THE PERPENDICULAR-TO-GRAIN MECHANICAL PROPERTIES OF RED OAK AS RELATED TO TEMPERATURE, MOISTURE CONTENT, AND TIME

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A Dissertation Presented to the Faculty of the Graduate School of Yale University in Candidacy for the Degree of Doctor of Philosophy

By

ROBERT L. YOUNGS

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Summary

The perpendicular-to-grain mechanical properties of northern red oak (Quercus rubra L.) were investigated in tension and in compression within the temperature range 80° to 180° F. and the moisture content range 6 percent to green. Included were short-time tension tests at three angles with respect to the growth rings and short-time compression tests at one angle to the growth rings; tests to determine the temporary and permanent effects of duration of heating; and tests to determine creep characteristics at several levels of stress, and stress relaxation characteristics at several levels of strain. Shear strength and modulus of rigidity associated with strain in the TR plane were calculated from tension data.

All properties except maximum tensile strain were reduced curvilinearly with increasing moisture content and linearly with increasing temperature within the range investigated. Maximum tensile strain appeared to be markedly increased with increasing temperature at moisture content levels below the fiber saturation point but less dependent on temperature in green material.

Most properties, particularly maximum stress in tension and stress at 2.5 percent strain in compression, were significantly affected by heating at 180° F. for periods of up to 30 days.

Creep and stress relaxation were increased by increasing either temperature or moisture content. A method of distinguishing between recoverable and irrecoverable creep by application of Boltzmann's superposition principle was employed. Recoverable creep appeared to increase linearly, and irrecoverable creep more than linearly with increasing stress. A large part of the increased creep at 180° appeared to be due to irrecoverable creep.

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Introduction

The fact that wood shrinks as it dries and thereby develops self-imposed perpendicular-to-grain stresses has been recognized for many years as the fundamental cause of most drying defects. These stresses develop and attain considerable magnitude even under closely controlled kiln-drying conditions. The magnitude and effect of these stresses depend on the perpendicular-to-grain strength, elastic, and rheological properties of the wood; the drying conditions to which the wood is exposed; and the length of time the wood is exposed to these conditions.

Wood does not dry evenly throughout its thickness, but develops a moisture gradient with a moisture content lower near the surface than in the interior. Since shrinkage is related to amount of reduction of moisture content below the fiber saturation point, and since this moisture content reduction does not take place evenly throughout the drying thickness, the result is differential shrinkage with consequent stress development in the direction of shrinkage. The stresses thus developed consist of tensile stress in any portion of the wood that is attempting to shrink against the restraint of other portions of the wood; compressive stress in the portions of the wood imposing the restraint; and shearing stress as adjacent portions of differentially shrinking wood tend to move relative to each other. The short-time perpendicular-to-grain strength properties determine the instantaneous effects of these stresses.

The drying of wood is not an instantaneous process, however, and the effect of time must be considered even for woods that dry somewhat rapidly. The drying time is influenced by the drying conditions and the ability of moisture to move through the drying wood. The drying time exerts a significant influence on the drying characteristics in two ways: (1) by introducing the effects of duration of exposure to heat; and (2) by introducing effects of creep and stress relaxation. These latter effects, in turn, influence the shrinkage of the wood and the development of plastic deformation, thus affecting the stresses developed during drying.

The conditions under which drying stresses develop and the influence of the stresses on drying characteristics may be understood more clearly by considering the events that occur within a board as it dries from the green condition. As soon as the board begins to dry, the outer fibers tend to reach a condition of equilibrium with the drying atmosphere. The rate at which this occurs depends on the permeability of the wood to moisture and the drying conditions. The net effect, however, is the lowering of the moisture content of the outer fibers to a moisture content below the fiber saturation point, with the result that the outer portion attempts to shrink. This shrinkage is restrained by the underlying wood, which is still well above the fiber saturation point, thus producing a tensile stress in the outer shrinking portion of the wood and a compressive stress in the wet inner portion.

A considerably simplified schematic illustration of these stresses is shown in figure 1A. The diagram shows the outer shrinking portion of the wood subjected to tensile stresses f_t and the inner non-shrinking portion of the wood subjected to compression stresses f_c. Hypothetical slices 1 and 2 in the two portions of the wood must then be restrained from free movement by the indicated shearing stresses f_s. The stresses thus developed produce strains in tension or compression that may be subdivided into three classifications, as follows: (1) elastic strain, (2) recoverable creep, and (3) "permanent" plastic strain (set). The tensile stress developed in the outer portion at this stage of drying is relatively high and sufficient to produce all three types of strain. The reaction in compression on the interior portion of the wood may also be sufficient to produce permanent plastic deformation in compression, especially since the interior portion is still in the green condition and thus is more readily strained and permanently deformed. The result is a drying of the outer portion in a set expanded condition, and possible permanent compression of the interior.

As drying continues, the interior of the wood gradually dries below the fiber saturation point and tends to shrink. The shrinkage of this interior portion, however, is restrained by the relatively dry outer portion that is set in an expanded condition. The result is a reversal of stresses with the interior in tension and the outer portion in compression; a simplified illustration of this is shown in figure 1B. This is the stress picture at the end of drying in typically casehardened wood.

The foregoing discussion shows that all portions of the wood are subjected to tensile, compressive, and shearing stresses as the wood is dried under a normal drying schedule, and that these stresses are operative under various moisture content and temperature conditions and for various durations of time. A drying schedule is designed to specify a series of temperature and relative humidity conditions that will enable wood to be dried as rapidly and as cheaply as possible, from the standpoint of both energy consumption and loss due to drying defects. It can readily be seen, therefore, that a knowledge of the perpendicular-to-grain properties of wood under kiln-drying conditions should contribute substantially to an understanding of the drying behavior of wood, and thereby provide fundamental information on which to base improvements in drying schedules.

Very little is known about the perpendicular-to-grain strength, elastic, and rheological properties of wood under kiln-drying conditions. It is the objective of this study to investigate these properties.

Studies of the Drying Behavior of Wood

Most of the scientific work related to wood drying has been concerned with investigation of the mechanism and rate of moisture movement through wood during drying. This work has dealt principally with the application of diffusion laws based by analogy on the Fourier heat-conduction analysis. Most of this fundamental work on moisture movement has been carried out under steady-state conditions (38,53)[1] because of the adaptability of this type of study to the close control required in the laboratory. Because the drying process is not a steady-state system, however, investigations have also been conducted under unsteady-state conditions in an effort to derive information not available from steady-state tests (13,49,60,63). Factors affecting drying rate and moisture movement have been subject to considerable research (15,50,51). Relatively little fundamental information has been obtained on the perpendicular-to-grain mechanical properties of wood that determine its drying behavior and its susceptibility to most drying defects. Only recently has much concentrated work been done on analysis of strains developed across the grain in drying wood in response to drying stresses.

Early publications of Tiemann (58,59) indicate that he was aware of the general nature of perpendicular-to-grain stress and set during drying at least 40 years ago. At that time Tiemann analyzed drying stresses in wood by means of a prong technique similar to that now in

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[1] Underlined numbers in parentheses refer to literature cited at the end of this dissertation.

common use for the determination of casehardening. A few years later, Tiemann (60) analyzed drying stresses by means of hypothetical slices taken across the width of a drying board. The general information on drying stresses obtained by means of such analyses was very useful in establishing drying schedules that were a long step forward in the search for improved methods of kiln drying during and shortly after World War I. This information was recognized as being very limited, however, and additional studies were made in an attempt to disclose the fundamental relationships underlying the development of stresses and set during the drying of wood.

The first attempt to follow the development of stresses entirely through the drying process by means of the measurement of thin transversely oriented slices was apparently made by Peck at the U. S. Forest Products Laboratory, working with 1-inch-thick quartersawed white pine boards. Peck employed what is now commonly called the "slicing technique." It consisted of marking off the cross section of a wafer cut from the board into six slices of nearly uniform thickness oriented parallel to the radial face of the board; next, measuring the length of these slices before and after cutting from the wafer; and then drying to the ovendry condition to determine differences in total shrinkage that would indicate set. The wafers were carefully protected against moisture loss between measurements. The change in length of the slice as it was cut free was taken as a measure of the nature and magnitude of the stress present in the slice just before it was cut--an increase in length indicating a compressive stress and a decrease in length indicating a tensile stress. The amount of dimension change was assumed to be approximately proportional to the stress. This procedure is basically the same as that currently used at the Forest Products Laboratory in drying strain analyses by the slicing technique. Subsequently, Peck applied this technique to an analysis of drying stresses in 2-inch-thick magnolia and 2-inch-thick blackgum sapwood (48), and developed a constant temperature drying schedule for the blackgum based on the indications of the outer prongs of sections cut from a drying board.

A later, more comprehensive study of this type on sweetgum heartwood was made by Loughborough and Smith (63). The principles developed as a result of these studies led to a new concept in drying schedules, as described by Rietz (49). A new set of kiln schedules for American woods, based on these principles, was published at the Forest Products Laboratory by Torgeson (61). During the last few years, McMillen (39,40) has expanded this work with more exhaustive and comprehensive studies on northern red oak. This latter work has been concerned principally with the effects of relative humidity and temperature during drying on the stresses and set developed in the material being dried, as indicated by the slicing technique. McMillen found that increasing severity of humidity conditions tended to increase tension set in the outer layers of 2-inch northern red oak dried at 110° F., but increasing temperatures up to 140° F. had little effect on this set development. Compression set in the interior of the drying boards was increased at the higher temperatures. Somewhat similar studies on Japanese beech boards have been carried out by Suzuki (57), who took into account not only the immediate change in length of slices as they were cut free but also the subsequent gradual change due to recoverable creep.

The Perpendicular-to-Grain Mechanical Properties of Wood Under Drying Conditions

Short-Time Effects of Temperature and Moisture Content

An awareness of the part played by perpendicular-to-grain drying stresses in the development of drying defects has led to an interest in the perpendicular-to-grain mechanical properties of wood under kiln-drying conditions. However, even less work has been done in this field than on the analysis of drying strains.

The first work on the effect of temperature and moisture content on perpendicular-to-grain mechanical properties was done by Greenhill at the Forest Products Laboratory in 1931, and published a few years later in Australia (17). This study was made on American beech and was confined to short-time tests in tension, with loading in the parallel-to-growth rings (0°) direction only. The investigation included all combinations of temperatures of 80°, 120°, 160° and 180° F., and moisture content levels of 7, 14, and 20 percent, and green. Greenhill encountered considerable experimental difficulties and on the basis of careful judgment he was forced to adjust some of his results, particularly those at the higher temperatures. Greenhill measured overall elongation because he did not have a strain gage capable of withstanding the conditions within his testing chamber. Although he made an effort to correlate such strains with those of preliminary tests under room conditions in which a strain gage attached to the specimen was used, there is no assurance that this correlation was valid for the other conditions of testing.

