 percent and 92 percent. They were successful in drying one-inch thick green white oak in ten days. However, only about half of the boards were free of honeycomb. They also found that "dry-salting" gave much better results than did dipping in a salt solution.

As far as the writer has been able to determine no work has been done on the drying characteristics of water-borne preservative or fire retardant treated wood.

EXPERIMENTAL PROCEDURE

Selection and Preparation of Samples

Northern red oak (*Quercus borealis* Michx.) was selected as the species to be used throughout this study. Oak is one of the woods on which chemical seasoning agents are used, and this particular species is available locally in the form of high quality logs. The logs were obtained from three different sites in southern Michigan. Black oak is also common in this area; the differentiation was made primarily on the basis of the bark. In one case the fruit was also checked. The ten high-quality logs used in this study were from 14 to 20 inches in diameter.

Nominal 1 1/2-inch thick, flat-sawn, heartwood sample boards were cut from the logs. The actual thickness of the samples varied from 1.63 to 1.75 inches. Five-foot long sample boards were selected which were apparently free of knots, decay, and tension wood. In some cases a small amount of sapwood was allowed on two corners of the boards. All boards were ripped to a 6 3/4-inch width. The growth rate varied from seven to ten rings per inch among the sample boards. The average oven-dry specific gravity of the samples was 0.59, with a range of from 0.56 to 0.61. There was no significant difference in the specific gravity among the samples used in the various tests or among the samples within a test. It thus appears that the sample can be considered homogeneous.

It did not seem advisable to investigate the effects of more than one salt due to the time which would be involved. The commercial sodium chloride seasoning agent was selected to be used throughout these tests. This chemical was chosen since it is the most widely used chemical seasoning agent in the United States, and because more is known about the sorption and shrinkage characteristics of common salt-treated wood than wood treated with other salts or organic compounds.

The tests were carried out in a 72 cu. ft. drying chamber constructed inside an internal-fan cross-circulation kiln. The chamber was built in such a way that all boards could be easily removed for periodic testing. The kiln was baffled so that the air flow was through the drying chamber and then past the wet and dry bulbs of the recorder-controller. By operating only one fan, an air velocity of 500 to 550 feet per minute through the drying chamber was obtained. This approaches the ideal air speed for maximum drying of about 600 feet per minute. In most commercial kilns the air speed varies from 250 to 350 feet per minute. The direction of the air flow was not reversed during the tests. The recorder-controller was checked with a mercury thermometer and water bath before the tests were begun. During the tests two hygrometers were used to check the recorder temperatures. The recorder and hygrometer dry bulb temperatures agreed within 3^{o} F., but the more important wet bulb depressions remained within 1^{o} F.

The sodium chloride preparation was applied in dry form to the test boards within an hour after the boards were cut from the log. The amount of salt to be applied per board was weighed out and applied with a shaker-box. The salt was applied on the bark side of the boards which were then placed one on top of the other.

Dummy boards, on which salt was also applied, were placed on the top and the bottom of six sample boards and this bundle was secured with steel strapping. These bundles were stored in a basement for from 7 to 14 days prior to kiln-drying. By the end of this period all the salt had diffused into the lumber. The storage time was varied to determine its effect on the salt concentration gradient.

Just prior to the beginning of a kiln-drying test the bundles were opened and the samples were cut to a length of four feet. Strips were taken from the discarded portion to determine the shrinkage, strain, salt concentration, and moisture content values prior to testing as will be described later. It was very important at this time and all through the testing to end-coat the samples with an efficient coating. Several types of end-coatings were tried and tested. These included a commercial resin base coating, a commercial latex base coating, aluminum paint under aluminum foil, and a mixture of two pounds of No. 320 aluminum powder per gallon of spar varnish. The efficiency of the end-coatings was evaluated by determining the moisture contents at various distances from the end of the boards after 24 hours of drying. The aluminum powder-varnish mixture was found to be the most efficient end-coating tested.

Experimental Design

The objective of this study was to evaluate the effects of salt on the drying characteristics of red oak. The drying characteristics considered were drying stresses, moisture gradients, drying times, and set development. It was felt that the effect of the quantity of salt had to be considered. Therefore, the quantity of salt was varied between treatments. In some cases the actual salt concentration was determined by chemical analysis. Table 1 is a summary of the tests showing the initial kiln conditions and the amount of salt used in each test.

The objective of test I was to compare the drying characteristics of untreated and salt-treated red oak when kiln-dried following the moisture content schedule recommended by the U.S. Forest Products Laboratory. The conditions of this run are described in Fig. 6. Although this schedule should not necessarily be considered the optimum for 6/4 red oak it was used since it is a standard and recognized procedure. Two levels of salt treatment were used in this test. The heavier treatment of 210 pounds per M sq. ft. corresponds to the salt manufacturers' recommendation of 140 pounds per M bd. ft.

In all the tests the initial dry bulb temperature was kept constant. Since other workers have met with little success in accelerating the drying of treated lumber with elevated temperatures, it was felt that accelerated drying might better be achieved by lowering the relative humidity. This point was discussed in the "Review of Literature".

The objectives of tests II, III, and IV were to evaluate the effect of the initial relative humidity on the drying characteristics, and also to determine the most severe drying conditions which were safe for the various levels of salt treatment. These tests were continued only until the surface stresses had obviously reached the maximum and until it was certain that no further surface-checking would occur.

TABLE 1. Outline of the Drying-Tests and the Levels of Salt Treatment Used in Each

Kiln Run (Test No.)	Initial Kiln Conditions		Subsequent Schedule	Treatment Symbol	Lbs. of Salt Per M Sq. Ft.
	Dry Bulb Temp. (°F.)	Wet Bulb Temp. (°F.)			
I	110	106	See Figure 6	A	0
				B	75
				C	210
II	110	100	See Figure 7	D	90
				E	150
				F	210
III	110	94	See Figure 7	G	90
				H	150
				I	210
IV	110	88	See Figure 7	J	45
				K	90
				L	150
				M	210
V	110	94	See Figure 8	N	45
				O	90
				P	210

From tests II, III, and IV the safe initial drying conditions for sodium chloride-treated 6/4 red oak were determined. This initial condition was used as the first in the sequence of drying conditions of test V. This relative humidity was decreased as soon as surface strains indicated that the danger of surface-checking had passed. The dry bulb temperature was not greatly increased until the center of the stock was below 30 percent moisture content. After this time the danger of developing honeycomb is very slight.

Throughout all the tests two replications were provided for all treatments. No prior information was available on the "within" variation which might be expected for the strains or shrinkages. No desired degree of accuracy was assumed when deciding upon two replications; rather it was determined by the length of time needed to perform the daily testing. Strain, shrinkage, and moisture content were determined at eight points through each sample. Thus, two values were obtained for each of the four depths. It was shown (see Tables 5, 6, and 11) that there was not a significant difference in the strain or salt concentration between the top and bottom surfaces, i.e., strips 1 and 8. These values were therefore combined, giving four values from which to determine the mean strain or salt concentration at a given depth in the board. The data points shown on the graphs thus represent the mean of four measurements.

Determination of Strain

The strip technique, similar to that used by McMillen, was employed to obtain the approximate stress condition in the samples. In making this test a one-inch section was cut from the board. A four-inch piece was then cut from the center of the section. Since the assumption of the existence of uniaxial tension or compression in a slice is more nearly true at the center of the width, only the center portion of the width of the board was used in obtaining the strain measurements. The length of this piece was measured at eight points, from one face to the other, using a dial-gauge jig. This four-inch piece was then cut on the bandsaw into eight strips, such that the saw cuts were parallel to the surface of the board. (See Fig. 4.) The length of each slice was then re-measured. The elastic strain for each slice was thus obtained. (See Fig. 5.) Measurements were made to the nearest 10^{-3} inches. More accurate measurements would have little value in this technique, due to the relatively uneven surface on which the measurements must be made.

The strain measurements were taken every 24 hours for the first 4 to 6 days of each test. After this period the rate of change in the strain was less, therefore, the measurements were taken every 48 hours. These measurements were also taken before and after the equalizing and conditioning period. Although the strains for all eight strips were measured, it was later found that the behavior of the surface strips, i.e., numbers 1 and 8, and the center strips, i.e., numbers 4 and 5, were of primary interest since the maximum and minimum strains occur in these layers. The figures in this paper deal with the behavior of only these layers.

Strip technique measurement errors can be rather serious due to the non-elastic change in length of the strip between the time it is cut from the sample and the time the measurement is made. The non-elastic change in length is due to both a change in moisture content and a thermal contraction, and is more serious at higher temperatures than when the kiln is operating at 110° F.

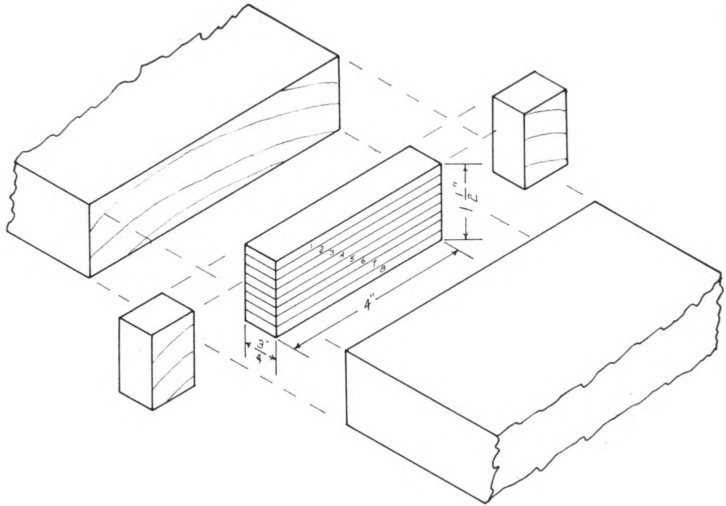


Fig. 4. Location of the eight test strips in a drying sample.

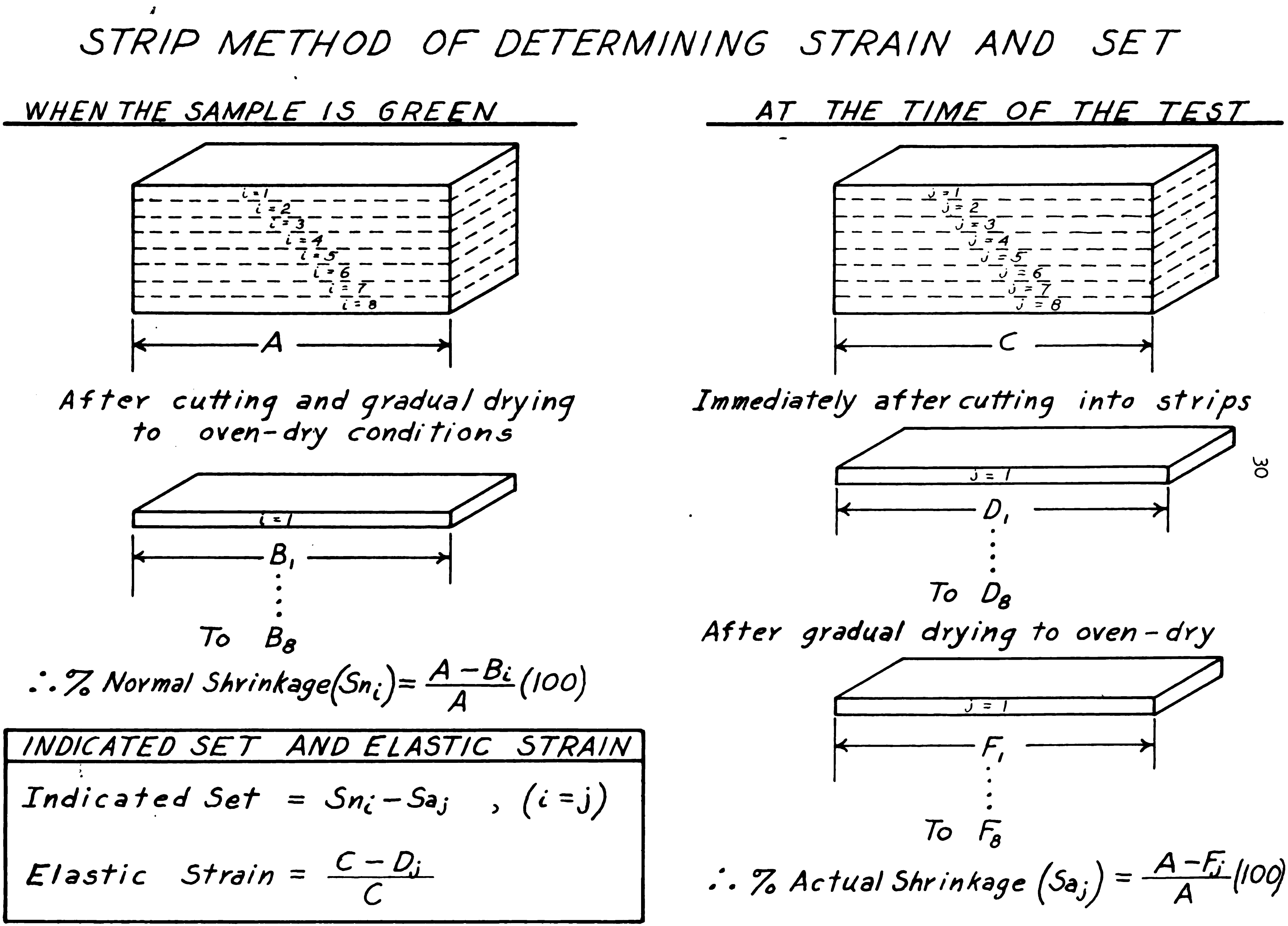


Fig. 5. Method of determining elastic strain and set.