Greenhill found that maximum load, proportional limit stress, and modulus of elasticity were all substantially reduced as temperature was increased, particularly above 100° F. Maximum load was reduced more noticeably over the range of temperatures employed at high moisture content than at low moisture content, but this effect was not evident for proportional limit stress or modulus of elasticity. The finding of Greenhill regarded as most significant was the apparent maximum unit deformation at failure in the vicinity of 120° F. at all moisture content levels. From this it was concluded that the use of temperatures in the neighborhood of 120° F. would be least likely to cause checking in kiln drying of American beech. That this is a valid and practicable conclusion remains to be proven. Greenhill's pioneering work in development of testing techniques and apparatus for that type of study probably should be considered as important a contribution as his research results. In revealing sources of experimental difficulty, he aided subsequent investigators in the field in modifications of testing technique.

In his study of the causes of drying defects in green oak, Kollmann (30) postulated that internal checking must occur when either the shear stress in a longitudinal-radial plane or the tensile stress perpendicular to such a plane exceeded certain limiting values. He then set out to determine the effect of temperature on these strength properties as well as on volume of checks and occurrence of morphological changes in the wood cells.

Kollmann employed high-frequency heating to obtain the desired temperature in both tension and shear tests, in order to minimize moisture and temperature gradients in the material during testing. For his tension tests he used necked-down specimens with a net section of 20 by 10 millimeters (approximately 0.8 by 0.4 inch), the direction of loading being parallel to the annual rings. For his shear tests he used a notched tensile type of specimen. Strain measurements of both phases of the study are open to considerable doubt, however, since he did not use a strain gage on the specimen but merely recorded head movement of the testing machine. By assuming that such strain measurements were fairly accurate representations of the actual strain of the necked-down portions of his tension specimens, Kollmann concluded that strain at failure in tension perpendicular to the grain may be considered to be independent of temperature.

This is in contrast to the results of Greenhill (17) and of subsequent investigators (4,14), which indicated a pronounced effect of temperature on strain at failure at all levels of moisture content. Kollmann found that the perpendicular-to-grain tensile strength in the parallel-to-ring direction decreased linearly with increasing temperature from 0° to 100° C. The strength at 0° C. averaged about 80 kilograms per square centimeter (1,135 p.s.i.) and that at 100° C. averaged about 15 kilograms per square centimeter (213 p.s.i.). As presented by Kollmann, the relationship of shear strength in the longitudinal-radial plane to temperature is sigmoid in shape, with the most rapid decrease in strength taking place between temperatures of 20° and 80° C., and relatively little change between 0° and 20° C. and between 80° and 100° C. Up to about

25° C. (77° F.) the tensile strength was considerably higher than the shear strength. From this Kollmann concluded that checks due to tensile stress are unlikely at these low temperatures. Between 25° and 80° C. the tensile strength and shear strength were about the same and were affected to the same extent by temperature. Above 80° C. (176° F.) the tensile strength decreased much more rapidly with increasing temperature than did shear strength. From this Kollmann concluded that 80° C. is a critical temperature for oak in terms of tensile failures.

Barnard-Brown and Kingston (4) studied the effect of temperature over the general range of 20° to 65° C. on the perpendicular-to-grain strength and elastic properties (in the parallel-to-ring direction) of green material from three Australian species. Tests at 30° C. were also conducted in both the parallel-to-ring and perpendicular-to-ring directions on green specimens from one tree. Necked-down specimens having a net section 5/8-inch square were used in these studies. The authors state that the results are not conclusive because of the small number of trees tested from each species. Nevertheless, several significant and noteworthy trends are evident from the results. (1) Modulus of elasticity and maximum tensile strength in the parallel-to-ring direction were reduced with increasing temperature in a generally linear manner for all three species. (2) Strain at maximum load was increased linearly with increasing temperature for one species and increased according to a cubic relationship for the other species. (3) Proportional limit stress was reduced in a generally quadratic relationship to increasing temperature for all three species.

(4) Modulus of elasticity, maximum tensile strength, and proportional limit stress were higher--and strain at maximum load lower--in the perpendicular-to-ring direction than in the parallel-to-ring direction.

Ellwood (14) conducted an extensive investigation of the effects of temperature and moisture content on the perpendicular-to-grain tensile and compressive properties of American beech. This was the first work in this field to consider compressive as well as tensile properties. Testing was confined to the parallel-to-ring direction, and covered temperatures of 80° to 160° F. and moisture content levels from green to 6 percent. Ellwood's results showed that tensile and compressive properties were affected quite similarly, in most respects, by similar temperature and moisture content conditions. Maximum tensile strength and compressive stress at 2.5 percent strain decreased linearly with both increasing temperature and increasing moisture content. The maximum temperature effect in tension was found at 18 percent moisture content, and the moisture content effect increased at higher temperatures. The effect of temperature on compressive stress at 2.5 percent strain was greater at low moisture content levels than the effect on tensile strength, but better agreement was found between tensile strength and compressive stress at maximum tensile strain. Modulus of elasticity and proportional limit stress in both tension and compression decreased in a predominantly linear manner with increasing temperature, and in a curvilinear manner (concavely upward) with increasing moisture content. Maximum tensile strain increased in a predominantly linear manner with increasing temperature at all moisture content levels, although the maximum strain at 6 percent moisture content was substantially lower than that at other levels of moisture content. All the strain increases were comparatively small. Ellwood conducted a few exploratory creep tests of limited duration which indicated a much higher creep rate under compressive loading than under tensile loading, other conditions being the same. Creep rate was considerably accelerated by increasing either temperature or moisture content. Duration of stress apparently did not affect tensile strain at failure.

Ellwood attempted to apply his test results to an explanation of drying behavior, although he recognized the limitations of basing such application on short-time test results only.

It is interesting to note that Kollmann (30), Barnard-Brown and Kingston (4), and Ellwood (14) all found a linear decrease in tensile strength in green material in the parallel-to-ring direction with increasing temperature. Kollmann (29) found a similar relationship to temperature for compressive strength parallel to the grain. Sulzberger (55) also found a linear relationship to temperature for parallel-to-grain compressive strength and for modulus of rupture, proportional limit stress, and modulus of elasticity in static bending. Kitahara and Suematsu (27) found that parallel-to-grain compressive strength and perpendicular-to-grain modulus of elasticity and proportional limit stress in compression decreased linearly with increasing temperature over the range of 10° to 50° C. for several Japanese woods in both the air-dry and the ovendry conditions.

In the Wood Handbook (64) the results of several of these studies are summarized. In general, the immediate effect of temperature on static strength properties of dry wood (12 percent moisture content) within the temperature range of 0° to 150° F. can be estimated as an increase or a decrease in the strength at 70° of about 1/3 to 1/2 percent for each 1° decrease or increase in temperature.

The relationship between strength and moisture content at room temperature is generally assumed to follow the exponential formula published by Wilson (66). Ellwood (14) found that maximum perpendicular-to-grain tensile strength did not follow this exponential relationship to moisture content, but showed a linear relationship at all temperatures investigated. Likewise, Sulzberger (55) found a departure from the exponential relationship in parallel-to-grain compressive strength, the relationship varying with temperature of test.

Effects of Duration of Heating

Very little investigation has been made of the problem of evaluating the effects of duration of heating on the mechanical properties of wood that are specifically associated with drying of the wood. The most significant work in the field is that of MacLean (33,34,35,36) on the effects of various temperatures and heating media on rate of disintegration and on strength properties as determined in static bending. MacLean's results show that the relationship of strength to heating time at constant temperature can be represented by a power function, while the relationship of strength to temperature at constant heating time is represented by an exponential function. The effects of heating were shown to be somewhat more pronounced in hardwoods than in softwoods and considerably greater when heating under wet conditions (as in steam or water) than when heating under dry conditions in an oven. This would suggest that, in drying a wood such as northern red oak, the effects of duration of heating might very well be sufficient to exert a significant influence on drying characteristics. This consideration assumes added importance in view of the trend toward the practice of faster drying at higher temperatures and the interest in drying systems in which temperatures above the boiling point of water are employed.

Effects of Duration of Loading

Wood, like most structural materials, deforms instantaneously under load in relation to the stress imposed, and continues to deform as the load is maintained at a constant level. The instantaneous deformation is largely elastic strain, conforming to Hooke's Law; and the increase in strain that occurs with time under constant load is commonly termed plastic strain, or yield. It has been shown, however, that plastic strain in wood is not entirely plastic in the true sense, but is at least partially recoverable with time after removal of the load. Wood in drying is subjected to self-imposed internal stresses that may continue for several hours or several days; thus even if they are known under all drying conditions of temperature and moisture content, the elastic properties of wood do not supply sufficient basis for describing drying behavior and for predicting the likelihood of drying defects. It is important that consideration be given to the time-related rheological properties of wood.

Much of the fundamental study of creep and its associated phenomenon, stress relaxation, has had its origin in the relationship suggested in 1868 by Maxwell, which combined the behavior of elastic materials conforming to Hooke's Law and viscous materials conforming to Newton's Law. Maxwell's relationship does not account for elastic aftereffect, the gradual recovery from creep after removal of load--an effect strongly exhibited by wood. These elastic aftereffects were discovered by Weber around 1835; subsequent observation of the phenomena led to the superposition principle expressed by Boltzmann in 1874. That principle states that the deformation at any instant of a body manifesting recoverable creep is due not only to the load acting at that instant but to the entire previous loading history of the body. Thus it appears that creep in wood should consist of two concurrent phases that Leaderman (32) has called primary and secondary creep. Primary creep corresponds to these elastic aftereffects or delayed elasticity and is recoverable in time after removal of load. Secondary creep is considered nonrecoverable and would correspond to what is called "permanent set" in drying wood. This designation of primary and secondary creep is different from the meaning of similar terms applied by Nadai (42) to creep of metals that follow Maxwell's relationship more exactly and are free from elastic aftereffects.

Leaderman states that, after creep of long duration where creep has essentially reached completion, recovery after unloading as a function of recovery time is the same as the recoverable creep as a function of creep time; for the recovery and recoverable creep curves have basically the same shape, and the magnitude of deformation remains proportional to the load. This relationship is complicated in wood by the fact that irrecoverable creep is usually present and is difficult to distinguish from recoverable creep. Leaderman introduced the concept of "mechanical conditioning" to describe the change in properties after application of stress due to irrecoverable creep. If it were possible to eliminate irrecoverable creep of wood by a process of mechanical conditioning, the study of fundamental rheological properties would be much simplified. This mechanical conditioning of high polymers was analyzed by Grossman and Kingston (25). They (24) conducted creep and recovery tests on wood plates loaded in shear, following the statement of Barkas (3) that the structure of wood converts up to 95 percent of an external hydrostatic pressure into shear stresses. Grossman and Kingston found that irrecoverable creep occurred approximately in proportion to the time of loading. They also found that strain mechanisms with retardation times of a few hours recovered more rapidly than they deformed. For longer periods of several hours or a few days, the two rates were very nearly the same, confirming the applicability of the principle of superposition.

In an earlier study (23) Grossman and Kingston investigated the creep and relaxation of small wood beams in static bending. They found that the relationship of the irrecoverable component to stress was nonlinear. After a relaxation test the immediate and delayed recovery were proportional to the residual stress at the end of relaxation but the magnitude of the irrecoverable component depended on the average stress, which was somewhat higher.

Minami (41) studied the compressive creep and recovery characteristics of two Japanese woods and derived from his results an expression for amount of creep as an exponential function of stress and time. This same function was also applicable to recovery from creep.

Norris and Kommers (44) studied the creep of yellow birch plywood plates subjected to constant shear stress in the LT plane. They found that creep at any given time was a parabolic function of load and the creep-load curve was concave donward. They presented an expression relating shear stress, shear strain, and time, but cautioned against application of these results to tensile or compressive creep.

Grossman and Kingston (22) studied the influence of stress on tensile and compressive creep in an Australian species. After about 2 months under constant stress, as the stress was greater the ratios of strain to stress were higher; the increase was due mainly to irrecoverable creep.

Armstrong (2) conducted short-term creep tests on small-scale wooden beams in static bending and found a linear relationship between initial extreme fiber stress and period of recovery, which increased with increase in initial stress.

Kitazawa (28) developed a relaxation formula for wood in compression perpendicular to the grain. The formula involved the stress at 1 minute after initial loading and the logarithm of the time under load. Grossman (21) found that Kitazawa's formula did not apply to his data on relaxation in static bending, and concluded that the stress at any time could be better represented by the sum of exponential terms with various relaxation times.

Ivanov (26) introduced the concept of a flow limit in wood, a minimum stress at which secondary creep takes place. Data of other investigations indicate that this flow limit is generally well below the proportional limit stress as it is usually determined; but measurements of the small strains involved at such low stresses are generally not accurate enough to define such a limit of plastic flow.

In summarizing duration-of-load studies at the Forest Products Laboratory, Wood (68) mentions this low stress level at which plastic yield commences. He states that the relationship between yield and time under constant loading is essentially the same for all types of loading and all levels of stress so far examined. This statement is based on very limited study, however, and remains to be proven by further investigation.

Scope of the Study

The tests conducted in this study were designed to investigate the perpendicular-to-grain mechanical properties and behavior of northern red oak with respect to temperature, moisture content, and time. Since these properties are primarily of interest from the standpoint of internal stresses developed in wood during drying, the ranges of temperature, moisture content, and time selected for study are common to ordinary kiln drying of the species. Because the study was so broad in scope, it was not possible to investigate any one phase intensively.

The program of testing was divided into three interrelated phases, each concerned with a specific portion of the overall problem. The first phase consisted of short-time mechanical tests in tension and compression at four levels of moisture content and three levels of temperature. Tension testing was conducted at three angles to the growth rings but compression testing was limited to a single angle. Data based on these tests are given in tables 1-5. The second phase of the study consisted of tests in tension and compression to determine the effects of duration of heating at two levels of temperature and moisture content (tables 6 and 7). The third phase consisted of creep and stress relaxation tests in tension and compression at two levels of temperature and moisture content (tables 8-11).

Analysis of variance was made for all properties in tension and compression as determined by the short-time static tests (tables 12-18). Comparisons of variances for the various components were made as described under "Statistical Design" (pp. 31-32), and the value of mean square used as a basis for calculation of the variance (F) ratio is indicated for each component. Analysis of variance of the relaxation coefficient is given in table 19; variance ratios in this table were computed on the basis of error variance.

Experimental Material and Sample Preparation

The material used for this study was taken from four 5-foot logs, one from each of four trees of northern red oak (Quercus rubra L.). The species identification was confirmed by herbarium material collected when the logs were cut. All the trees were from a nearly pure stand on a good site in southern Wisconsin. The trees were about 110 years old and 82 to 100 feet high. Test material for this study was taken from the butt logs, the number of rings per inch varying from 9 to 12 and the diameter averaging 16 to 18 inches inside the bark. These logs were part of a lot procured in 1952 for use in the present study as well as in drying strain studies reported by McMillen (39,40). The logs were end-coated and stored under controlled conditions of 35° F. and 90 percent humidity at the Forest Products Laboratory, until they were cut into planks in the fall of 1954.

Planks were cut from the logs as shown in figure 2. Five planks, each 2 inches thick by 8 inches wide, were sawed from each log by means of a circular saw. Three of the planks were oriented in such a way that the growth rings were principally at 0° to the width direction. The fourth plank was oriented so that the growth rings were principally at 90° to the width direction and the fifth plank so that the growth rings were principally at 45°. Care was taken to have the same growth ring or group of rings at the center of each plank in order to minimize variability due to differences in wood structure or specific gravity. The planks were jointed and planed to final dimensions. Between all machining operations the planks were protected by damp cloths to prevent drying from the exposed surfaces. A 6-inch length was cut from each end of each plank to eliminate any material that may have been subjected to drying.

A wafer 1 inch in length along the grain was cut from each end of each plank. The central 2 inches of width of each wafer were used for determination of specific gravity (green volume, ovendry weight) and of moisture content by the ovendrying method. Heterogeneity of within-log variances of specific gravity was tested by means of a maximum F-ratio test, as described by Bliss and Calhoun (6). On the basis of the test for the present study, it was concluded that the within-log variances were homogeneous. An analysis of variance indicated no significant difference between log means of specific gravity. The moisture content of all the samples was between 75 and 90 percent, the usual green moisture content of this species.

The green planks were then cut on a table saw into wafers 1/2 inch along the grain. Cutting was started at the end of the plank corresponding to the lower end of the log in each case and the wafers were numbered consecutively as they were removed. The wafers were wrapped tightly in polyethylene bags and stored under controlled conditions of 35° F. and 90 percent humidity. When all the wafers had been cut, they were dipped in a dilute solution of sodium pentachlorophenate for additional protection against fungal deterioration.

Each test to be conducted was assigned a number and the wafers were assigned to the various tests by means of a table of random numbers. The numbering of the tests and wafers was done by pairs so that two adjacent wafers from each log would be assigned to each test, the odd-numbered wafer to be used for a tension specimen and the adjacent even-numbered wafer for a compression specimen. The three 0° planks from each log were pooled for this purpose, although the number identifying each wafer as to log, plank, and location was retained.

Wafers assigned to green tests were left in storage at 35° F. Those assigned to tests at 18 percent, 12 percent, or 6 percent moisture content were placed on stickers in a small dry kiln and dried slowly to the approximate moisture content of test at temperatures not exceeding 110° F. As the wafers attained their approximate test moisture content they were removed from the dry kiln and placed on trays in a room controlled at 80° F. and a relative humidity corresponding to the final desired moisture content. After the wafers had been stored under these conditions for at least 2 months, they were removed and a tension or a compression specimen was prepared from each wafer. This conditioning in wafer form prior to cutting of specimens prevented the warping that would have developed if the specimens had been prepared from green wafers and dried in specimen form; also it prevented the seasoning defects that might have developed if the material had been dried in plank form.

The tension and compression specimens were cut as shown in figure 3. The shape of the tension specimen is one that had proven in previous exploratory tests to give good results, with failure generally occurring in the net section. The standard ASTM specimen for testing in tension perpendicular to the grain (1) could not be used because of stress-concentration effects that make it basically unsuitable, and because no suitable provision could be made for taking load-deformation data. The compression specimen was designed to correspond to the net section of the tension specimen.

Tension specimens were first cut accurately to a width of 1 inch and a length of 7-1/2 inches. In this operation approximately equal amounts were cut from each edge in order to keep in the central portion of the specimen the same growth rings that had originally been in the center of the plank. The specimens were then cut to rough shape on a band saw and machined to final dimensions on a shaper, using a jig designed especially for the purpose. Compression specimens were first cut slightly oversize on a table saw. As in cutting tension specimens, care was taken to center the specimen around the growth rings that had originally been in the center of the plank. The specimens were then jointed accurately to a width of 1/2 inch and cut to a length of 2 inches; they were carefully cut to length so that the ends were smooth and square. Prior to testing, tension and compression specimens were stored in the controlled temperature and humidity rooms in which the wafers from which they were cut had been conditioned.

Short-Time Tests in Tension and Compression

Test Conditions

Perpendicular-to-grain tension tests at 0°, 45°, and 90° to the growth rings and compression tests at 0° to the growth rings were conducted under each combination of the following temperature and moisture content conditions.

Temperature: 80°, 130°, and 180° F.

Moisture content: Green, 18, 12, and 6 percent.

Two replicates from each of four logs were tested at each angle of loading under each combination of temperature and moisture content conditions, providing a total of eight tests at each test condition.

Experimental Equipment

Short-time tension and compression tests were conducted in a testing chamber in which temperature and humidity could be controlled at the desired level, and which was permanently mounted on a 100,000-pound capacity Olsen mechanically driven universal testing machine. The testing apparatus is shown in figures 4 and 5.

The apparatus consisted of four basic components, as indicated in figure 4: (A) the testing chamber, (B) the testing machine, (C) the air-conditioning unit, and (D) ducts for carrying the conditioned air to and from the testing chamber.

The testing chamber was a double-walled, insulated copper box that completely enclosed the head of the testing machine. The box was equipped with observation windows on three sides and access doors on two sides.

It was tightly made, and all openings were sealed as thoroughly as possible against leakage of air and moisture.

The air-conditioning unit contained all the facilities for conditioning the air to the proper temperature and relative humidity, and for circulating it through the system. Two sources of heat were available: (E) a steam-heating coil, and (F) a battery of electrical resistance heaters. The steam-heating coil was equipped with a reducing valve to reduce steam pressure to a level just adequate for the temperature desired. Thermostatic control was provided by a control bulb in the testing chamber and an air-operated reverse-acting control valve on the steam line. The battery of electric heaters was made up of six manually operated 1100-watt heaters and one thermostatically controlled 550-watt heater, each capable of being set at full, one-half, or one-quarter output. The control bulb (G) for the thermostatically controlled heater was located in the entering-air duct at the entrance to the chamber. Humidification was provided by a steam spray (H), controlled by a direct-acting air-operated valve actuated by a wood-element hygrostat inside the testing chamber. A thermostatically controlled refrigeration unit (not shown) could be used either for dehumidification when operating at low temperature and relative humidity, or to control overshoot of temperature when operating at low or moderately high temperatures. Air, conditioned to the proper temperature and relative humidity, was circulated through the testing chamber by means of a variable-speed blower (J). Hand-operated dampers (K) could be closed to shunt the air through a by-pass duct rather than through the testing chamber, when specimens were being placed or removed. This equipment enabled dry-bulb temperature to be controlled to ± 1.5° F. and wet bulb temperature to ± 2° F., as indicated by thermometers in the testing chamber near the test specimen.

Load was measured during testing by means of a load cell (L), mounted on a platform above the testing chamber. This load cell consisted of a steel bar 1 inch wide, 5/8 inch deep, and 24 inches long, mounted on standard static-bending supports over a 22-inch span. A knife edge resting at the center of this bar was connected to a steel rod projecting through the top of the testing chamber and connected to the grips holding the specimen. Both tension and compression testing grips were designed to apply a tensile load to the connecting rod, which resulted in a downward deflection of the steel bar. An SR-4 Type A-1 strain gage was bonded to the upper surface of the bar near the load point, and a similar gage was bonded to the lower face directly below the upper gage. One gage was used as the measuring gage and the other as the compensating gage, providing automatic temperature compensation and increased sensitivity. The bar was calibrated before use and periodically thereafter, enabling the strain indicated in microinches on an SR-4 Strain Indicator to be converted to pounds by means of this simple conversion factor: approximately 0.20 pound per microinch of indicated strain.