A correction procedure was devised which should improve the accuracy of the strain determinations. Let S be the stress in the tangential direction, E the modulus of elasticity in the tangential direction, e the true elastic strain, and e' the measured elastic strain. Let the subscripts 1, 2, 3, and 4 represent the depth of the strips, 1 being the surface strip, 4 the center strip, etc. Now, since the strips are the same thickness:

$$S_1 + S_2 + S_3 + S_4 = 0.$$

Therefore,

$$E_1 e_1 + E_2 e_2 + E_3 e_3 + E_4 e_4 = 0.$$

The E values are dependent upon the temperature and the moisture content of each strip and, therefore, are not equal. If the error is the same in all strips then the difference between the elastic strain readings will not change during the measuring process, or:

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

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

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

These values of D are then the differences between the strains which are actually measured. From these last four equations, which are independent, an expression for e_1 can be obtained.

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

The other "true" strains can then be obtained since:

$$e_2 = e_1 - D_1$$

$$e_3 = e_2 - D_2$$

$$e_4 = e_3 - D_3$$

The values of E used for these corrections were obtained from the work of Youngs (50). Three assumptions are necessary when using this correction procedure: (1) that a uniaxial stress situation exists, (2) the errors due to temperature and moisture content changes are the same for all strips, (3) that the E values determined by Youngs for untreated lumber are also valid for treated stock.

It was not necessary to correct all the strain readings by the use of the above procedure. Until the kiln temperatures exceeded 130° F. the corrections made by using this procedure were less than 0.0005 in.; no corrections were deemed necessary since the precision of the measuring device was 0.001 in. At a kiln temperature of 180° F. these corrections amounted to from 0.0008 in. to 0.0020 in. so that it was felt the use of this procedure was required.

The elastic or instantaneous strain was obtained by the methods just described. This instantaneous strain could be related to stress by means of the modulus of elasticity E, if E were known. This holds true whether dealing with stresses in the elastic or beyond the elastic range. It has been shown (16) that in most cases the instantaneous unloading process exhibits linear elasticity. A hysteresis effect may alter this slightly, causing the apparent E in unloading to be less than in loading. In this study no attempt was made to relate the strains to the corresponding stresses since the perpendicular-to-grain modulus of elasticity for treated oak has not been determined.

Assuming that E were known, at least two inherent difficulties would be encountered when determining drying stresses. The first is that a three dimensional stress situation actually exists rather than the uniaxial one assumed. The stresses in the longitudinal direction are small except near the ends of the boards. The stress in the radial direction, in a flat-sawn board, is also small at the beginning of the run (51), but it quite probably would be a significant factor toward the end of the drying cycle. The second difficulty is that the stresses computed from the elastic strain represent the average stress in the strip. This is apparent when it is recalled that the indicated strain is a response to the stresses existing when the strip is cut. Early in the drying cycle the moisture and stress gradients are very steep near the surface of the board. Therefore, the tensile stress at the surface may be several times as high as the average tensile stress in the surface strip.

Determination of Moisture Content

After the elastic strains were measured the strips were weighed on a direct-reading automatic balance. All eight strips could be weighed on this balance in less than two minutes. The strips were then gradually dried to the oven-dry condition. The weights were again determined and the moisture content of each strip calculated.

There was not a significant difference in the moisture content of strips from corresponding positions on the top and bottom of the sample. Therefore, an average moisture content was obtained for each depth in each treatment from two strips in each of the two replications.

The presence of salt in the strips affects the calculated moisture content because the oven-dry weight includes the weight of the salt. In this study no correction was felt to be necessary to compensate for the salt content. The moisture content was computed in the usual way. In most cases the salt content of even the surface strips was less than 5 percent of the oven-dry weight of the wood. At this salt content the apparent MC is 48 percent when the actual

MC is 50 percent. When the actual MC is 10 percent the apparent MC is 9.5 percent. The important moisture content comparisons were between samples all containing salt, therefore, the comparison error would be much less than in the example above.

Determination of Set

Set is a permanent strain which remains in a body after the stresses have been released. This permanent deformation results from either stress beyond the proportional limit or irrecoverable creep under long-time loading at stress below the proportional limit.

The importance of a knowledge of set to drying stress analysis is threefold: (1) the development of tension set in the surface layer and compression set in the core of a board affect the magnitude of stresses which develop after stress-reversal, (2) irrecoverable strains are associated with stress relaxation and therefore affect the initial stresses, (3) prior to stress reversal the magnitude of set is an indication of the integral of the stresses existing during the drying cycle.

The difference between the percent of green to oven-dry shrinkage of a strip and the unstressed shrinkage of a like strip was used in this study as an indication of set. (See Fig. 5.) After the strips were cut from the four-inch long sections and the elastic strain measurements taken they were placed in a series of humidity chambers and gradually dried. The drying of the strips was extended over seven days in conditions starting at 75 percent relative humidity in order to avoid producing further drying stresses. When dry, the length of the strips was re-measured. The shrinkage in the width of the board was measured throughout the drying cycle. From board shrinkage and strip shrinkage data the green to oven-dry shrinkage of each strip was calculated. The difference between the total shrinkage and the shrinkage of an unstressed strip from the same location in the same board was called the percent of indicated set. The shrinkage of the unstressed strip was obtained before the kiln run was begun.

Several workers (36) (27) (20) have used this method of estimating set during the drying process. The basis of this procedure is that irrecoverable creep does not affect the amount of shrinkage which takes place in a given specimen. If the specimen size is reduced by the occurrence of creep then the percent of total shrinkage based on the new length is increased. Conversely, if the specimen size is increased, then the percent of total shrinkage based on the new length is decreased. Kauman (20) points out that the change in percent shrinkage is affected by collapse, stress, and what he calls the "Poisson Effect". The Poisson effect was noted by Perkitny who found that wood restrained in a particular direction during swelling would swell more than normal at right angles to that direction. The perpendicular-to-surface stresses during the early stages of drying are quite low; therefore, this characteristic would have little effect on the indicated set.

Determination of Salt Concentration

Mohr's method of chlorine analysis for near-neutral solutions (40) was used to determine the sodium chloride concentration in the strips. The strips were ground by hand into a fine powder. The powder was then washed repeatedly with deionized water to remove the salt. It was necessary to wash the powder at least five times before all the sodium chloride was removed. The salt content of the washing solution was then determined using Mohr's method. The salt concentration was expressed as a percent of the oven-dry weight of the wood.

Salt determinations were made for both the 210 pound and the 90 pound (75 lbs. in test I) treatments. The salt content for other levels of treatment could be extrapolated if desired. In test I the salt concentration was determined four times during the drying cycle: at the start, after eight days, after 20 days, and at the end. In this way the movement of salt during the drying cycle could be studied.

In tests II and III, the salt concentration was determined at the beginning of the test and after eight days of drying. Here it was the effect of the initial relative himidity on the salt movement which was of interest. Finally, the salt concentration at the beginning and end of test V was determined.

A problem was encountered when analyzing the results due to the fact that there was considerable variation in the total salt content of the four-inch long sections cut from boards treated with the same amount of salt. This variation was presumably caused by uneven application. Comparisons between threatments with the same nominal amount of salt, but dried under different conditions, were obscured by this variation. To overcome this difficulty the percent salt concentrations were converted to relative salt concentrations by the relation:

$$\text{Relative salt concentration for a given depth} = \frac{\text{\% salt conc. in the 2 strips from that depth} \times \text{Dry wt. of these strips}}{\text{Gms. of salt in all 8 strips}}$$

Such a procedure is justified only if it can be shown that the salt concentration gradient is not affected by small changes in the amount of salt applied. The evidence presented in Table 11 and in Fig. 15 justifies the use of the relative salt concentration comparisons.

Even more than doubling the amount of salt, i.e., 90 lbs. to 210 lbs., does not cause a significant difference in the relative salt concentration at like times and conditions.

RESULTS

Behavior of Elastic Strain

The perpendicular-to-grain tension strains developed rapidly in the surface strips of the untreated material in test I. (See treatment A in Fig. 6.) The maximum tension strain occurred during the fourth day of drying. At this time there were small surface-checks in several of the samples indicating that the maximum allowable strain had been approached. The strain of the surface strips rapidly decreased after the fourth day. The shell went into compression on the seventeenth day. The maximum strain and point of strain reversal in the center strips lagged somewhat behind the corresponding points for the shell.

From the time of reversal until severe casehardening developed, during the last two days of the run, there were no severe strains in the core.[1] This suggests that tension-failure type honeycomb is not the limiting factor of this particular schedule. It indicates that if surface-checking is avoided during the first portion of the run there is no danger of any type of honeycombing when using this schedule on this type of untreated material. The strain pattern was similar to the results of McMillen and of Loughborough. There was a notable difference, however, during the period from 24 to 30 days. During this time the shell again went into tension.

[1]In this discussion the strains referred to are the strains recorded when the strips are cut free. This is, of course, not the strain developed in the core while still a part of the board.

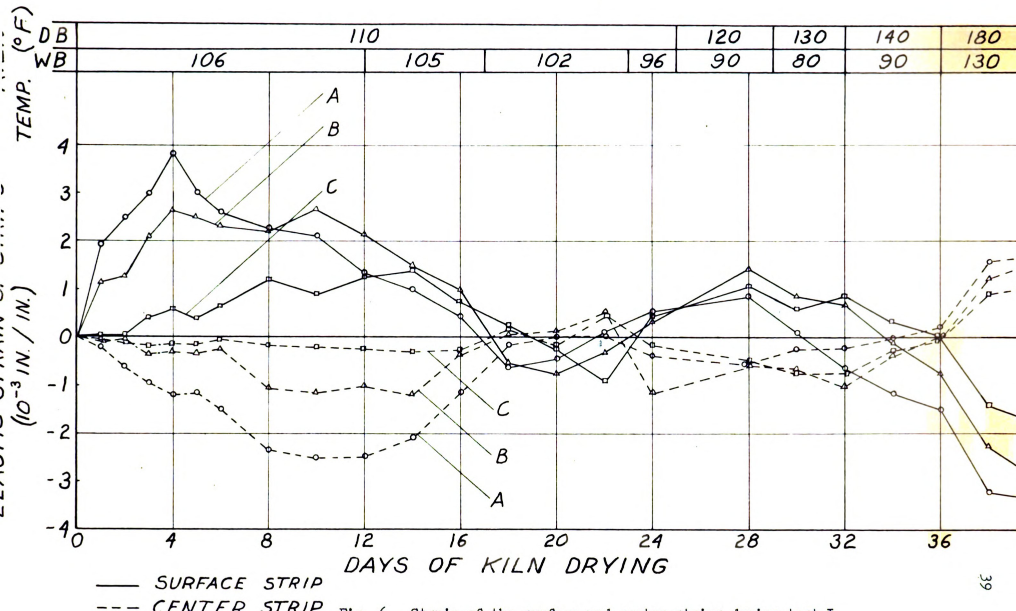


Fig. 6. Strain of the surface and center strips during test I.

In test I the surface strips from treatment B, i.e., 75 lbs. of salt per M sq. ft., exhibited a strain pattern similar to that for untreated material with one main exception (See Fig. 6.). The difference was noted during the critical period of the first four days of drying, during which time the maximum tension strain in the shell was reduced by about one-third. No surface-checking occurred in the case of treatment B or C (See Table 2.). The elastic strain in the core was affected to a greater extent by the salt than was the surface strain. The samples treated with 210 lbs. per M sq. ft. showed a much less severe strain development prior to stress reversal than those of treatment B. From stress reversal to the end of the run the strain pattern was about the same as for untreated stock, with the exception that casehardening was less severe. The high tension stresses which have been predicted (5) in the core of the treated samples due to anti-shrink effect of the salt on the surface, did not materialize.