Strain of specimens during test was measured by means of a pair of clip gages between the "ears" of a modified Peters averaging extensometer. The sensing elements of each clip consisted of two SR-4 Type AB-3 high-temperature strain gages bonded to a 0.030-inch-thick strip of phosphor bronze by means of a phenolic resin adhesive supplied with the gages. Brass legs rigidly fixed to each end of the phosphor bronze strip served to connect the clip between a pair of ears of the extensometer, where it was held in place by the spring action of the phosphor bronze strip. The outer gages of the two clips were connected in series, as were the two inner gages, one series being used for measuring and one for compensating. This pair of clips was calibrated before use and periodically during use by means of a Zeiss Comparator. The calibration curve was linear, corresponding to about 0.00007 inch per microinch of indicated strain on an SR-4 strain indicator. The phosphor bronze strips with the attached gages and lead connections were given several thin coats of Goodyear Pliobond adhesive to minimize the penetration of moisture into the electrical circuits.

Testing Procedure

In the testing chamber the proper temperature and humidity conditions of test were established. Specimens conditioned to the proper moisture content at 80° F. (or 35° F. in the case of green specimens) were then placed in the chamber, as required to provide a half-hour storage period under test conditions before testing. Estimates of rate of heating based on the various temperature and moisture content conditions employed in this study indicated that this conditioning period was adequate for all parts of the test specimens to reach a temperature within 2 degrees of testing conditions. Sample specimens with thermocouples on the surface and at midthickness showed that test temperature was attained throughout the specimens in less than 10 minutes.

Tension specimens were removed from the chamber, measured, and gripped between steel grips, using a specially designed jig to center the specimens both vertically and horizontally in the grips. The extensometer was attached over a 1-inch gage length at the center of the net section. Specimens were returned to the chamber for testing as shown in figure 6. The lower grips were connected to the movable head of the testing machine by means of a pin-connected joint that allowed free rotation. The upper grips were connected to a universal joint at the lower end of the connecting rod from the calibrated load bar, and the clip gage was attached to the extensometer. When the conditions in the chamber had stabilized and the specimen was again in equilibrium with the chamber conditions, the test was begun.

Tension specimens were loaded to failure at a machine head speed of 0.037 inch per minute with strain read at predetermined load increments to give at least 10 or 12 readings below the proportional limit. These load increments varied from 10 to 50 microinches on the strain indicator attached to the load cell (approximately 2 to 10 pounds). After the specimen failed, it was weighed, and moisture content was determined by the ovendrying method. Specimens that failed outside the net section were discarded. Load-deformation curves were plotted for all specimens and from these curves values were taken for computation of modulus of elasticity, proportional limit stress, and maximum stress.

Testing procedure for compression specimens was similar to that for tension specimens, except that the extensometer was placed to give a 1-1/8-inch gage length and the specimen was held in a stirrup-type jig as shown in figure 7. Since the load cell was designed to operate in tensile loading only, this jig was designed so that a compressive load could be applied with the same machine movement used in tension. The stirrups were rigidly attached to upper and lower connecting rods and were completely free of each other. A 1/4-inch-diameter dowel pin was loosely fitted between them so as to guide their movement in a parallel direction but not restrain it in any manner. The upper end of the specimen rested against a carefully machined bearing surface and the lower end of the specimen rested against a plate with a spherical mounting to take up slight irregularities in machining the ends of the specimen. Compression specimens were loaded at a machine head speed of 0.012 inch per minute in order to give approximately the same rate of loading in inches per inch of specimen length as in tension testing. Since there is no real maximum load in compression perpendicular-to-grain, compression tests were continued to 2.5 percent strain. This point was generally higher than the maximum load in tension under similar conditions; in most cases it was beyond that point in the load-deformation relationship at which deformation begins to increase very rapidly with small increases of load. Specimens were removed from the chamber when 2.5 percent strain had been reached. Moisture content and specific gravity based on volume at test were computed, volume being determined by measurement. Load-deformation curves were plotted for all specimens and from these were computed values of modulus of elasticity, proportional limit stress, and stress at 2.5 percent strain.

A slight modification was made in testing green specimens in both tension and compression. In order to avoid the electrical measurement difficulties due to short-circuits in the strain gages at 100 percent relative humidity, the chamber was set to maintain a wet-bulb temperature equal to the desired test temperature with about a 5° wet-bulb depression. A cloth wick was wrapped around the specimens before they were tested, as shown in figure 8. This wick was given enough slack between the gage points to avoid any restraint in tension testing. The wick was kept moist at all times by means of a separate wick connected between it and the water box for the wet-bulb thermometer inside the chamber. The specimen then became--in effect--a wet-bulb, and was maintained at the wet-bulb temperature of the chamber in a localized atmosphere of 100 percent relative humidity, while the relative humidity of the chamber was approximately 90 percent.

Statistical Design

Tension and compression tests conducted in this phase of the study were organized for statistical analysis according to a randomized block factorial design, as described by Cochran and Cox (10). Tension testing was set up as a 4 x 3 x 3 x 4 factorial (4 logs x 3 angles to the growth rings x 3 temperatures x 4 moisture content levels). Compression testing was set up as a 4 x 3 x 4 factorial (4 logs x 3 temperatures x 4 moisture content levels). This type of experimental design was selected because it offers the advantages over other designs of (1) increased efficiency, since each observation supplies evidence on the response to two or more factors; (2) a more comprehensive experiment, since it measures both the direct effects of the factors and their interactions; and (3) providing a broader base for inferences concerning any individual factor than if the experiment were limited to a single combination of the remaining factors. Main effects and most first-order interactions were broken down into linear and quadratic components according to methods outlined by Yates (70) and by Bliss and Calhoun (6). In determining linear and quadratic components of the moisture content main effect, values based on green specimens were separated from those based on specimens at 18, 12, and 6 percent moisture content. The breakdown of first-order interactions involving the moisture content effect was confined to those data taken on 18, 12, and 6 percent material. Main effect of the random variable (log) and interactions involving this variable were tested for significance by the F-test based on the mean square of the error term. Main effects of the fixed variables (temperature, angle, and moisture content) and interactions involving these variables only were tested for significance by the F-test based on the next higher order interaction with the random variable, as described by Bennett and Franklin (5). This procedure seems to offer a more accurate basis for the variance ratio involving fixed variables, particularly when the next higher order interaction with the random variable is statistically significant.

Shear Properties

It is very difficult to determine accurate values of modulus of rigidity experimentally by means of a shear test involving direct measurement of stress and strain. It is also difficult to determine accurate values of maximum shearing stress experimentally, since shear tests (for example, the block-shear test) generally introduce stress concentrations that render the accuracy of the maximum stress values obtained extremely doubtful. Relationships that have been developed on the basis of the mathematical theory of elasticity as applied to orthotropic materials--that is, materials having three mutually perpendicular planes of elastic symmetry--make possible the calculation of theoretical values of modulus of rigidity and maximum shearing stress; these values are probably more nearly descriptive of the shearing properties of the materials concerned than are values based on actual tests in shear. On the basis of these relationships, shearing properties in the plane of two orthotropic axes can be calculated from the results of tension tests conducted parallel to each of these axes and in one direction intermediate to the two axes.

Norris and McKinnon (45) present an equation based on fundamental relationships developed by March (37), which relates modulus of rigidity to the moduli of elasticity determined from tension tests conducted along two orthotropic axes and in one intermediate direction, as follows:

$$\frac{1}{E_x} = \frac{\cos^4\phi}{E_\alpha} + \frac{\sin^4\phi}{E_\beta} + \left[\frac{1}{G_{\alpha\beta}} - 2\frac{\mu_{\alpha\beta}}{E_\alpha}\right] \sin^2\phi \cos^2\phi \qquad (1)$$

Where E_α = modulus of elasticity parallel to orthotropic axis α

E_β = modulus of elasticity parallel to orthotropic axis β

E_x = modulus of elasticity at angle ϕ to α

$G_{\alpha\beta}$ = modulus of rigidity associated with strain in the $\alpha\beta$ plane

$\mu_{\alpha\beta}$ = Poisson's ratio of contraction in the β direction to extension in the α direction due to a tensile stress in the α direction.

When E_α, E_β, E_x, and $\mu_{\alpha\beta}$ are known, $G_{\alpha\beta}$ can be computed by transposing equation (1) to the form

$$\frac{1}{G_{\alpha\beta}} = \frac{1}{\sin^2\phi \cos^2\phi \, E_x} - \frac{\cos^2\phi}{\sin^2\phi \, E_\alpha} - \frac{\sin^2\phi}{\cos^2\phi \, E_\beta} + \frac{2\,\mu_{\alpha\beta}}{E_\alpha} \qquad (2)$$

In the special case where angle ϕ is taken as 45°, equation (2) reduces to the form

$$\frac{1}{G_{\alpha\beta}} = \frac{4}{E_x} - \frac{1}{E_\beta} - \frac{1 - 2\,\mu_{\alpha\beta}}{E_\alpha} \qquad (3)$$

Since the present study involves perpendicular-to-grain tension tests at 0°, 90°, and 45° to the growth rings under various conditions of temperature and moisture content, it is possible to calculate the value of modulus of rigidity G in 0° to 90° (TR) plane under these conditions by substituting in equation (3) the appropriate values of modulus of elasticity at 0°, 90°, and 45° for E_α, E_β, and E_x, respectively. This has been done, using for $\mu_{\alpha\beta}$ the value 0.30 reported by Kollmann (31) as the μ_{TR} of oak.

Norris (43) presents an equation relating shear strength to tensile strength in the direction of two orthotropic axes and one intermediate direction, as follows:

$$\frac{1}{F_x^2} = \frac{\cos^4\phi}{F_\alpha^2} + \frac{\sin^4\phi}{F_\beta^2} + \left[\frac{1}{F_{\alpha\beta}^2} - \frac{1}{F_\alpha F_\beta}\right] \sin^2\phi \cos^2\phi \qquad (4)$$

Where F_α = tensile strength parallel to orthotropic axis $\underline{\alpha}$

F_β = tensile strength parallel to orthotropic axis $\underline{\beta}$

F_x = tensile strength at angle $\underline{\phi}$ to $\underline{\alpha}$

$F_{\alpha\beta}$ = shear strength associated with strain in the $\underline{\alpha\beta}$ plane.

Where $\underline{F_\alpha}$, $\underline{F_\beta}$, and $\underline{F_x}$ are known, $\underline{F_{\alpha\beta}}$ can be computed by transposing equation (4) to the form

$$\frac{1}{F_{\alpha\beta}^2} = \frac{1}{\sin^2\phi \cos^2\phi F_x^2} - \frac{\cos^2\phi}{\sin^2\phi F_\alpha^2} - \frac{\sin^2\phi}{\cos^2\phi F_\beta^2} + \frac{1}{F_\alpha F_\beta} \qquad (5)$$

In the special case where angle $\underline{\phi}$ is taken as 45°, equation (5) reduces to the form

$$\frac{1}{F_{\alpha\beta}^2} = \frac{4}{F_{45}^2} - \frac{1}{F_\alpha^2} - \frac{1}{F_\beta^2} + \frac{1}{F_\alpha F_\beta} \qquad (6)$$

The relationship shown in equation (6) makes possible the calculation of maximum shear strength in the 0° to 90° (TR) plane by substituting the experimentally determined values of maximum strength in tension perpendicular to the grain at 0°, 90°, and 45° to the growth rings, for $\underline{F_\alpha}$, $\underline{F_\beta}$, and $\underline{F_x}$, respectively.

Results

Results of tests in tension perpendicular to the grain at 0°, 45°, and 90° to the growth rings at all combinations of temperature and moisture content investigated are shown in table 1. Results of tests in compression perpendicular to the grain at 0° to the growth rings at all combinations of temperature and moisture content investigated are shown in table 2. Theoretical values of modulus of rigidity and maximum shear strength associated with the radial and tangential directions, calculated on the basis of tension tests at 0°, 45°, and 90° to the growth rings, are presented in table 3. Modulus of rigidity values were calculated from data on modulus of elasticity in tension at 0°, 45°, and 90° to the growth rings by means of equation (3). Maximum shear strength values were calculated from data on maximum stress in tension at 0°, 45°, and 90° to the growth rings by means of equation (6).

Curves showing the relationship of modulus of elasticity in tension and compression perpendicular to the grain to moisture content and temperature are shown in figure 9, 10, 11, 13, and 14. A composite graph showing the relationship of modulus of elasticity in tension to temperature, moisture content, and angle of loading is shown in figure 12. Curves showing the relationship of proportional limit stress in tension and compression perpendicular to the grain to moisture content and temperature are shown in figures 15 through 18. Curves showing the relationship of maximum stress in tension perpendicular to the grain to moisture content, temperature, and angle of loading are shown in figures 19 through 22. Curves showing the relationship of maximum strain in tension to moisture content and temperature are shown in figures 23 through 25. Curves showing the relationship of compressive stress at 2.5 percent strain to moisture content and temperature are shown in figure 26. Curves showing the relationship of calculated values of modulus of rigidity and maximum shear strength in the TR plane to moisture content and temperature are shown in figures 27 and 28, respectively.

Since control of temperature during testing was more precise and accurate than control of moisture content, especially at the nominal 18 percent moisture content level, a family of curves for the three temperature levels was fitted mathematically to the test data for each property at each angle of loading at the actual test moisture content values. It was found that the data for each property at each angle of loading could be fitted by a family of curves based on a general equation that assumed a parabolic relationship to moisture content and a linear relationship to temperature. This equation has the form:

$$Y = a + bT + cM + dM^2 + eTM + fTM^2 \qquad (7)$$

Where Y = the value of the property in question

T = temperature

M = moisture content

and a,b,c,d,e, and f are constants.

In view of the differences in curvature of the moisture content relationships of many properties, the parabolic form gave a better fit, in general, than would the exponential relationship to moisture content proposed by Wilson (66) and subsequently found to be applicable to most mechanical properties. The assumption of a linear temperature effect for all properties is not strictly accurate, as evidenced by the significant (though small) quadratic component of the temperature effect for a few properties. Since this study was designed to be extensive in nature rather than intensive and to indicate trends rather than exact relationships, the assumptions would seem tenable.

It is worth noting in this connection that values cited by Wilson for many properties at moisture content levels of less than 8 percent showed a definite tendency to fall below the lines indicating the exponential relationship to moisture content. Wilson recognized this tendency and omitted those values in computing values of intersection point. Likewise, Wilson omitted data from specimens tested at the highest moisture content below the green condition because of difficulty in obtaining uniformity of moisture distribution within and between specimens. Furthermore, the primary purpose of Wilson's work was to provide a convenient and reasonably accurate method of adjusting strength values for differences in moisture content within the most common range below the fiber saturation point, rather than to establish the fundamental relationship between properties and moisture content. It should also be remembered that the data on which Wilson based his computations were not obtained under controlled temperature conditions; since this testing took place over a rather extended period, it is possible that normal fluctuations in room temperature had considerable effect on the results.

Sulzberger (56) found that quadratic equations gave an appreciably better fit of his strength-moisture data on tests at 20° C. than did the exponential relationship. This was particularly true at low moisture content levels. Many of Sulzberger's (55) curves have the same basic form as those reported in this study--convex upward at low temperatures and concave upward at high temperatures, with a gradual transition through a nearly linear relationship to moisture content at some intermediate temperatures. Sulzberger's study included tests at more temperature and moisture content levels than did this study and therefore provided considerably more data on which to establish the relationship between various static properties and moisture content.

The equations calculated for the various properties are listed in table 4 and are plotted in the figures showing the relationship of the property in question to moisture content and temperature, along with the average test values. The average test values for green material were also plotted in the "A" portion of each figure; the intersection point was indicated by extending a horizontal line at the level of the average for green material to the point of intersection with the fitted curve for the corresponding temperature. A straight-line relationship of green values to temperature was added to those based on fitted curves in the "B" portion of each figure.

The effect of temperature on perpendicular-to-grain properties in tension, compression, and shear was calculated from the slopes of the lines in the "B" portions of figures 9 through 28, and is shown in table 5. These values express the reduction per degree F., with increasing temperature within the range 80° to 180° F. as a percentage of the values at 80° F. for each moisture content level investigated.

Discussion of Results

General

The equipment used for measurement of deformation and load throughout this phase of the study performed satisfactorily, although increased sensitivity of both the clip gages and the load cell would have been advantageous. Temperature in the test chamber was well controlled, especially at the 130° and 180° levels. The 80° temperature level was so close to the usual room conditions that considerable care and adjustment were required to prevent fluctuations of more than 2° F. The moisture content control during testing was generally reliable except at the 18 percent moisture content level. Although the conditioning apparatus for the test chamber was originally designed to be operated as a reheat system, which would continually reheat and recirculate saturated air to produce steady humidity conditions, it could not be operated successfully as such. This probably contributed to the variability of moisture content.

The test results reveal that tensile properties under 0° loading are generally quite similar to those under 45° loading, while tensile properties at 90° loading are generally different from those at both 0° and 45° loading. This appeared to be the case for all tensile properties except maximum strain, which was about the same at all angles of loading. The reason for this similarity of properties under 0° and 45° loading probably lies principally in the fact that deformation and final failure at these two angles of loading appear to be associated with the large rays that are characteristic of red oak. Loading at 90° to the growth rings was parallel to the large rays, so that the load was probably supported mainly by the vessels and thick-walled fibers. Specimens loaded in tension at 90° to the growth rings characteristically failed in a zone of large springwood vessels, which are normally the weakest portion of the wood at this direction of loading.

The points of intersection of the curves fitted to the data for 6, 12, and 18 percent moisture content with the horizontal lines drawn at the level of the green values are generally below the 25 percent value that would ordinarily be applied to this species (64). Stamm (67) has indicated that the fiber saturation point of wood would be expected to decrease linearly about 0.1 percent for each 1° C. increase in temperature above 25° C. The intersection point as ordinarily determined on the basis of strength tests is lower than the fiber saturation point, but is undoubtedly related to the fiber saturation point and would be expected to show this same tendency. Ellwood (14) observed a decrease in the intersection point with increasing temperature for most perpendicular-to-grain mechanical properties of beech. Data of the present study show a decrease in the intersection point with increasing temperature for some (but not all) perpendicular-to-grain properties of red oak.

The inconsistency in the observed values of the intersection point is probably due to one or more of several likely sources of error. It is quite apparent, for instance, that any error in the value for green material will have a marked effect on the intersection point corresponding to that temperature. This is particularly noticeable in the curves based on data taken at 180°, where the approach to the intersection point is almost asymptotic in some instances. Since values for green material could not be included in the mathematical fitting of the curves, the horizontal lines indicating the level of these green values are subject to considerably more error than the lines fitted to the values for material at moisture content levels below the fiber saturation point. The "A" portions of several of the figures show that the values for green material deviated from the linear temperature relationship that was indicated by the statistical analysis of the values for drier material and assumed in fitting curves to the latter values. If the values for green material were extended to the intersection point at a level corresponding to the linear relationship indicated in the "B" portions of the curves, some of the inconsistency in the intersection points would be removed.

Sulzberger's (55) curves, indicating the relationship between maximum crushing strength and moisture content at low temperatures (room temperature and lower), have a flattened sigmoid form; the curves are convex upward at moisture content levels below about 16 percent, changing to concave upward at higher levels of moisture content near the intersection point. Continuing the simple parabolic curvature to the intersection point (as was done in this study) tends to lower the apparent intersection point when the curve is convex upward. The data of this study are too limited, however, to justify a reverse curvature like that indicated by Sulzberger.

In view of the inconsistency in the intersection points observed in this study, it is apparent that the curves must be interpreted with considerable caution, particularly in drawing conclusions relative to their intersection points. The data gathered in this study were not intended to establish exact relationships and do not justify drawing such conclusions.

The mean specific gravity of the material tested in the present study was 0.55 based on green volume and ovendry weight, a value that compares closely to the value of 0.56 listed in the Wood Handbook (64) as the average specific gravity for a large number of specimens of this same species.

Modulus of Elasticity

The analyses of variance of the data on modulus of elasticity in tension and in compression perpendicular to the grain (tables 12 and 13) show that for both types of loading this property was strongly affected by moisture content and temperature independently, and by interaction of the two. The modulus of elasticity was decreased by increasing either moisture content or temperature. In addition, the analysis of the tension data shows that the perpendicular-to-grain modulus of elasticity increased as the angle of loading (with respect to the growth rings) increased from 0° to 90°. This increase takes place almost entirely between 45° and 90°, with practically no difference between results obtained at 0° and 45° loading. (See figs. 9, 10, and 11 and the data of table 1.) There was very little difference between the four logs with respect to this property in either tension or compression; this is shown by the fact that the log effect is not significant in either case.

It is generally assumed in elasticity theory that modulus of elasticity is the same in tension and compression along the same orthotropic axis. This assumption is basic to the calculation of elastic bending properties of beams, for example. However, comparison of the analyses of variance of modulus of elasticity at 0° to the growth rings in tension and compression indicates that differences may exist in the relationship of this property to moisture content. The analysis of variance of the tension data indicates a very significant[2] linear component and a small but significant quadratic component of the moisture content effect. On the other hand, the analysis of variance of the compression data indicates that the linear effect of moisture content is very significant but that the quadratic effect is not quite significant. The plotted compression data in figure 13A show a slight but consistent curvature at each temperature level, and the sum of squares of the error

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[2] The term "very significant" denotes statistical significance at the 1 percent or 0.1 percent level of probability. The term "significant" denotes statistical significance at the 5 percent level of probability.

about the line is reduced by fitting a family of curves rather than a family of straight lines.

In order to compare modulus of elasticity at 0° to the growth rings in tension and in compression, data based on both types of test were plotted in figure 14, and were fitted by an equation based on the combined data. It is evident that the data are very similar, for both the tension and the compression data are fitted practically as well by the equation based on combined data as by the equation based on data from the particular type of test involved. This indicates that there is probably no real difference between the modulus of elasticity based on tension tests and that based on compression tests, other conditions being the same. A statistical analysis of the difference between modulus of elasticity in tension and that in compression at 0° to the growth rings confirmed this observation.