The strains which developed in tests II, III, and IV (Fig. 7), during the first six to ten days of drying, show the same pattern as the untreated samples in test I. The strain measurements do not indicate that a decrease in the initial relative humidity causes an increase in the surface stresses (Table 6). Such an increase is evidenced, however, by the increasing occurrence of surface-checking as the relative humidity is lowered (See Table 2.). Also, it should be noted that as the EMC is lowered the moisture content gradient becomes steeper. This should result in a steeper stress gradient which would cause the surface stress to be higher at the same average stress.

Both the strain measurements and the occurrence of checks indicate that higher stresses are developed in samples treated with

TABLE 2. Drying Time and Elastic Strain of Surface Strips when Surface-Checks Appeared

Test No.	Treat-ment	Days of Drying When Checks Appeared	Elastic Strain of Surface Strip When Checks Appeared (10^{-3}in./in.)	Description of Largest Checks on First Day of Occurrence
I	A	3	4.25	3/4" x 1/32" on 3 of 6 samples
	B	no checking	----	-----
	C	no checking	----	-----
II	D	no checking	-----	-----
	E	no checking	----	-----
	F	no checking	----	-----
III	G	3	2.00	1/2" to 1" x 1/64" on 2 of 2 samples
	H	3	2.12	3/8" x 1/64" on 2 of 2 samples
	I	no checking	----	-----
IV	J	1	2.88	1 1/2" x 1/16" on 2 of 2 samples
	K	1	2.25	1/2" x 1/32" on 1 of 2 samples
	L	2	1.75	1" x 1/64" on 1 of 2 samples
	M	1	2.50	1" x 1/64" on 1 of 2 samples
V	N	1	2.38	1 1/4" x 1/16" on 3 of 4 samples
	O	2	2.75	3/4" x 1/32" on 2 of 4 samples
	P	no checking	----	-----

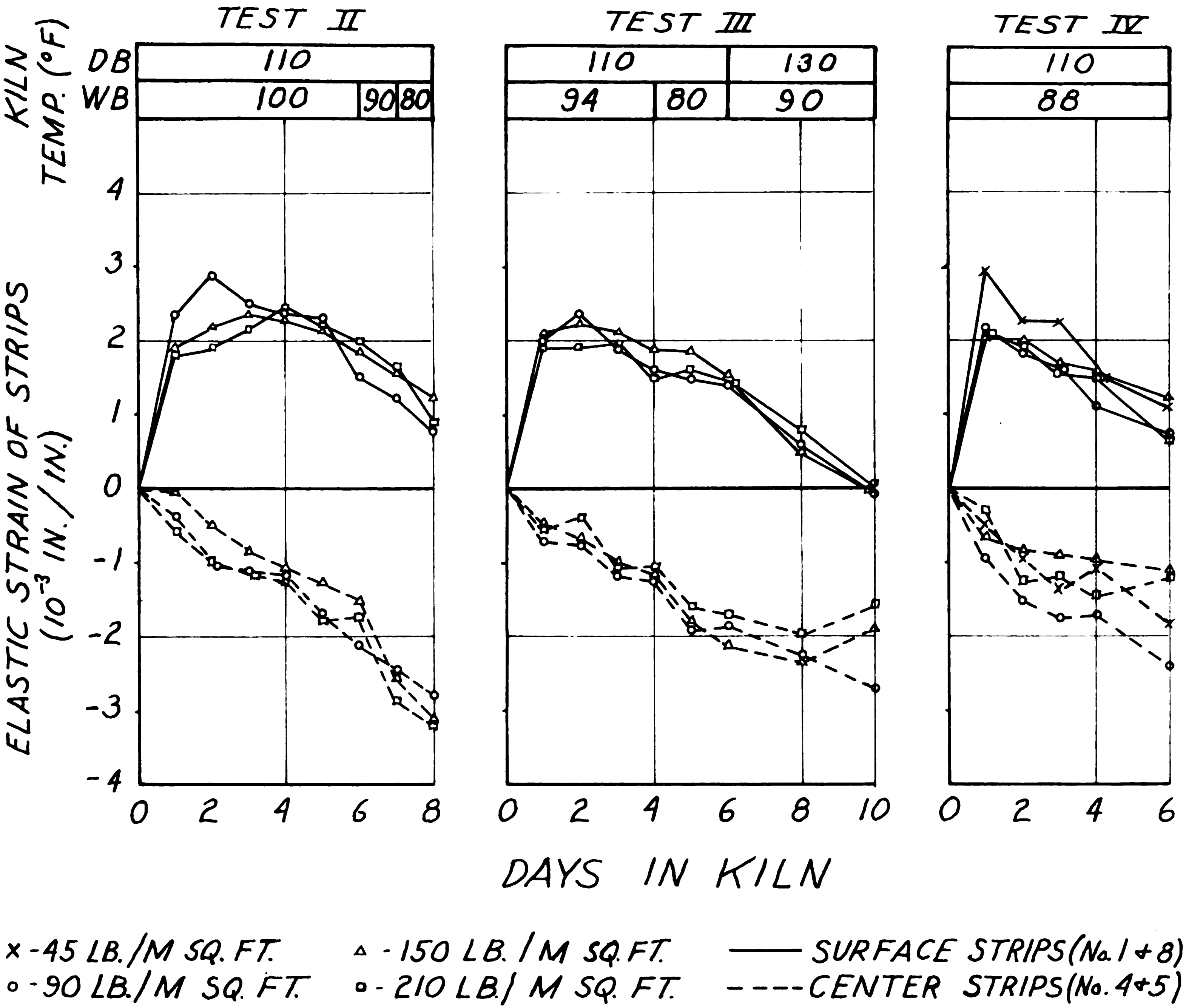


Fig. 7. Strain of the surface and center strips from three treatments during test I.

90 lbs. of salt per M sq. ft. than in those treated with 150 or 210 lbs. per M sq. ft. There was not a significant difference between the maximum strains of the 150 and the 210 pound treatments. (Table 6). As the initial relative humidity is lowered, the time for maximum strains to develop is decreased. On the basis of the occurrence of surface-checks serious enough to permanently damage the samples, it was found that the conditions of test IV were too severe for the 45 and 90 pound treatments.

The strains which were measured in the 45 and 90 pound treatments during test V (Fig. 8) followed the same general pattern as the untreated material in test I with one exception. Namely, the casehardening stresses began to develop immediately after stress reversal. The strain readings indicated that maximum tensile stresses in the 45 and 90 pound treatments were equal, yet more frequent and severe checking was noted in the 45 pound treatment. The relatively small strain readings of the 210 pound treatment during the early portion of the run are not in agreement with the findings in tests II, III, and IV. No explanation for this can be given.

The casehardening strains developed in test V are generally of the same magnitude as those in treatments A and B of test I. The 90 pound treatment in test V exhibited the same degree of casehardening as the 75 pound treatment in test I, despite the more severe drying conditions. The 210 pound treatment developed greater casehardening strains during the more severe drying conditions of test V, as would be expected.

The strains indicated before and after the equalizing and conditioning periods are illustrated in Fig. 9. Unfortunately, in test I

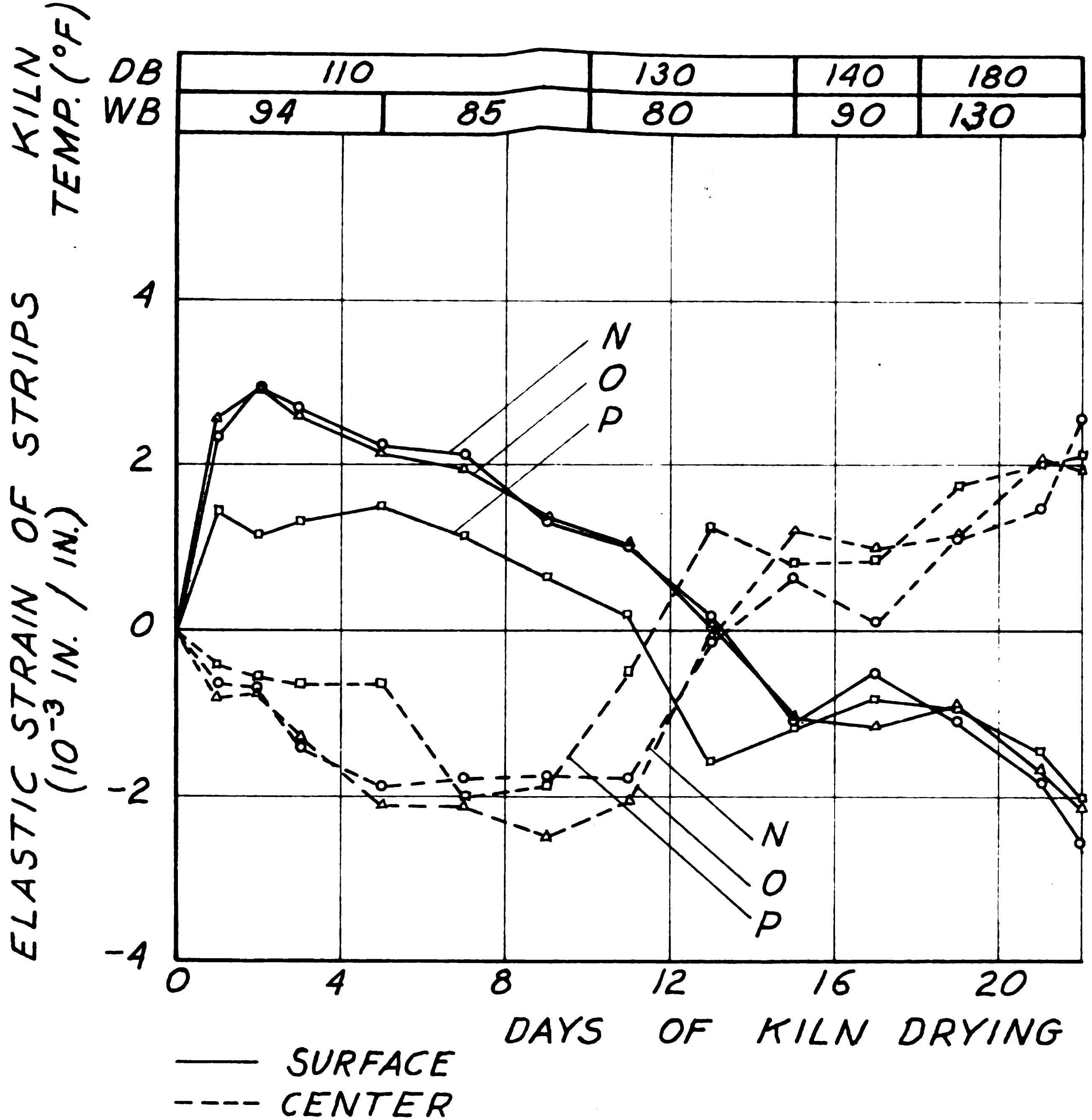


Fig. 8. Strain of the surface and center strips during test V.

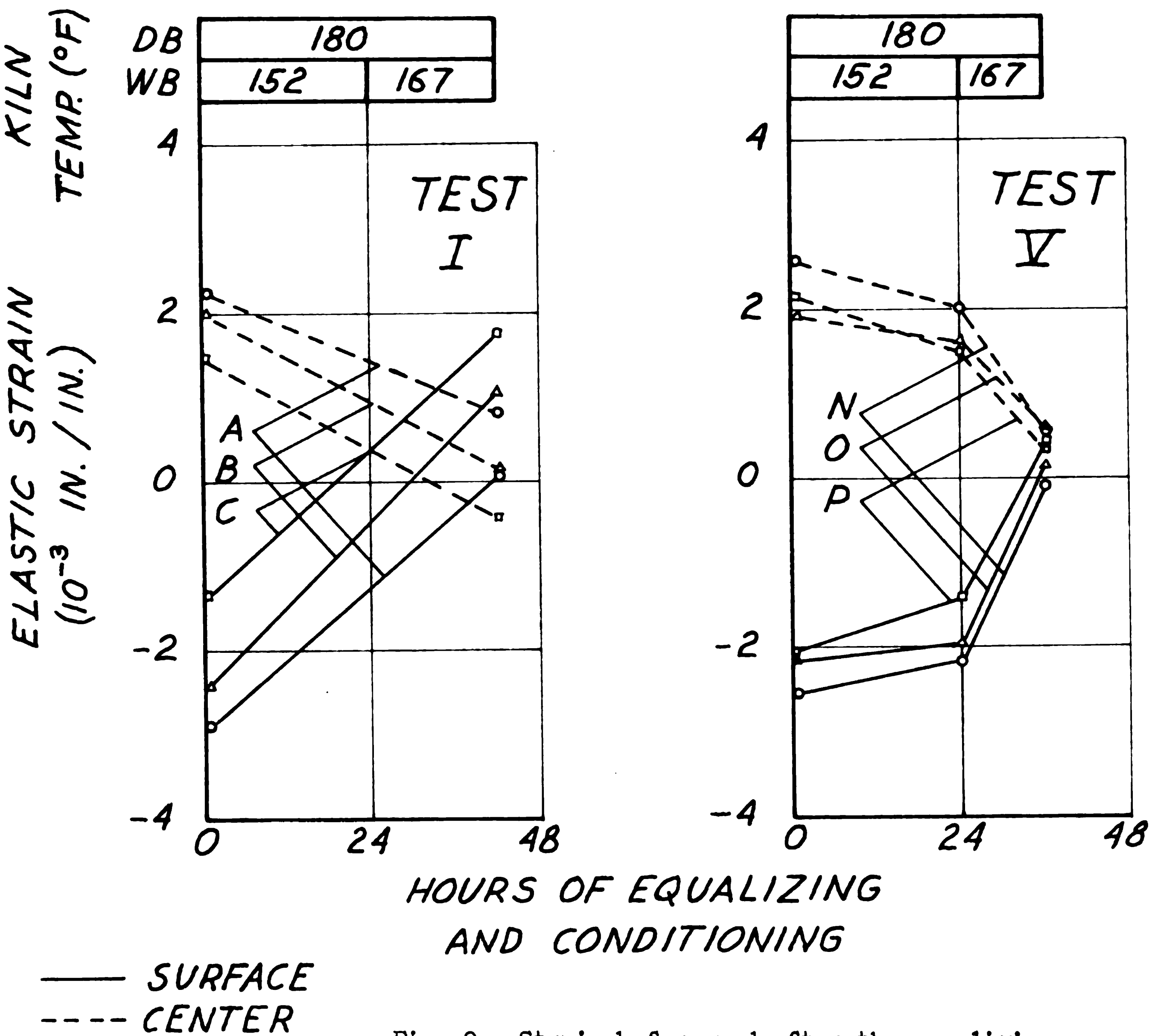


Fig. 9. Strain before and after the equalizing and conditioning periods in tests I and V.

no strain measurements were taken between equalizing and conditioning. As would be expected, the conditioning period in test I which was designed for untreated material was too severe for both treatments B and C; therefore, reverse casehardening was produced. The important fact is, however, that the change in stress during equalizing and conditioning was the same for both the untreated and treated stock. This suggests that a normal conditioning period could be easily altered for treated stock by changing the conditioning time rather than the conditioning temperatures.

In designing the conditioning period for test V the above findings were taken into consideration. An equalizing period of 24 hours was used in both test I and V, but the 18 hour conditioning period of test I was reduced to 12 hours for test V. It was found that this treatment produced complete stress relief for treatment O. The casehardening stresses in treatment N were not completely removed, while very slight reverse casehardening was produced in treatment P.

Moisture Content Gradients

The moisture gradients during test I are shown in Fig. 10. During the first 23 days of drying there was a difference of over 10 percent between the average moisture contents of the surface strips of treatments A and C. After this time the gradients of all treatments were very similar. Samples of treatment C exhibited an essentially flat gradient for the first 20 days of the run.

Fig. 11 shows the moisture gradients after two days of drying in tests II, III, and IV. After two days there was no significant difference between the surface moisture contents of the 150 and the 210 pound treatments. (See Table 8.) However, the MC of the 90 pound

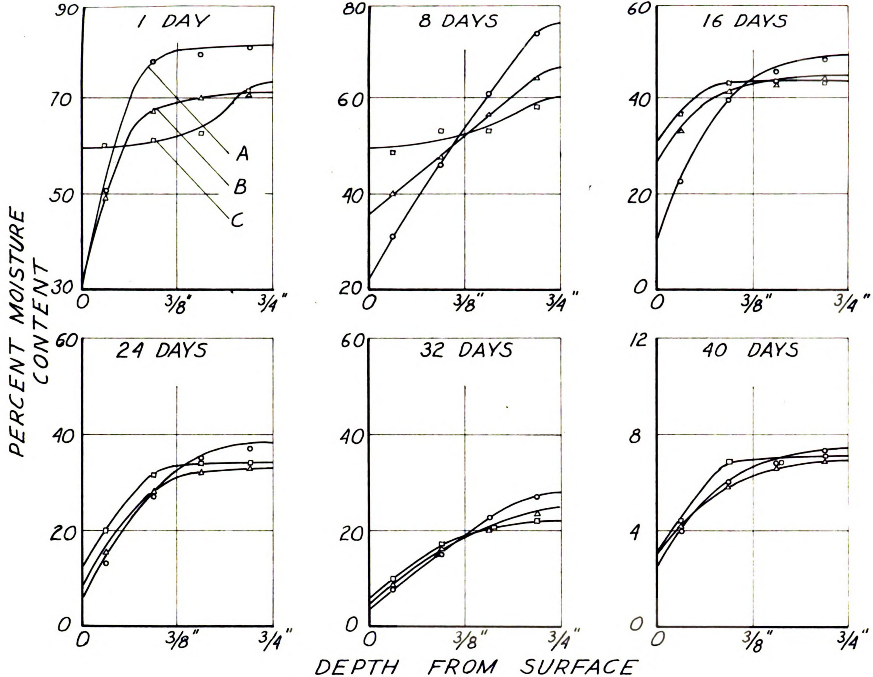


Fig. 10. Moisture content gradients during test I.

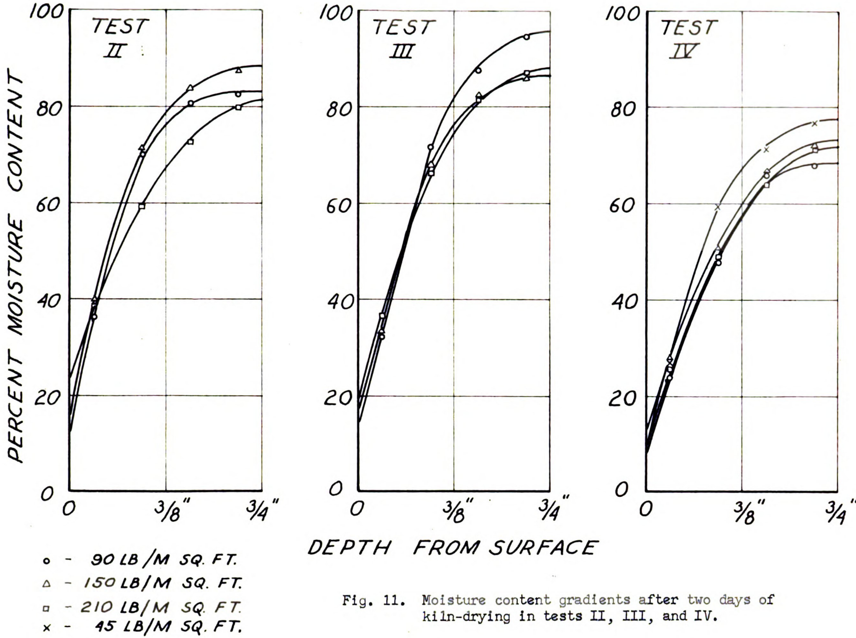


Fig. 11. Moisture content gradients after two days of kiln-drying in tests II, III, and IV.

treatment was significantly lower.

These results agree with the fact that the maximum tensile strain of the 90 pound treatment during tests II, III, and IV was significantly greater than the strains of the 150 and 210 pound treatments.

Indicated Set

In treatment A, a slight change in the green to oven-dry shrinkage of the surface and center strips occurred after only one day of drying (See Fig. 12.). Very little change occurred in treatment B until the 10th day of drying. The tension set in the untreated stock developed more rapidly than did compression set, but the opposite was true for the treated material. The amount of tension set in the treated stock remained very small throughout the kiln run; for the last 16 days of the run it was nearly zero. After the first 16 days, the compression set in the core of treatment B increased rapidly until the end of the test when it was about twice as high as the compression set in treatment A. The behavior of indicated set can be explained on the basis of the magnitude of the elastic strains up to the time of stress reversal. After stress reversal there does not appear to be a direct relation between set and the magnitude of strain.

The conditioning period in test I was found to remove both the tension and compression sets in treatment B. A small amount of compression set remained in the core of treatment A after conditioning, although the tension set on the surface was apparently relieved.

During test V (Fig. 13), set in both the shell and the core developed rapidly in all three treatments. The final set was approximately the same in tests I and V. The tendency of the tension set to

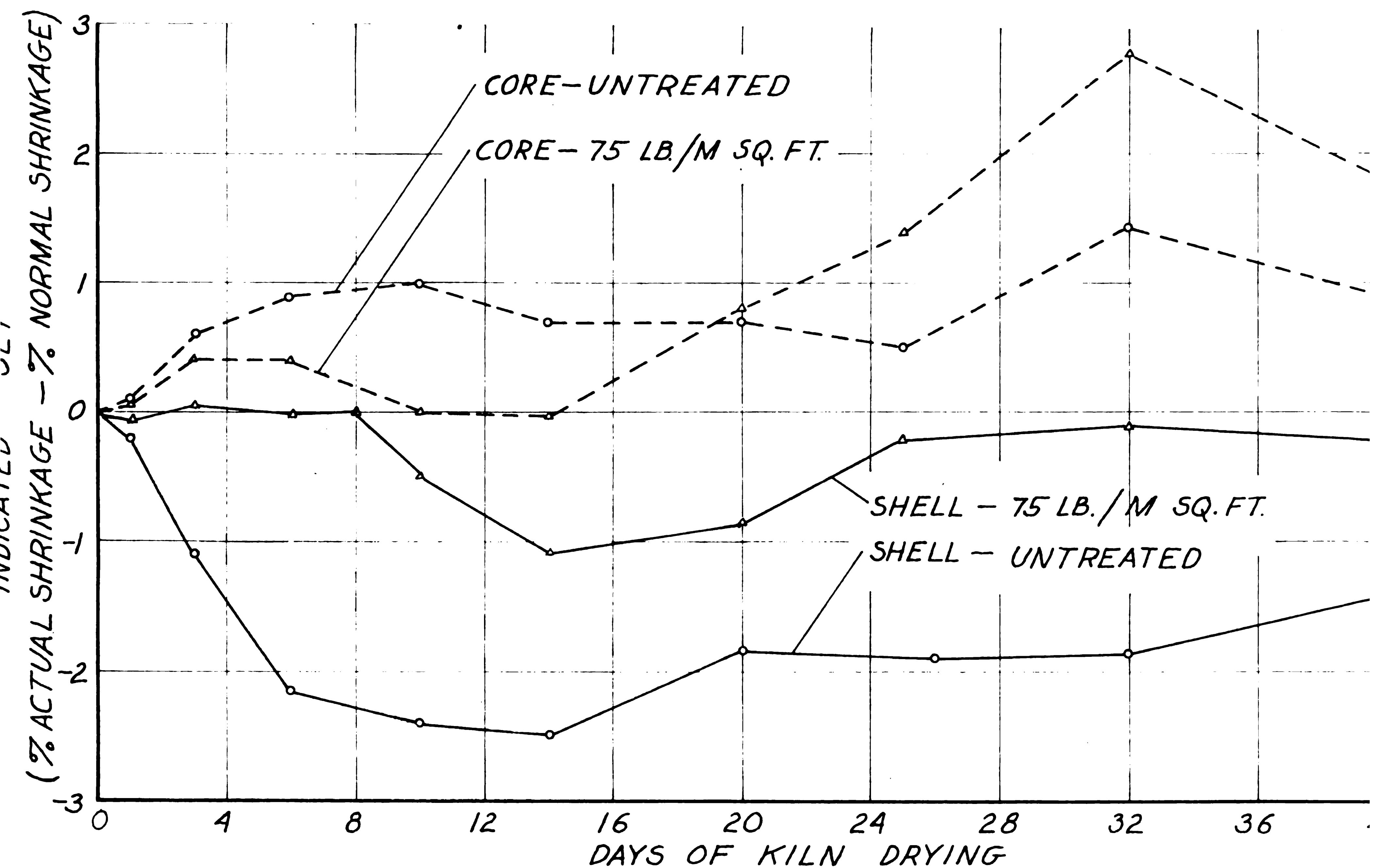


Fig. 12. Tension and compression set in treated and untreated boards during test I.