In applying these results to the interpretation of drying strain data, the use of the modulus of elasticity relationship based on combined data would apparently be justified. It is not necessarily true that compression data would be as closely comparable to tension data at angles of loading with respect to the growth rings of other than 0°. In compression testing by the method employed in this study, the ends of the specimen cannot move laterally; shearing deformation is thus restrained and the apparent modulus of elasticity tends to increase. It seems likely, however, that compression data based on a test which allowed the shearing deformation to take place would yield modulus of elasticity results similar to those observed in this study under tensile loading at 45° and at 90° to the growth rings.

In studying the perpendicular-to-grain properties of American beech, Ellwood (14) found some slight differences between the modulus of elasticity values at 0° to the growth rings based on tension tests and those based on compression tests. His results indicated a curvilinear relationship to temperature under tensile loading and a linear relationship to temperature under compressive loading, with a curvilinear relationship to moisture content under both types of loading. The nonlinear component of the tension relationship to temperature was quite small, however, and could be disregarded without introducing any substantial error. Ellwood's data were very similar under both tensile and compressive loading, and he attached no significance to any differences he found between modulus of elasticity in tension and that in compression.

The effect of temperature on modulus of elasticity in both tension and compression was predominantly linear. The reduction of modulus of elasticity with increasing temperature, expressed as a percentage of the value for 80°, was appreciably less at 6 percent moisture content than at 12 percent moisture content or higher, as is shown by the values of table 5. This reduction was also appreciably less under 90° loading than under 0° or 45° loading in tension testing at all moisture content levels. The temperature effect was slightly less under 45° loading than under 0° loading at the lower levels of moisture content, although such was not the case for material in the green condition or at 18 percent moisture content. The values of table 5 indicate that the percentagewise temperature effect was somewhat greater than that reported by Ellwood for beech. Ellwood's values of modulus of elasticity for beech are higher than those of the present study for oak, providing a larger base for the computation of percentages; however, the actual reduction of modulus of elasticity in the present study was greater up to 160° F. --the upper temperature limit of Ellwood's study--than that reported by Ellwood. This is particularly true at the lower levels of moisture content.

The three-dimensional graph of figure 12 shows quite clearly the relationship between angle of loading and temperature for tensile modulus of elasticity at several levels of moisture content. This figure illustrates the rapid increase in modulus of elasticity as angle of loading was increased from 45° to 90° to the growth rings at all temperature levels. This effect tended to decrease as temperature was increased and was also markedly less pronounced in green material than in material at 6 percent moisture content.

Proportional Limit Stress in Tension

Proportional limit stress in tension perpendicular to the grain was reduced by increasing temperature or moisture content, and increased by increasing the angle of loading with respect to the growth rings. The increase in proportional limit stress in tension with angle of loading was not as great, in general, as that of modulus of elasticity. The data on proportional limit stress are characterized by somewhat more scatter than those on modulus of elasticity or maximum load in tension. This is to be expected, since the value of proportional limit stress is largely dependent on the judgment of the person analyzing the individual load-deformation curves.

The analysis-of-variance table for proportional limit stress in tension (table 14) indicates very significant linear effects of both temperature and moisture content and very significant linear and quadratic effects of angle of loading. The source of material had little or no effect on this property. Although the quadratic component of the main effect of moisture content was not significant, both linear and quadratic components of the moisture content effect showed very significant interactions with the linear temperature component. This interaction of the moisture content and temperature effect was characteristic of all properties studied; it reflects the greater weakening of the wood due to increased temperatures in the presence of a greater amount of moisture below the fiber saturation point.

The trends in the relationship of proportional limit stress in tension to moisture content are generally similar to those observed by Ellwood (14). The relationship to temperature is slightly different, in that Ellwood reports a significant quadratic component; but the fact that the coefficients of the quadratic terms in Ellwood's regression equations for this property are all small, and the curvature of the regression lines rather slight, indicates that although the departure from linearity is statistically significant, it must not be large.

The values of percentage reduction in proportional limit stress in tension listed in table 5 indicate that the percentagewise temperature effect increased with increasing moisture content at all angles of loading. In general, the temperature effect decreased with increasing angle of loading. This is not apparent at all levels of moisture content, however; it was most pronounced at the 6 percent moisture content level. The temperature effect on proportional limit stress in tension was greater at all levels of moisture content than that reported by Ellwood for beech.

Proportional Limit Stress in Compression

The results of this study indicate that proportional limit stress in compression perpendicular to the grain at 0° to the growth rings was very nearly the same as that in tension at the same angle of loading at intermediate moisture content levels; it was higher at 6 percent moisture content and in the green condition. Since the assumption in elasticity theory that presupposes equality of modulus of elasticity in tension and compression does not extend to include strength properties, the proportional limit stress in compression is treated separately in this discussion.

The analysis-of-variance table for this property (table 15) indicates that the main effects of both temperature and moisture content consisted primarily of large and very significant linear components, though in both cases small but significant quadratic components were also present. The source of material had a very significant effect on this property, in contrast to the comparable property in tension on which differences between logs had no significant effect.

The proportional limit stress in compression was reduced slightly less per 1 percent increase in moisture content and appreciably more per degree increase in temperature than was observed by Ellwood for beech. The percentage decrease in proportional limit stress with increasing temperature was likewise considerably higher than that reported by Ellwood.

The relationship of proportional limit stress in compression to both temperature and moisture content was very similar to that observed in tension at the same angle of loading. The compression values are slightly higher than the tension values at 6 percent moisture content under all temperature conditions and at 80° F. under all moisture content conditions, though the fitted curves coincide very closely at moisture content levels of 12 percent and 18 percent. The percentage of temperature effect was practically the same in compression as in tension except in green material, where the tension data show a substantially greater temperature effect.

Maximum Stress in Tension

Maximum stress in tension was reduced by increasing either moisture content or temperature within the range of 6 to 18 percent moisture content and 80° to 180° F. It was also considerably higher at 90° to the growth rings than at either 0° or 45° to the growth rings.

The analysis of variance of this property (table 16) indicates a strong linear relationship to moisture content. The data at 80° and 180° F. indicated a definite curvature; the 80° data formed a distribution that was concave downward and the 180° data formed a distribution that was concave upward, to suggest that these two opposing types of curvature might be compensating to give a linear overall effect. Separate statistical analyses were therefore carried out on the data at each temperature level. These analyses indicated a pronounced departure from linearity at 80° and 180° F., but not at 130°, and led to the conclusion that this opposing curvature should be taken into consideration when fitting curves to the data. The fact that the relationship to moisture content varied at the different temperatures is indicated by the large and very significant components of the moisture content-temperature interaction, particularly the interactions involving the linear and quadratic moisture components and the linear temperature component.

The relationship of maximum stress in tension perpendicular to the grain to moisture content at 80°, and to some extent at 130°, is at variance with the exponential relationship that is generally considered to apply to most strength properties under room temperature conditions. Ellwood (14) observed a linear relationship to moisture content for maximum stress in tension perpendicular to the grain of beech. Sulzberger (55) found that the maximum crushing strength of several Australian species was related to moisture content in a manner quite similar to that observed in the present study, as discussed above (pp. 42, 43).

The effect of temperature on maximum stress in tension was predominantly linear, both in its main effect and in its interactions with moisture content and with angle of loading. The values in table 5 show that the percentage of temperature effect increased with increasing moisture content, and at the same moisture content level decreased with increasing angle of loading. The curves of figures 19, 20, and 21 show that the lines expressing the relationship of this property to temperature are nearly parallel for material at 12 and 18 percent moisture content and in the green condition. These lines are all steeper than those showing the comparable relationship for material at 6 percent moisture content. Sulzberger (55) found that the temperature effect on parallel-to-grain crushing strength expressed as a percentage of the value for 20° C. increased with increasing moisture content up to a level of about 20 percent moisture content. Sulzberger also found the relationship of maximum crushing strength to temperature to be linear at all levels of moisture content with the lines expressing this relationship steeper at 8, 12, and 20 percent moisture content than at 0 percent moisture content. Ellwood (14) observed a similar linear effect for beech over the temperature range 80° to 160° F. at several levels of moisture content. Kollmann (30) established a linear relationship to temperature for maximum tensile strength perpendicular to the grain of oak (*Quercus pedunculata* Ehrh.) between 0° and 100° C. Kollmann (29) also found a linear relationship of parallel-to-grain crushing strength to temperature in ovendry material over the range from -190° C. to +160° C. These observations are all somewhat different from those of Greenhill (17), who found a curvilinear and slightly sigmoid relationship to temperature for maximum perpendicular-to-grain tensile stress of beech at several moisture content levels over the temperature range from 60° to 180° F.

The effect of angle of loading with respect to the growth rings was generally curvilinear, most of the increase taking place as the angle was changed from 45° to 90°. Figure 22 and the data of table 1 indicate that this effect was less pronounced at 180° than at 80° for material at the higher levels of moisture content, but about the same at all levels of temperature for material at 6 percent moisture content. Gaber (16) found a similar relationship to angle of loading for perpendicular-to-grain crushing limit of several hardwoods at about 13 percent moisture content. Gaber's results also indicated that softwoods may show a considerably different relationship to angle of loading than hardwoods.

Values of maximum tensile stress perpendicular to the grain obtained in the present study at 80° F. under 0° loading are lower for green material and higher for material at 12 percent moisture content than values based on the standard ASTM test for maximum strength in tension perpendicular to the grain (64). The ASTM test is based on loading at both 0° and 90° to the growth rings. Results of the present study at 80° F. for 90° loading are higher for both green and 12 percent material than the standard ASTM values for the species. These comparisons indicate that the shape of the tension specimen used in the present study eliminates much of the stress concentration that tends to lower the apparent tensile strength in the ASTM test.

Maximum Strain in Tension

Maximum strain in tension perpendicular to the grain was related to both moisture content and temperature and was very nearly the same at all angles of loading. The analysis-of-variance table for this property (table 17) shows that both the linear and the quadratic components of the main effect of moisture content were very significant, while only the linear component of the temperature effect was significant. In addition to these main effects, the interaction between the quadratic moisture content component and the linear temperature component was very significant. In view of the extreme variability of maximum strain data, it is somewhat remarkable that so few interactions were significant.

It is generally expected that maximum strain in tension will increase as either temperature or moisture content is increased. The data of table 1 and the curves of figures 23, 24, and 25 show that the effect of moisture content on maximum tensile strain was strongly dependent on temperature. At 80° F. the maximum strain at all angles of loading increased almost linearly with increasing moisture content up to the intersection point. At both 130° and 180° F., however, the maximum strain appeared to reach a peak value at a moisture content below the intersection point and thereafter to recede to a lower value of maximum strain for green material. The maximum temperature effect seemed to take place (in terms of actual values) between 12 and 16 percent moisture content, with a relatively smaller effect for green material. The percentagewise temperature effect (shown in table 5) tended to reduce with increasing temperature at all angles of loading. It should be emphasized that these data on maximum tensile strain were characterized by a high degree of scatter, and the relationships shown should be considered as trends rather than as exact values. The type of curve shown in the figures appeared to give the best fit of the data at all angles of loading.