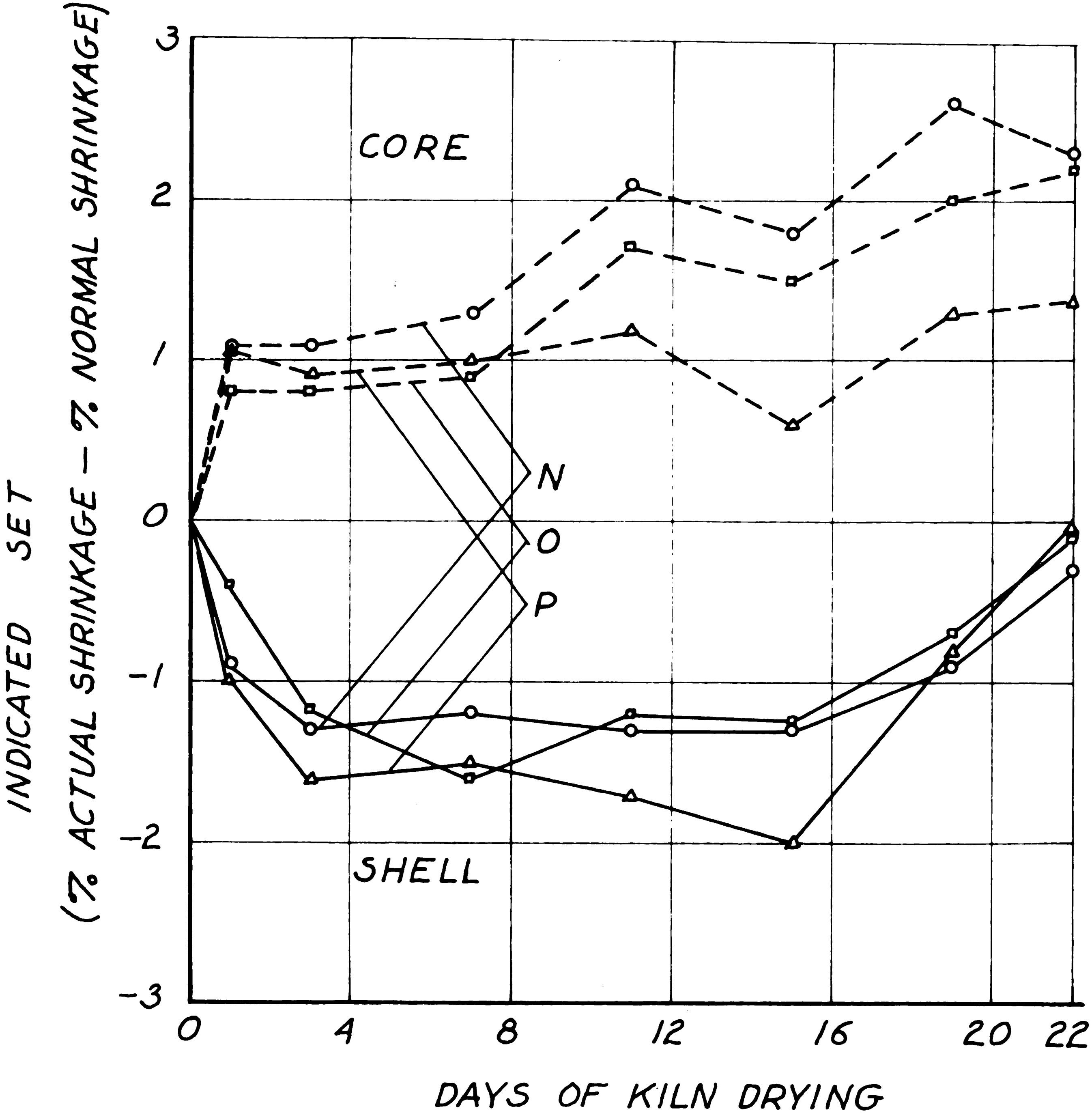


Fig. 13. Tension and compression set in samples with three different amounts of salt during test V.

be relieved and the compression set to be increased during the final stages of the run was again apparent in test V. The relief of the tension set on the surface can be explained on the basis of the compression strains present at the end of the run. However, in the core, increasing compression set was accompanied by increasing tension strain. These observations appear to be contradictory.

Fig. 14 illustrates the relationship between the initial relative humidity and the tension set of the surface strips. An analysis of variance (Table 9) indicated that the tension set in tests I and II was significantly less than the set in tests III, IV, and I-untreated. It can be seen that as the initial relative humidity decreased the amount of tension set increased. Presumably, this is a response to the increasing surface stresses which develop as the relative humidity is decreased. It should be noted that this increase in surface stresses was not indicated by the elastic strain measurements, but was indicated by the increasing occurrence of surface-checking.

Salt Concentration

The samples for the different tests were "dry-salted" and then bulk-piled for periods of time varying from 7 to 14 days. At the end of this period, the salt concentration gradient was determined. (See Fig. 15.) The salt gradient did not appear to change appreciably between one and two weeks of bulk-piling. In fact, after 14 days, the surface strips in test I had a slightly higher salt concentration than strips in other tests after shorter periods of piling. There was no statistically significant difference in the relative salt concentration of the surface strips after the different periods of bulk-piling (Table 11). Though all samples were bulk-piled in a room at constant

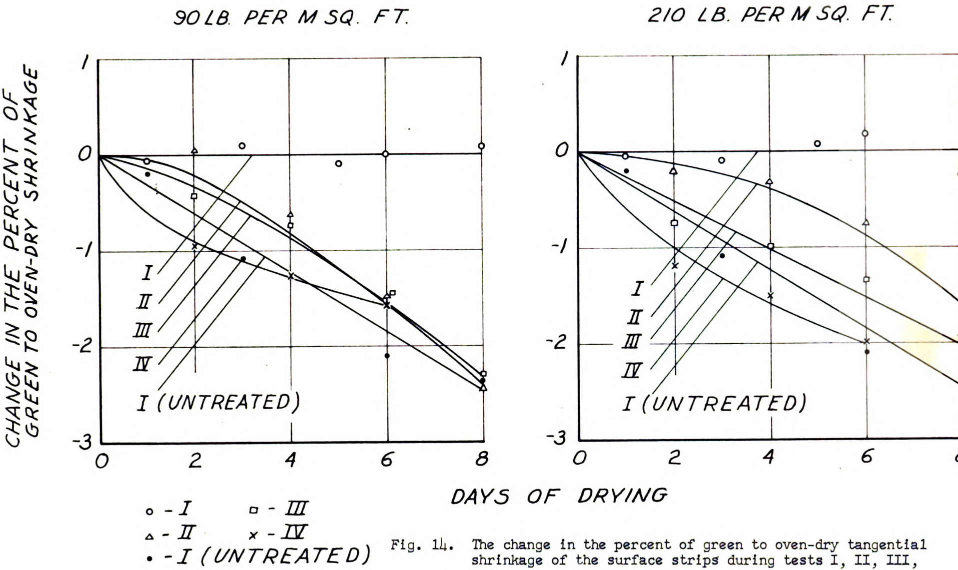


Fig. 14. The change in the percent of green to oven-dry tangential shrinkage of the surface strips during tests I, II, III, and IV.

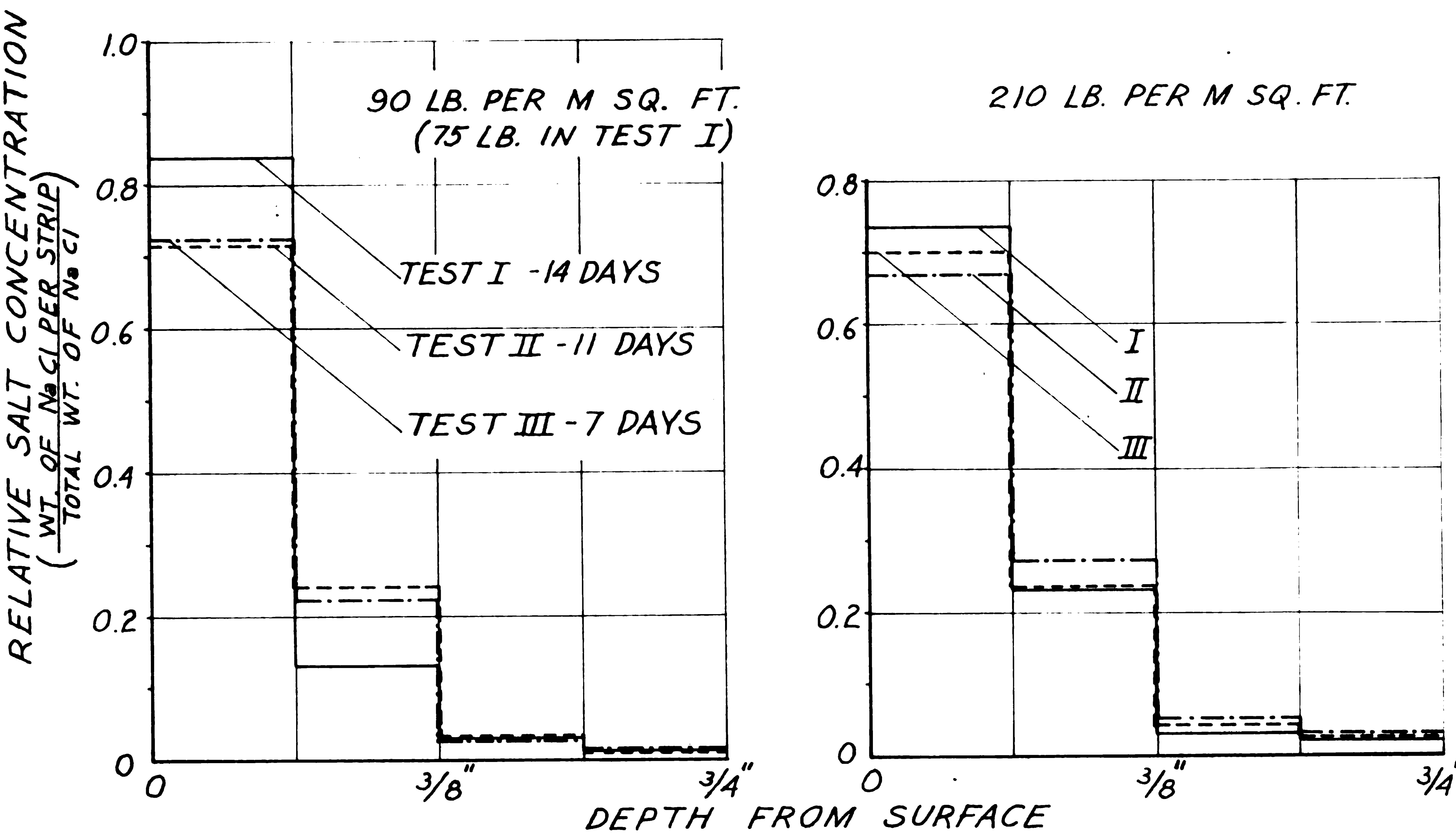


Fig. 15. Relative salt concentrations after bulk-piling for various periods.

temperature the samples in test I were frozen when the salt was applied. This probably accounts for any reduced diffusion. Although the tests are not precisely comparable as far as diffusion conditions are concerned, they do suggest that the movement of salt is slight during the second week of bulk-piling.

Although it might be expected that the salt concentration would be higher on the top surface of the bulk-piled boards than on the bottom surface, there was found to be no significant difference (Table 11). This would not be the case if the piling is done in such a way that the faces are not brought into close contact.

When kiln-drying is begun the salt movement is accelerated. (See Figs. 16 and 17) This is due to a temperature increase and to the fact that as the amount of free water in the cells is reduced the salt concentration is increased, resulting in accelerated diffusion. The zone of cells containing a saturated salt solution would move inward as the outer portion of the board drops below the fiber saturation point. After the cells drop below about 30 percent MC little if any salt movement occurs. The concentration in the surface strips at 20 and 43 days of drying substantiates this. At the completion of kiln-drying the salt concentration in the center of the samples was one-third to one-fourth as high as on the surface.

Under the lower initial relative humidity conditions of tests II and III, there was considerably less salt movement during the first eight days of drying than occurred in test I. (See Fig. 18.) This is probably due to the fact that the surface layers drop below the FSP more quickly, thus providing less time for diffusion to occur. It should be noted that in Fig. 18 a horizontal line corresponds to zero change in salt concentration. In a case where the presence of

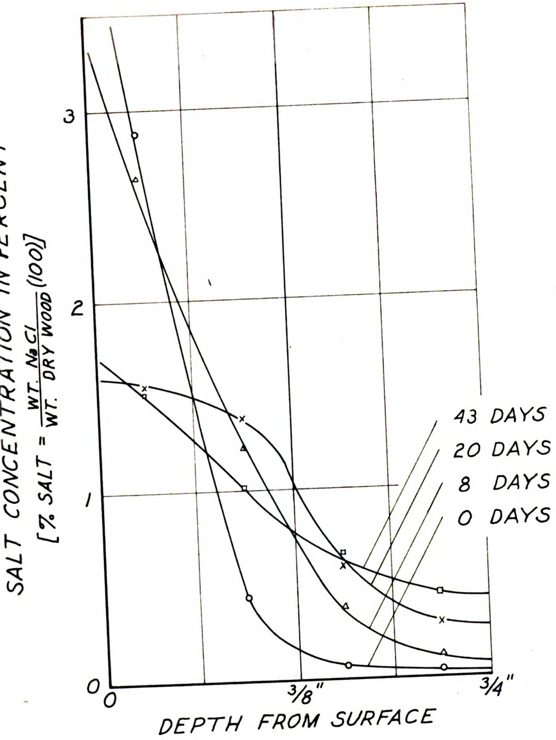


Fig. 16. Salt concentration gradients of the 75 lb. per M sq. ft. treatment at various times during test I.

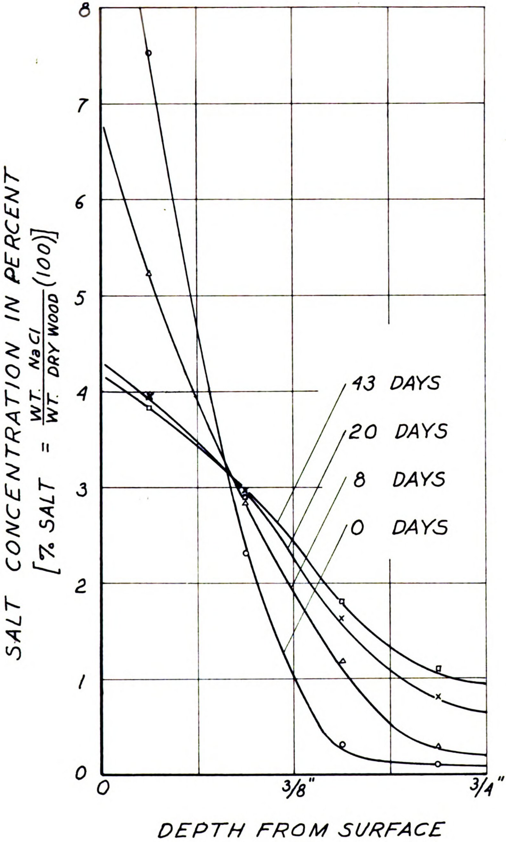


Fig. 17. Salt concentration gradients of the 210 lb. per M sq. ft. treatment at various times during test I.

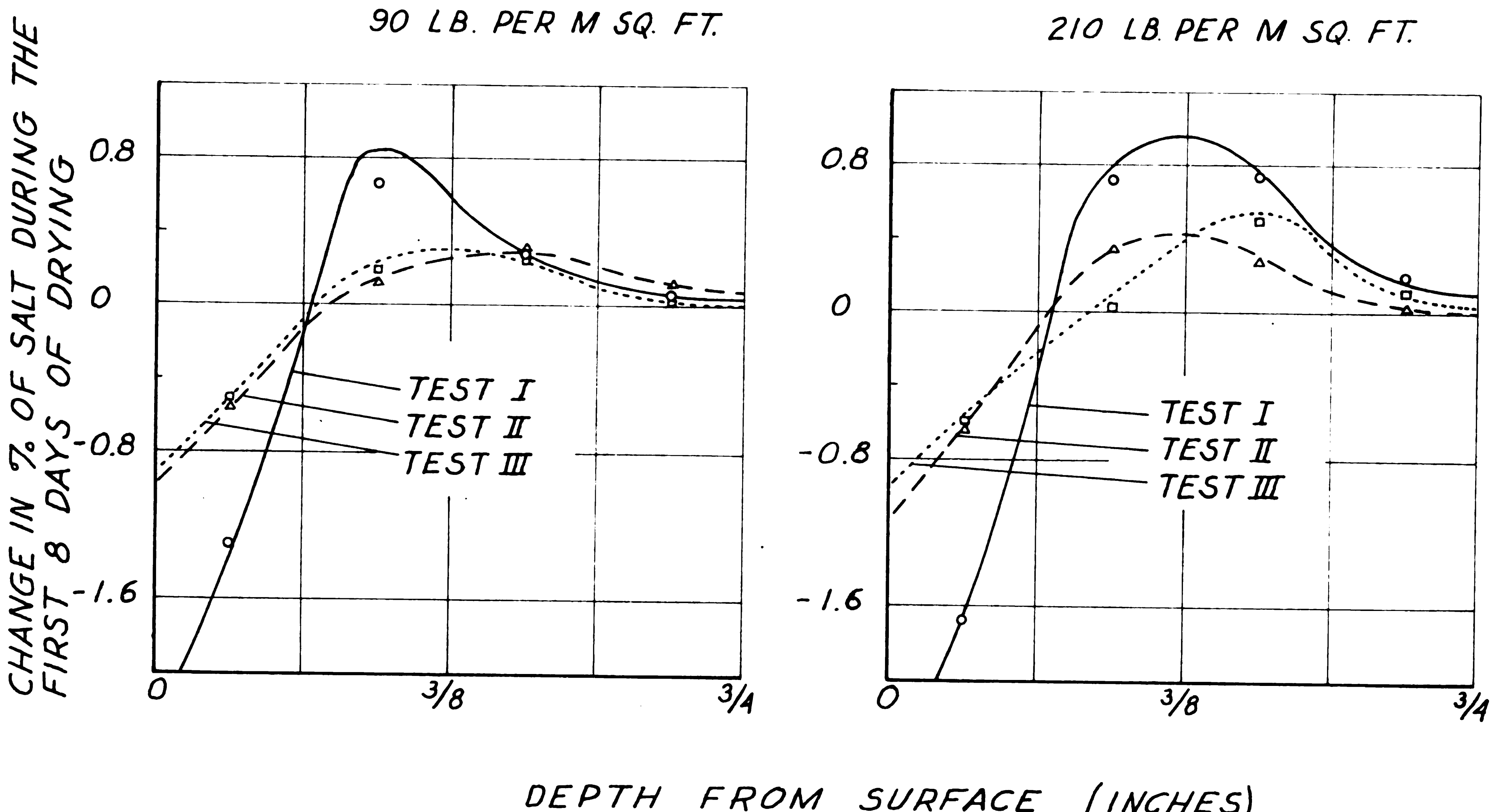


Fig. 18. The relationship between the drying conditions and the change in the salt concentration gradient during the first eight days of drying.

the salt is not desired in the finished product, it would obviously be desirable to use a drying process which produces results as close to this horizontal as possible.

The results from test V (Fig. 19) confirm the comments based on tests II and III regarding salt movement. The relative salt concentrations at the end of tests I and V are shown in Fig. 19. The sequence of drying conditions, primarily the initial relative humidity, has a marked effect on the final salt concentration in the core.

Drying Time and Quality

No seasoning defects were present in any of the samples dried in test I. The small surface-checks noted early in the drying of treatment A were closed at the end of the run. It is probable that the drying in test I could have been accelerated somewhat without producing defects in the samples of treatment A. However, the drying time of 40 days is believed to be within four or five days of the minimum which could be safely obtained with this particular quality of sample, kiln, thickness, and original moisture content.

The drying curves for test I and V are shown in Fig. 20. A summary of the quality of drying can be found in Table 4. In both tests the rate of drying was essentially constant after the first four days. There was no indication, therefore, that the salt retarded the drying during the final portion of the run. The average moisture content of treatments N and P was within two percent of treatment O (Fig. 20) throughout the test. Thus, under given drying conditions, the rate of drying does not seem to be affected by changes in amount of salt.

Twenty-two days of drying were required in test V. The schedule

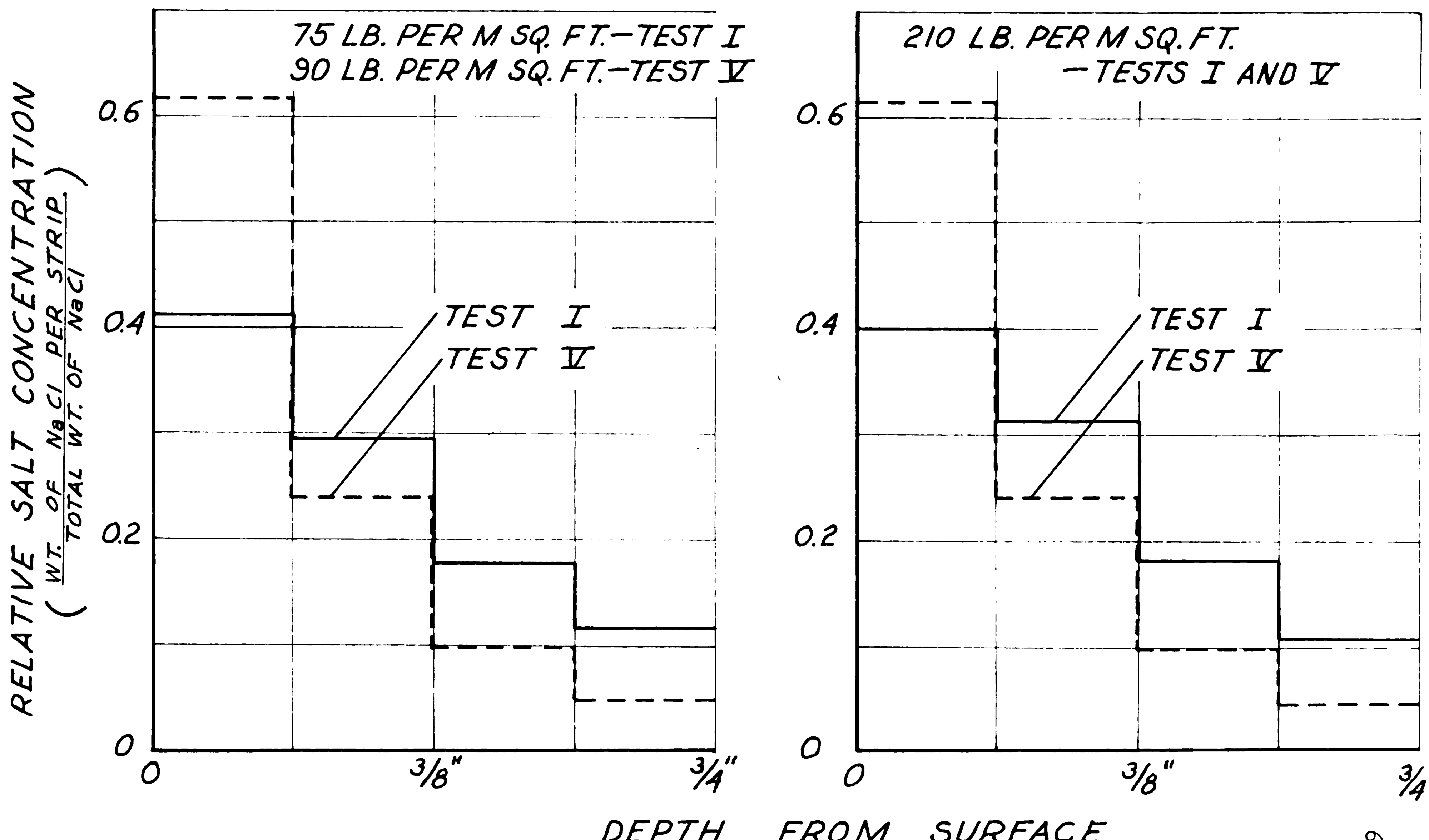


Fig. 19. The relative salt concentration gradients at the end of tests I and V.