There is nothing in the present data to corroborate Greenhill's (17) observation of a peak maximum tensile strain at 120° F. for beech. Data of the present study indicate a general linear increase in maximum tensile strain with increasing temperature over the entire range of 80° to 180° F. In this respect, the results agree more closely with those of Ellwood (14), who observed a general linear strain-temperature relationship for beech over the range 80° to 160° F. The results of the present study also agree in general with Ellwood's observation of a lower maximum strain at 6 percent moisture content under all temperature conditions up to 160° F. than at moisture content levels of 12 percent or higher, though the demarcation between maximum strain at 6 percent moisture content and that at higher levels of moisture content was not as sharp as was that observed by Ellwood. Kollmann (30) concluded on the basis of his studies of water-saturated oak in tension perpendicular to the grain that maximum tensile strain could be considered to be practically independent of temperature over the range of 0° to 100° C. Results of the present study indicate a very small temperature effect on maximum strain in green material, particularly at 0° to the growth rings (the angle of loading employed by Kollmann); these results reasonably agree with Kollmann's findings in this respect. It appears, however, that Kollmann's conclusion regarding the negligible effect of temperature on maximum tensile strain must be restricted to green (or water-saturated) material, and possibly also to tests conducted at 0° to the growth rings.

Compressive Stress at 2.5 Percent Strain

As discussed previously, the compressive stress at 2.5 percent strain was evaluated in lieu of a maximum stress, since there is no real maximum stress in compression perpendicular to the grain. The analysis-of-variance table for this property (table 18) shows that both linear and quadratic components of the effect of moisture content on stress at 2.5 percent strain were very significant. The temperature effect was characterized by a very significant linear component. In addition, several components of the moisture content-temperature interaction were very significant.

The relationship of stress at 2.5 percent strain to moisture content (shown in figure 26) appears to conform reasonably well to the generally assumed exponential relationship, although a better fit of the data is obtained by the parabolic relationship assumed in this investigation. Ellwood (14) observed that the relationship of stress at 2.5 percent strain to moisture content for beech was linear, a marked departure from the exponential relationship. However, Ellwood's linear stress-temperature relationships agreed with those of the present study, although at all levels of moisture content the temperature effects observed by Ellwood were generally less in terms of both percentage and absolute reduction than those observed in the present study. The temperature effect observed in the present study was less, percentagewise, at 6 percent moisture content than at any of the higher levels of moisture content; and was about the same at 12 and 18 percent moisture content as in green material. The slopes of the lines expressing the stress-temperature relationship are about the same at 6 percent as at 12 percent moisture content, but are less steep for material at 18 percent moisture content and for green material. In the present study the effect of temperature on compressive stress at 2.5 percent strain was very closely comparable to that observed for other strength properties.

Shearing Properties

No statistical analyses of data on modulus of rigidity or maximum shearing strength in the TR plane was made, since the values presented were not based directly on test data, but were calculated on the basis of tension test results. As would be expected, the trends observed in the relationship of these shearing properties to moisture content and temperature are similar to those observed for the properties in tension upon which they are based: a curvilinear relationship to moisture content and a linear relationship to temperature. These relationships are shown in figures 27 and 28.

The values of modulus of rigidity listed in table 3 are generally about one-third of the modulus of elasticity in tension observed under comparable conditions of temperature and moisture content at either 0° or 45° to the growth rings, and about one-sixth of the modulus of elasticity values observed at 90° to the growth rings. The values of maximum shearing strength listed in table 3 are generally somewhat greater than one-half of the comparable values of maximum stress in tension under 0° and 45° loading, and from one-quarter to slightly greater than one-third of the comparable values of maximum stress in tension under 90° loading.

Only one other investigator, Kollmann (30), appears to have investigated shearing characteristics in connection with a study of perpendicular-to-grain mechanical properties. Kollmann conducted shear tests employing a notched tensile shear specimen designed to produce shearing stress along a radial-longitudinal plane. It has been observed in comparative tests of plywood (46) that neither the block shear test nor the notched tensile shear test give accurate indications of shear strength.

The curves of figure 28 indicate that shear strength associated with strain in the RT plane at 80° F. tends to level off and possibly decrease slightly as moisture content is decreased below 8 percent. This tendency has also been observed in ASTM block shear tests of several species at low levels of moisture content (66). No similar tendency was observed in the present study at either 130° or 180° F.

Both modulus of rigidity and maximum shear strength showed a lower percentagewise effect of temperature at 6 percent moisture content than at any higher level of moisture content. The percentagewise effect on modulus of rigidity did not change appreciably above 12 percent moisture content, but the effect on maximum shear strength increased with increasing moisture content over the entire range observed.

Tests to Determine Effects of Duration of Heating

This phase of the study was designed to provide some indication of the effect of duration of exposure to temperatures within the ordinary kiln-drying range on the short-time perpendicular-to-grain tensile and compressive properties of red oak. With a view toward application of the data to problems of kiln drying, the exposure times were planned to cover exposure periods likely to be encountered in ordinary drying schedules for a refractory wood of the type under investigation. Of considerable interest also in this phase of the study was the technique of maintaining specimens at nearly constant moisture content during the exposure period at moisture content levels intermediate between ovendry and saturation. In the extensive investigations of effects of duration of heating conducted by MacLean (34,35,36) the test material was heated in steam, in water, in a hot press, or in an oven, without regard to control of moisture content.

Tests and Test Conditions

Tension and compression specimens of the type shown in figure 2, identical to those used in the initial phase of the study, were subjected to various periods of exposure at 130° F. and 180° F. at 12 percent moisture content or in the green condition. Exposure periods were designed to give six uniformly spaced intervals on a logarithmic time scale, the maximum exposure period being 30 days.

In order to obtain suitably matched specimens, material from logs 1 and 4 only was used in this phase of the study. Material from logs 2 and 3 was reserved for subsequent creep and relaxation testing. The grouping of logs was based on the fact that material from logs 1 and 4 appeared to be relatively similar in mechanical properties, as observed in the basic short-time tests in tension and compression; this similarity was apparent also in material from logs 2 and 3.

Specimen material consisted of 2 tension and 2 compression specimens from each of the 2 logs for each of the 6 exposure times at each of the 4 combinations of temperature and moisture content--a total of 96 tension specimens and 96 compression specimens.

Testing Procedure

Specimens either conditioned to 12 percent moisture content at 80° or kept green in the cold room at 35° F. were exposed in the chamber of the test machine, in which were maintained conditions of 12 percent equilibrium moisture content at either 130° or 180° F. Specimens at 12 percent moisture content were exposed directly to the conditions of the test chamber. Green specimens were placed in a desiccator, the bottom of which was filled with distilled water and the top of which was fitted with a glass tube drawn out to a fine tip with a very small opening. The purpose of the opening was to maintain atmospheric pressure within the desiccator. This desiccator was placed in the test chamber to maintain the green test specimens in an atmosphere of essentially 100 percent relative humidity at the exposure temperature. It was found that a cloth wick extending from the water up to the level of the test specimens aided in providing more nearly 100 percent humidity in the vicinity of the specimens.

As each pair of tension specimens and each pair of compression specimens from each log completed their preassigned exposure time, they were removed from the test chamber. One specimen of each pair was then placed into a humidity room for reconditioning before testing at 80° F.; the other specimen of the pair was wrapped in a plastic bag to await testing at the elevated temperature. Specimens at 12 percent moisture content were reconditioned in a controlled atmosphere of 80° F. and 65 percent relative humidity for at least 1 month. Green specimens were stored in plastic bags in the cold room at 35° F. Specimens that were not to be reconditioned were tested immediately in the testing chamber, according to the procedures used in the basic short-time tests. Reconditioned specimens were tested in the same test chamber at 80° F. after the exposure of all specimens had been completed. Again, the testing procedures were the same as those used in the basic short-time tests in tension and compression.

Presentation of Results

Results of tests in tension perpendicular to the grain on specimens exposed for various lengths of time to 130° or 180° F. either at 12 percent moisture content or in the green condition are presented in table 6. Results of tests in compression perpendicular to the grain on specimens subjected to the same exposure conditions are presented in table 7. Data on modulus of elasticity, proportional limit stress, stress at maximum load, and maximum strain in tension perpendicular to the grain are plotted against the logarithm of exposure time in figures 29, 30, 31, and 32, respectively. Data on modulus of elasticity, stress at proportional limit, and stress at 2.5 percent strain in compression perpendicular to the grain are plotted against the logarithm of exposure time in figures 33, 34, and 35, respectively.

A linear relationship between percentage values of the various properties and the logarithm of heating time has the disadvantage of implying that the value of a property would be reduced to zero at some finite heating time; this assumption is not justifiable on a theoretical basis. The semilogarithmic plot presents the data much more clearly than would a logarithmic plot in this instance, however, and is not objectionable on a theoretical basis if the relationships indicated are not extrapolated beyond the 30-day limit of this investigation.

No overall analyses of variance were attempted, since it was apparent from the data that most of the effects relating to duration of heating would be involved in interactions. Rather, the analysis was directed toward establishing the significance of the regression of the various properties with the logarithm of exposure time under the various conditions of test. Several analyses of variance of the slopes of regression lines for the various test conditions were carried out for each property in order to determine which slopes, if any, could be combined to make best use of the experimental design for evaluating the duration of heating effects. Test condition groups for each property for which a significant negative regression was thus established are so designated in tables 6 and 7, and the regression coefficient is presented for each significant regression. Statistically significant slopes are shown in the figures presenting duration of heating data as solid lines. Where no significant slope was indicated by the analysis, a horizontal dashed line is drawn at a level corresponding to the group mean.

Discussion of Results

In spite of the fact that the data were generally too limited to indicate clearly more than the most pronounced effects of duration of heating, several instances of significant reduction in the values of perpendicular-to-grain mechanical properties with duration of heating were noted. In general, where a significant reduction in the value of a property was indicated, the relationship of the percentage of the control value to the logarithm of exposure time was quite well described by a straight line. This indicates an exponential relationship of the various properties to exposure time under constant conditions of temperature and moisture content. It has been observed by MacLean (34,35,36) that similar relationships for many parallel-to-grain mechanical properties are best represented by power functions, rather than exponential functions; MacLean's data have generally been fitted by straight lines relating the logarithm of the percentage of the control value to the logarithm of heating time.

It is evident from the values in tables 6 and 7 and the curves in figures 29 through 35 that the effects of duration of heating were much more pronounced at 180° than at 130°, and tended to be more pronounced in green material than in material at 12 percent moisture content. Both of these tendencies would be expected on the basis of MacLean's results, which showed an exponential relationship of strength to temperature at constant heating periods; these results also showed a more pronounced effect at all temperatures when heated in water than when heated in an oven. These tendencies also agree with Stamm's (53) conclusions relative to thermal degradation of wood. Stamm concluded that thermal degradation is greater under steaming than under dry heating conditions, and that activation energies of degradation reactions are about half as large under steaming conditions as under dry heating conditions at the same temperature.

Only in maximum stress and maximum strain in tension perpendicular to the grain were significant permanent effects of heating observed at 130° F. The effect on maximum strain of heating at 130° is extremely doubtful (even though statistically significant) since no such effect could be established for 180° heating. Significant permanent effects were observed for most properties after heating at 180°, particularly in the case of green material. It is generally considered that temperatures above 150° F. will have a permanent effect on strength (64). In this respect, the data of the present study indicate that some perpendicular-to-grain properties may be more sensitive to permanent heating effects than are the parallel-to-grain mechanical properties previously investigated. This is especially apparent for green material heated at 180° F., which showed somewhat greater reduction in strength than was reported by MacLean for the same duration of heating in water at 200° F. Such comparisons are necessarily somewhat uncertain, however, because of the differences in test conditions, species, and types of test involved.