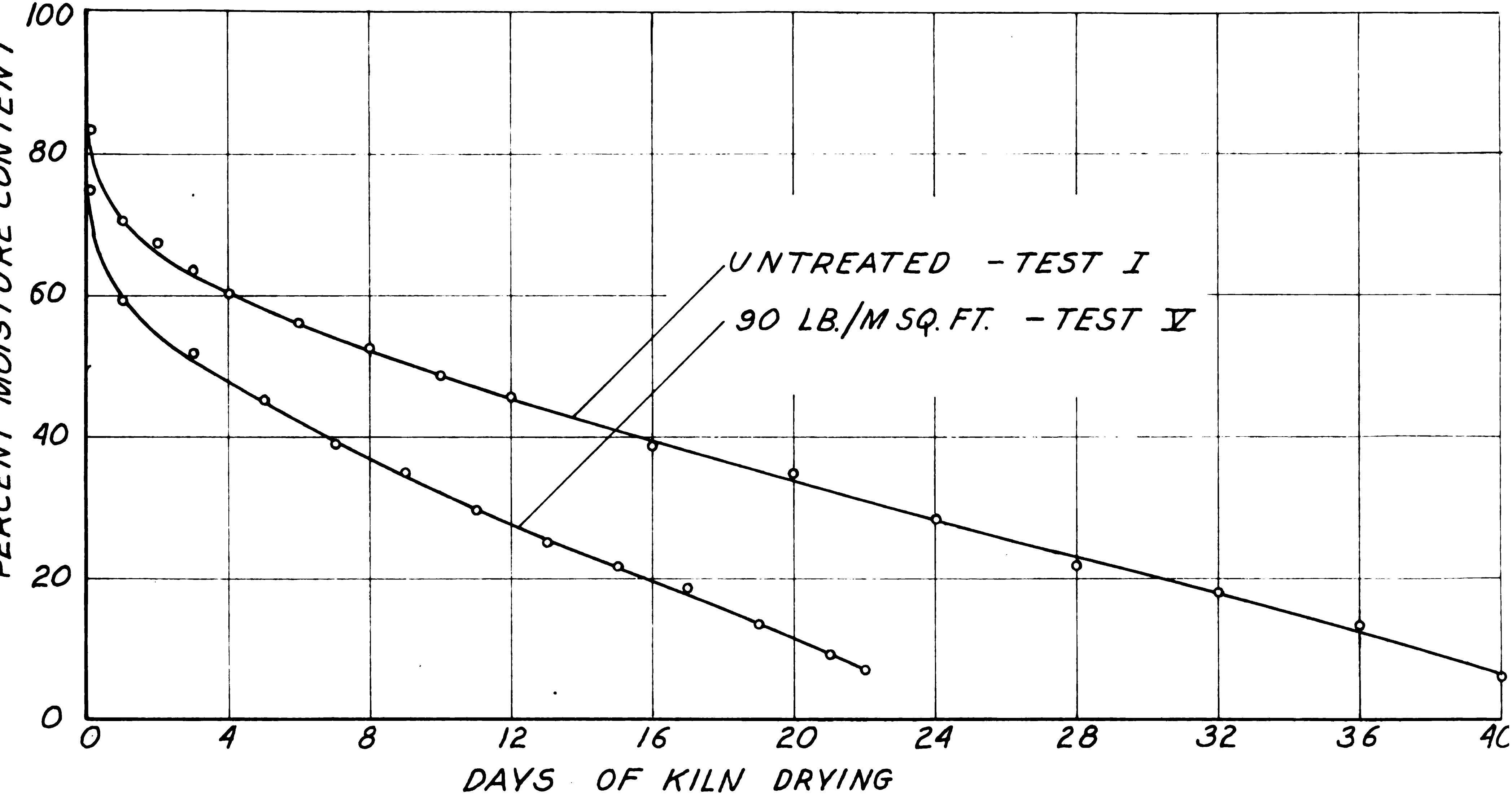


Fig. 20. Average moisture contents of entire samples during tests I and V.

used was too severe for treatment N, 45 pounds of salt, as evidenced by rather serious surface-checks which reappeared when the casehardening stresses were relieved. Untreated stock was found to contain considerable honeycomb (Fig. 21). Treatment O, 90 pounds of salt, was dried without serious defect; the checks which developed early in the drying cycle were closed and generally did not reappear. No seasoning defects were noted at any time in samples of the 210 pound treatment.

The overall shrinkage in the widths of the boards is shown in Table 3. The shrinkage of the untreated stock was significantly greater than for any of the treated samples (Table 10). The differences between the shrinkage of comparable treatments in test I and V were not statistically significant. Some cupping was evident in all treatments during all the tests, but there was no difference in the amount of cupping among the treatments and tests. The samples were not loaded from above as would be the case in a stickered pile; thus cupping could occur without restraint.

TABLE 3. The Percent of Tangential Shrinkage from Green to Seven Percent Moisture Content in Flat-Cut Red Oak Boards

Test No.	Treatment	Pounds of Salt/M Sq. Ft.	Percent Shrinkage
	A	0	7.74
I	B	75	7.08
	C	210	6.20
	N	45	6.96
V	O	90	7.20
	P	210	6.71

TABLE 4. Drying Times and Quality of Drying

Test No.	Time for Drying from 85 to 7 percent MC (days)	Lbs. of Salt Per M Sq. Ft.	Description of Season-Checks and Honeycomb in Kiln-Dried Samples
		0	none
I	40	75	none
		210	none
		0	All 4 samples contained honeycomb
V	22	45	In 2 of 4 samples-checking on 50% of area, over 3/4" deep
		90	On 2 of 4 samples-several checks of 2" x 1/32" or less, less than 1/8" deep
		210	none

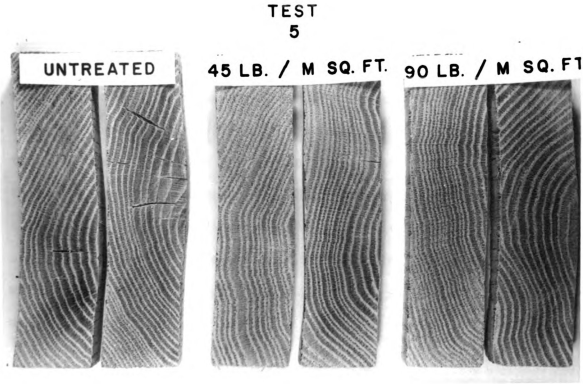


Fig. 21. Representative samples showing the occurrence of honeycomb and surface-checks in the dried stock from test V.

DISCUSSION AND CONCLUSIONS

Basic Properties of Salt-Treated Lumber as Related to Drying Stresses

Drying stresses are produced when the moisture content of the outer portion of the board drops below the fiber saturation point. At the start of the drying cycle, these stresses could be considered a function of: (1) the expected normal shrinkage to the moisture content at the point in question, (2) the elastic properties of all portions of the board at the corresponding temperature and moisture content. As drying progresses creep occurs accompanied by stress relaxation. This greatly complicates drying stress analysis. By using the strip technique, instantaneous strain measurements can be obtained which are helpful in studying the relationship between stress behavior and drying conditions.

If wood is treated with sodium chloride, the drying stresses which would develop under a given set of drying conditions are altered. The stress changes because the amount of shrinkage which would occur in a particular unrestrained layer is changed. In Fig. 2 it can be seen that white pine containing a saturated salt solution would not start to shrink until the relative humidity at 68° F. drops below 76 percent. If such a sample is placed in a kiln at a higher relative humidity no drying takes place and thus no stresses develop.

Relative initial tensile stresses at the surfaces of treated and untreated stock, at various initial relative humidity conditions, could be obtained from a family of curves of the type shown in Fig. 2. Several assumptions must be made when making such a comparison: (1)

the elastic properties of sodium chloride-treated wood are the same as those for untreated wood, (2) the surface of the drying boards reaches the EMC shortly after drying begins, (3) the moisture in the surface layers of the board is saturated with salt, or else the salt concentration is known. For example, suppose an initial relative humidity of 80 percent is known to be safe for untreated white pine. If it is desired to produce the same initial tensile stresses on the surface of white pine treated with a saturated salt solution, the initial relative humidity would be set at 40 percent.

The initial relative humidity conditions of the tests in this study are indicated in Fig. 2 by the vertical arrows. The initial conditions for test V were the same as for test III. The relative initial tensile stresses for untreated oak in test I and treated oak in tests II, III, and IV are indicated by the length of the vertical arrows. It is assumed here that a similar family of curves is valid for red oak and that the surfaces of the samples contain a saturated salt solution.

The results of the tests indicate that the comparison of relative initial stresses discussed above is valid. In test I small surface-checks developed indicating the maximum tensile stress was approached. In test II no checking occurred on any of the samples. In test III no checking occurred in the 210 pound treatment, but in the 90 and 150 pound treatments some season checks occurred. In test IV surface-checks were produced in all treatments indicating that the stresses developed were higher than in the untreated samples of test I. The indicated set measured during the first portion of these tests also indicates that surface stresses were lower in test III, but higher in test IV than those of the untreated samples in test I.

The most important decision regarding the optimum conditions to be used for drying salt-treated oak is the selection of the initial relative humidity. If that decision is made correctly, then the subsequent drying conditions can be determined by following the procedure recommended by the U.S. Forest Products Laboratory. Basically, the FPL recommends that the relative humidity be reduced when one-third of the evaporable water has been removed, and the temperature be increased to about 180° F. when the core of the stock drops below the fiber saturation point.

If the shrinkage-relative vapor pressure-salt concentration relationship were known for water-borne preservative or fire-retardant treated stock, then this information could be used as a guide in determining the initial relative humidity to be used for drying. About the only related information available today is that of Kollmann (22). He investigated only the sorption and not the antishrink characteristics.

Drying Conditions and Stress Development

Red oak treated with 75 pounds of sodium chloride, when dried under a normal schedule,[1] developed maximum elastic strains about one-third lower than the strain in untreated samples. The moisture content of the surface strips at this time was about 4 percent higher than that of the untreated controls. The shrinkage measurements during the first few days of the kiln run did not indicate that set occurred in the surface strip. In comparison, a set of 0.5 percent was noted in the untreated material after only two days of drying.

[1]In this discussion the "normal schedule" is the schedule recommended by the U.S. Forest Products Laboratory for untreated green 6/4 red oak.

From these observations it can be concluded that the surface tensile stresses developed in the 75 pound treatment are considerably lower than the stresses in untreated material. For the 210 pound treatment, the maximum tensile strains were lower and occurred later than in the 90 pound treatment.

Stress reversal occurred at approximately the same time in the treated and untreated stock. After stress reversal, the elastic strains of treated and untreated oak followed the same general pattern. The final casehardening stresses developed were more severe in the case of untreated stock as would be expected. When dried under a normal schedule, the casehardening stresses which developed in the treated material evidently resulted from rather high compression set in the core. In untreated stock casehardening resulted from a combination of tension and compression.

It is apparent that as the drying progresses the moisture gradients for the treated and untreated lumber converge. Kollmann (22) found that below 60 percent relative humidity the EMC of treated and untreated stock was essentially the same. The relative humidity during test I was dropped below 60 percent on the 23rd day. There was a significant difference between the moisture contents of the surface strips of all three treatments on the 20th day (Table 7). On the 25th day, however, there was no significant difference in the surface moisture contents of treatments A and B. After 29 days of drying, at which time the relative humidity was 31 percent, there was no significant difference between treatments A, B, or C. It appears that the moisture content of the surface layers of treated boards is not significantly different from untreated boards after the relative humidity drops below a certain point. This point is dependent upon the salt concentration in the surface strips.

A relative humidity of 73 percent used during the conditioning periods in this study was found to produce an equal rate of stress relief in both treated and untreated oak. This was despite the fact that the moisture content of the 210 pound treatment increased 3 percent during conditioning, compared to 1 percent in untreated material. If a relative humidity higher than 75 percent is used during conditioning, an increase in the rate of stress relief would probably occur due to the rapid increase in the EMC as the humidity increases. The danger of producing reverse-casehardening would then be greater. The length of a conditioning period must be based on a knowledge of the magnitude of casehardening stresses, as is the case in normal kiln practice.

The results of this study indicate that behavior of the measured casehardening strain is similar to that of the maximum surface tensile strain. If a given sequence of drying conditions produces a relatively low strain, then lowering the relative humidity conditions will increase the strain. However, if the first sequence produces a relatively high strain, then lowering the relative humidity conditions will not produce a significantly greater strain. The set produced would be increased regardless of the stress level.

An explanation for the behavior discussed above can be based on the shape of the stress-strain curve for tension and for compression. In both of these curves there is a stress level above the proportional limit at which a very small increase in stress will result in a large strain. In the case of tension a slightly greater stress will then result in tension failure. If the stresses in the board are near this level, irrecoverable strain is produced rather than the elastic strain which is measured by the strip technique. After the stresses reach this value which is beyond the proportional limit, further stress increases cause changes in elastic strain which are so small that they cannot be detected by use of the strip technique.

From the strain, set, and moisture gradients determined during a normal schedule it is apparent that these drying conditions do not approach the optimum for treated material.

By properly selecting a sequence of relative humidity conditions, while using the normal dry bulb temperature sequence, the strain, moisture content, and indicated set gradients can be made to approach those normally developed in untreated material. It is probable that the optimum schedule is then being approached. If the revised sequence of drying conditions is set up as described, very significant reductions in drying time can be realized at no increase in drying degrade. Until methods of accurately determining the internal stresses and strength characteristics are perfected, the truly optimum schedule cannot be designed.

Elastic strain measurements do not provide an accurate estimate of the surface stresses. Set measurements can be used to obtain more reliable indications of initial surface stresses, but this method is very laborious and the results are not known immediately. When the stresses are below the proportional limit, elastic strain measurements in the core may provide an accurate picture of the stress condition. The stress gradient in the core is rather flat throughout the drying cycle. Therefore, the average stress value is a good indication of the stresses at any point. The problem of thermal and moisture content shrinkage which occurs during the strain measuring procedure must be met, however, if accurate strain readings are to be obtained. The correction procedure used in this study was helpful in this regard.

Drying Conditions and Salt Distribution

When using the dry-spread method of salt application it is important that the lumber be piled carefully so that the faces are in contact. When this is done, the salt concentration on the top and bottom of the boards will be essentially the same. In order to reduce the problems which may result from the use of sodium chloride-treated lumber, the salt concentration in the center portion of the board should be kept as low as possible. As much salt as possible will then be removed during the manufacturing process. For this reason, it would be best to break down the bulk pile and begin kiln-drying immediately after the salt has disappeared. These studies indicate that this is not as important as has been thought. There was found to be very little salt movement between 7 and 14 days of bulk-piling. Longer periods of piling, of course, might be detrimental to maintaining a low salt concentration in the core.

The final distribution of salt through a board is dependent upon the drying conditions. Sodium chloride-treated lumber dried under a normal schedule was found to have a salt concentration 1/4 to 1/3 as high in the core as on the surface. It has been claimed that most of the salt will surface off when the treated boards are machined. Surfacing 1/8th of an inch from each face of these boards would remove less than 1/3 of the salt.

If the initial relative humidity is decreased the shell of the lumber dries out faster, and the diffusion of salt is retarded. When an initial relative humidity of 55 percent was used the salt concentration in the surface strips decreased only 0.6 percent during the first eight days of drying, as compared to 1.4 percent during drying under a normal schedule.

The final salt concentration in the center portion of stock dried according to the revised schedule was found to be much lower (See Fig. 19) than the stock dried under a normal schedule. The surface strips in the first case contained 62 percent of the salt in the board, while in the second case only 42 percent of the salt was found in the surface strips.

The relative salt concentration at a given time in a given drying cycle seems to be constant regardless of the amount of salt applied (See Figs. 15 and 19.) There is a very striking similarity in the relative salt concentrations of the 90 and 210 pound treatments at the end of both complete drying cycles. The salt distribution in oak treated with different amounts of sodium chloride can thus be predicted if the effects of the drying conditions on the distribution are known for only one amount of salt.

Further Research

Further research in the area of the drying of salt-treated lumber should first be directed toward investigations of the shrinkage-salt concentration-relative humidity relationships. With this information for a particular chemical and species, a safe yet efficient drying schedule could be designed.

Before a truly optimum schedule can be designed, however, a better way must be devised for determining the internal stresses than the strip technique used in this investigation.

Since it appears, at least in the case of oak, that the initial tensile stresses are of primary concern, new attempts at measuring stresses might be directed toward measuring only initial surface stresses. One possible approach would be to measure the tangential strain of the entire board by the means of a clip-attached strain gage. If the moisture content gradient were determined at the same time, then the theoretical stresses could be calculated on the basis of being analogous to thermal stresses.

SUMMARY

Clear, straight-grained flat-sawn samples of one species, northern red oak (*Quercus borealis* Michx.), and one thickness were used throughout this investigation. It could be expected, however, that the findings would be valid for other species with similar drying characteristics. The samples in this study were treated with sodium chloride. Other salts would produce different stress, set, and moisture gradients at a given drying condition depending upon the sorption and antishrink properties of the particular salt.

1. As would be expected, the surface and core stress pattern was less severe for treated than for untreated stock when both were dried under a normal[1] schedule. If reduced relative humidity conditions are properly chosen the stress development produced in treated stock will be very similar to that normally encountered in drying untreated lumber. Under these humidity conditions the treated stock will be dried safely in a much shorter time.

2. The optimum sequence of relative humidity conditions can be approached experimentally in a method similar to that used in this experiment. The primary limitation of this method, as far as relative humidity conditions are concerned, is that the proximity to the point of failure is not known until the failure is produced. The optimum sequence of temperature conditions must also be determined if the truly optimum schedule is to be found. In this experiment the normal

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[1]Normal conditions refer to the sequence of drying conditions recommended by the U.S. For. Prod. Lab.

temperature conditions were used. Near optimum temperature conditions could be obtained experimentally in a manner similar to that used for humidity conditions in this work. This would require extensive testing, however, and would appear to be prohibitively time consuming. A theoretical approach is needed, but cannot be obtained until the surface failure-stress relationship is better understood and until surface stress can be measured.

3. The strip technique of strain measurement was found to be a satisfactory method of comparing the stress pattern developed by different sequences of drying conditions. It provided useful information regarding the time of stress reversal, degree of casehardening, and the relief of casehardening. It was not found to be adequate, however, for indicating the stress level which results in surface-checking. The elastic strain obtained by the strip measurement method increases as the stress increases up to approximately the proportional limit. When the stress in a portion of the strip increases beyond the proportional limit the increase in the elastic strain is evidently too small to be detected by the strip technique.

4. An initial relative humidity which is safe, yet efficient, can be predicted if shrinkage-relative humidity relationships are known for the particular salt and species in question. This relationship can be used as a check on initial conditions which are determined theoretically from sorption and shrinkage data. It can also be used as a guide when determining experimentally the optimum initial conditions. The salt concentration at the surface of the lumber must be known if the prediction is to be accurately made.

5. Casehardening develops in sodium chloride-treated lumber

whether dried under a normal or relatively severe sequence of drying conditions. Casehardening in treated lumber results from a combination of the antishrink effect of the salt on the surface and compression set in the core. Casehardening stresses in the treated stock can be effectively removed by using a conditioning period designed for untreated stock. The rate of stress relief is essentially the same for treated and untreated material at relatively mild humidity conditions. It is not advisable to condition treated lumber at a high relative humidity since excessive moisture pickup may occur. The maximum relative humidity which can safely be used during the conditioning period can be obtained from the sorption curve of the species and salt in question. The highest relative humidity, at which the sorption curves for treated and untreated wood have the same gradient, should be used for the conditioning period. Below this point the conditioning period will be unnecessarily prolonged. Above this point there is a danger of producing reverse casehardening.

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APPENDIX

STATISTICAL TABLES

TABLE 5. Analysis of Variance of the Maximum Tension Strain in the Surface Strips During Test I

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	$F_{.05}$
Total	11	15.016			
Treatments (A, B, C)	2	12.594	2.996	32.67*	4.46
Surface (Top, Bottom)	1	0.880	0.880	4.57	5.32
T x S	2	0.761	0.380	2.92	5.14
Within	6	0.781	0.130		
Combined EMS	8	1.542	0.193		

*Indicates significance at the 5% level.

From a Studentized Range Test

Treatments: A > B > C

Summary

Treatments	Means
A	3.75×10^{-3} in./in.
B	2.69×10^{-3} in./in.
C	1.25×10^{-3} in./in.

TABLE 6. Analysis of Variance of the Maximum Tension Strain in the Surface Strips in Tests II, III, and IV

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	$F_{.05}$
Total	35	6.686			
Treatments (90, 150, 210 lbs.)	2	2.212	1.106	9.45*	3.32
Tests (II, III, IV)	2	0.941	0.471	4.02*	3.32
Surfaces (Top, Bottom)	1	0.0156	0.0156	0.133	4.17
Tr x Te	4	0.455	0.114	1.46	2.93
Tr x S	2	0.761	0.380	2.87	3.55
Te x S	2	0.0938	0.0469	0.60	3.55
Te x Tr x S	4	0.802	0.201	2.58	2.93
Within	18	1.406	0.0781		
Combined EMS	30	3.517	0.117		

*Indicates significance at the 5% level.

From a Studentized Range Test

Treatments: 90 lbs. > 150 lbs. & 210 lbs., 150 lbs. = 210 lbs.
Tests: II > III, IV = III = II

Summary

Treatment	Means
90 lbs.	2.71×10^{-3} in./in.
150 lbs.	2.27×10^{-3} in./in.
210 lbs.	2.13×10^{-3} in./in.

Test	Means
II	2.56×10^{-3} in./in.
III	2.17×10^{-3} in./in.
IV	2.37×10^{-3} in./in.

TABLE 7. Analysis of Variance of the Moisture Content of the Surface Strips After 20 and 25 Days of Test I

20 DAYS

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	$F_{.05}$
Total	11	313.9			
Treatment (A, B, C)	2	295.4	147.7	70*	4.26
Within	9	18.52	2.06		

*Indicates significance at the 5% level.

From a Studentized Range Test: A < B < C

Summary:

Treatment	Mean
A	17.4% MC
B	23.2% MC
C	29.5% MC

25 DAYS

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	$F_{.05}$
Total	11	93.3			
Treatment (A, B, C)	2	73.6	36.8	16.9*	4.26
Within	9	19.7	2.18		

From a Studentized Range Test: A, B < C, A = B

Summary:

Treatment	Mean
A	11.8% MC
B	13.0% MC
C	17.5% MC

TABLE 8. Analysis of Variance of the Moisture Content of the Surface After Two Days in Tests II, III, and IV

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	$F_{.05}$
Total	35	1260.4			
Tests (II, III, IV)	2	970.1	485	77*	3.31
Treatments (90, 150, 210 lbs.)	2	94.99	47.5	7.5*	3.31
T x T	4	41.44	10.36	1.82	3.31
Within	27	153.9	5.70		
Combined EMS	31	195.3	6.30		

*Indicates significance at the 5% level.

From a Studentized Range Test

Treatments: 90 lbs. < 150 lbs.& 210 lbs.
210 lbs. = 150 lbs.

Tests: II > III > IV

Summary

Treatment	Means
90 lbs.	30.3%
150 lbs.	33.8%
210 lbs.	33.8%

Tests	Means
II	38.1%
III	34.1%
IV	25.7%

TABLE 9. Analysis of Variance of Indicated Tension Set in the Surface Strips After Two Days of Drying in Tests I, II, III, and IV

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	$F_{.05}$
Total	39	13.385			
Treatments (90, 210 lbs.)	1	.621	.621	2.971	4.13
Tests (I,II,III,IV,I-Untr.)	4	6.216	1.554	7.435*	2.65
T x T	4	.794	.198	.95	2.69
Within	30	6.313	.210		
Combined EMS	34	7.107	.209		

*Indicates significance at the 5% level.

From a Studentized Range Test

Tests: I & II < I-Untreated & IV & III
I = II
I - Untreated = IV = III

Summary

Tests	Means
I	.01% change in % shrinkage
II	.15% change in % shrinkage
III	.64% change in % shrinkage
IV	1.03% change in % shrinkage
I-Untr.	.85% change in % shrinkage

TABLE 10. Analysis of Variance of Percent Tangential Shrinkage of the Entire Board

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	$F_{.05}$
Total	23	7.099			
Treatments	5	4.781	.956	7.41*	4.60
Within	18	2.318	.129		

*Indicates significance at the 5% level

From a Studentized Range Test

(I - 210) < (I - Untreated), (V - 45), (I - 90), (V - 90)
(I - 210) = (V - 210)
(I - Untreated) > all the other treatments

Summary

Test	Lbs. of Salt	Mean % Tangential Shrinkage
I	0	7.65 %
I	90	7.05 %
I	210	6.20 %
V	45	6.96 %
V	90	7.21 %
V	210	6.71 %

TABLE 11. Analysis of Variance of the Relative Salt Concentration in the Surface Strips After Different Periods of Bulk Piling

Source of Variation	Degrees of Freedom	Sum of Squares	Mean Square	F	$F_{.05}$
Total	23	3399.5			
Surfaces (Top, Bottom)	1	3.60	3.60	.02	4.38
Times (7, 11, 14 days)	2	313.6	156.8	1.03	3.52
Treatments (90, 210 lbs.)	1	188.7	188.7	1.24	4.38
S x Ti	2	53.57	26.8	.14	3.88
Ti x Tr	2	54.94	27.5	.15	3.88
Tr x S	1	61.13	61.1	.34	4.75
S x Tr x Ti	2	551.90	275.9	1.52	3.88
Within	12	2172.1	181.0		
Combined EMS	19	2893.6	152.3		

Summary

Times	Mean Relative Salt Concentration of Surface Strips
7 days	69.7%
11 days	71.1 %
14 days	77.7 %