Heating for 30 days at 130° F. did not have any significant effect on modulus of elasticity in either tension or compression in material either conditioned at 12 percent moisture content or kept in the green condition. However, a significant reduction of modulus of elasticity in tension with increased heating time was established for 180° heating at both moisture levels; the effect of heating was much more pronounced in green material than in material at 12 percent moisture content. The comparable compression data were too scattered to permit establishment of significant regression lines for the material heated at 180°, except for green material that was tested at 80° F. The slope of the line expressing the reduction in modulus of elasticity of this latter group with time of heating was very nearly the same as that for the comparable tension data. This fact, coupled with the general trends of the other 180° compression data, indicates that the reduction of modulus of elasticity in compression was probably very similar to that in tension, and could be expressed with reasonable accuracy by the same regression coefficients.

No significant effect of heating at 130° on proportional limit stress in either tension or compression was observed. Data on proportional limit stress in tension show a significant permanent reduction for green material heated at 180°, but the other data taken at this temperature were too scattered to establish significant regression lines. These other data do show indications of a slight reduction, however, which would very likely be established by a larger number of tests than were conducted in the present study. The permanent reduction in proportional limit stress in tension at 180° for green material was about the same as that for modulus of elasticity under the same conditions. This latter relationship also held true in compression at 180° for green material; the regression lines for proportional limit stress in compression at 12 percent moisture content have about the same slope as those for modulus of elasticity in tension under comparable conditions.

Maximum stress in tension perpendicular to the grain was apparently somewhat more sensitive to duration of heating effects than were the other properties investigated. Significant reduction in maximum stress was observed at 130° for reconditioned material at both 12 percent moisture content and in the green condition; the percentage reduction was about the same at both levels of moisture content. Marked reduction in this property was observed at both moisture content levels under 180° heating, both in the material tested at 180° and in that reconditioned and tested at 80°. The percentage reduction was greater for green material than for material at 12 percent moisture content, as would be expected. In all cases, the regression coefficient for this property is higher than that for other tensile or compressive properties investigated under comparable test conditions, except for the single instance of a steeper significant regression of tensile strain at maximum load under 130° heating. This marked reduction in perpendicular-to-grain tensile strength with duration of heating is likely to have a very great influence on the development of drying defects, particularly in the case of thick stock in which the core is likely to be at a moisture content above the fiber saturation point for a long period under kiln-drying conditions.

Data on tensile strain at maximum load were too scattered, in general, to establish significant regression lines. The only group for which the data showed a small enough variance--consistent with the slope--to establish a significant regression line was the 12 percent moisture content material heated and tested at 130° F. Several other groups show evidence of a slight downward trend with increasing heating time, although extreme variability rendered the regressions not statistically significant. The overall indication is that the immediate effect of heating was to increase the strain at maximum load and that this strain was then reduced slightly by continued heating at the same temperature. As was observed in the basic portion of the study, the immediate effect of temperature was appreciably less for green material than for material at 12 percent moisture content, and was less for material at 12 percent content heated to 130° than for material at the same moisture content heated to 180°.

Compression stress at 2.5 percent strain, though not really comparable to maximum stress in tension, was affected in a somewhat similar manner by duration of heating. However, it was apparently less sensitive to permanent effects of heating than maximum stress in tension. No significant effects were observed at 130°, but significant regression lines were established for all groups at 180°. These regression lines indicate a greater permanent effect of heating for the reconditioned green material than for reconditioned material at 12 percent moisture content, though the percentagewise effect on material tested at 180° was about the same at both levels of moisture content.

The overall impression given by these data is that the perpendicular-to-grain mechanical properties of wood are subject to heating effects under the conditions of temperature, moisture content, and heating time involved in normal kiln drying. The reduction in strength indicated on the basis of the present test results appears to be great enough to contribute significantly to the development of drying defects, and is somewhat greater than that previously indicated by the work of MacLean (34,35,36), Stamm (53), and Comben (11), which was based on parallel-to-grain properties. It is interesting to note, however, that work done in Australia (12) did indicate a significant effect of temperature and duration of heating on the strength and modulus of elasticity in tension perpendicular to the grain of four species. The magnitude of the strength reduction indicated by the results of the present study can be fully appreciated only when it is remembered that the time scale of the regression lines is logarithmic. This means that 1/3 of the observed reduction took place within the first 3 days, and well over 1/2 of the observed reduction took place within the first week, of heating. Figure 31 indicates, for example, that maximum tensile strength perpendicular to the grain in a direction parallel to the growth rings would be reduced from the value obtained by merely heating to 180° before testing (as in the first phase of this investigation) to about 80 percent of this value after heating at 180° for a week at 12 percent moisture content, or for just 3 days in the green condition. This fact, coupled with the reduction in effective strength due to creep under load, could have serious implications with regard to the development of drying defects.

Another interesting conclusion to be derived from these data is that most of the reduction in strength that is caused by duration of heating is permanent, not recoverable by reconditioning to the same moisture content at room temperature. Furthermore, in most instances where a significant regression could be established for both material tested at exposure conditions and that reconditioned and tested at 80°, the ratio of the value of the property at exposure conditions to that for material reconditioned and tested at 80° after the same duration of heating was approximately constant at a value very nearly equal to the ratio for the control material (zero time). If substantiated by additional experimentation, this fact would prove useful for the determination of perpendicular-to-grain mechanical properties under drying conditions; it would also prove useful for the application of data on parallel-to-grain heating effects (such as that presented by MacLean) to conditions where structural timbers are heated for long periods of time while in service. A knowledge of the immediate effect of heating, coupled with existing data on the strength reduction observed in material reconditioned after various periods of heating, would make possible the consideration of permanent heating effects in the design of such structures.

Creep and Recovery Tests

This phase of the investigation was designed to explore one portion of the perpendicular-to-grain rheological properties of red oak in tension and compression, as related to temperature, moisture content, and level of stress. As in other phases of the study, tests and test conditions were planned to provide data that would be applicable to a fundamental understanding of problems associated with kiln drying. The usual duration of test was approximately 3 days (72 hours), a much shorter time than those of several months or years that are commonly used in creep or stress relaxation tests of wooden members for structural applications. The short duration of test was selected because drying strain studies (39,40) have indicated that any one portion of the cross section of a drying board is rarely subjected to stresses in the same direction of even approximately a constant order of magnitude for longer than 3 days under normal drying conditions. Actually, of course, the stresses to which any one portion of a drying board are subjected are never constant and are in a continual state of flux. For that reason, any analysis based on constant stress (as in creep) or constant strain (as in stress relaxation) is only an approximation at best. It is highly probable, however, that such data based on steady stress or strain conditions can be applied to the solution of drying problems involving unsteady conditions. Moreover, such an approach is probably the only practical one, since controlled testing under unsteady conditions would be virtually impossible either to execute or interpret.

Tests and Test Conditions

The investigation was designed to include creep and recovery tests in tension and compression perpendicular to the grain at two levels of temperature, 80° and 180° F.; two levels of moisture content, 12 percent and green; and six levels of constant stress under each condition, with one specimen from each of two logs to be tested at each stress level. The stress levels selected were 40, 50, 60, 70, 80, and 90 percent of maximum load in tension, as determined by the short-time static tests of the first phase of the investigation. Experimental difficulties and rapid failure of specimens--particularly in testing at 180° F.--prevented the collection of good data for many specimens, however; and it was not possible to obtain a complete set of data for the entire range of test conditions.

Specimens were assigned to test conditions on the basis of the random assignment carried out at the beginning of the investigation for all tests of all phases. Tension and compression specimens were identical in size and shape to those used in other phases of the work. Specimens for tests at a nominal moisture content of 12 percent were conditioned for several months in a room that was controlled at 80° F. and 65 percent humidity. Specimens for tests in the green condition were stored in plastic bags in a room controlled at 35° F. and 90 percent humidity.

The testing equipment for creep and recovery tests in tension and compression is shown in figure 36. Each unit consisted of a tall sawhorse from the top of which was suspended a system for holding the specimen and applying to it a steady load. The system of holding the specimens was similar to that used in the basic mechanical tests, except that the design of the compression jig was changed slightly to reduce weight and improve stability. The specimen-holding system was attached to the sawhorse by means of a bolt eye fitting over a clevis, allowing rotation in any direction to compensate for specimen and loading eccentricity. To the bottom of the specimen-holding system was attached a redwood box for holding weights. This, too, was attached by means of a universal joint to take up loading eccentricity. In the unloaded condition, the weight box was supported by two wood blocks 6 inches square in cross section. Load was applied by turning the hand screw at the top of the sawhorse, which raised the loading system off the blocks and transferred the load to the specimen. To one of the blocks was attached a lever-actuated microswitch connected to an hour meter. The microswitch turned on the hour meter when the box was raised off the blocks and stopped the hour meter when the box returned to its resting position on the blocks, thus providing an accurate measure of time under load.

Strain was measured by means of clip gages similar to those used in the short-time tests. Legs cut from a section of stainless steel angle iron were substituted for the brass legs, however. These legs were somewhat shorter than those of the clip gages used in the earlier phase of the study and were designed to permit use of a longer phosphor bronze backing strip. The strain was measured over a 1-1/4-inch gage length at the center of the net section, between brass knife edges that were mounted in pairs on opposite sides of the specimen and screwed together to give a rigid attachment to the specimen. The slightly different clip gage design and greater gage length approximately doubled the sensitivity of the strain measurements. One microinch of indicated strain on an SR-4 strain indicator corresponded to a specimen strain of about 0.000034 inch per inch, as compared to 0.00007 inch per inch for the clip gages used earlier in the investigation.

Four of these units were constructed, two for tension testing and two for compression testing. For creep and recovery tests at 80° F. the equipment was set up in the 80°-65 percent humidity room used for conditioning the 12 percent specimens. For tests at 180° F. the four units were placed in a small drying chamber that could be controlled at the desired testing conditions. For these latter tests the strain gages were connected to an SR-4 strain indicator outside of the chamber, making possible remote strain readings without disturbing test conditions. The hour meters were also located outside the test chamber. The short hand screw for applying and removing load was replaced by a long screw that extended through the roof of the drying chamber to permit loading and unloading without opening the chamber.

Testing Procedure

The specimens for creep and recovery testing were measured and weighed before being placed in the test apparatus. Green specimens, which had been stored at 35° F., were allowed to come to room temperature in a plastic bag before measuring in order to eliminate effects of thermal expansion. The knife edges were then located on the specimen by means of a gage block designed for the purpose and were secured in place by tightening the thumbscrews finger tight. Specimens were gripped in the same manner as for the short-time tests. When the specimens had been placed in the testing apparatus, the clip gages were attached to the knife edges. Green specimens tested at 80° F. were kept green by enclosing the specimen and grips in a plastic covering that was secured at the top and bottom and in which was placed a water-saturated cloth to maintain a high relative humidity within the enclosure. Green specimens tested at 180° F. were kept green by means of a wick wrapped around the specimen and attached to a water supply, an arrangement similar to that for short-time tests of green material. The chamber was then controlled at a wet-bulb temperature of 180° with about a 5° wet-bulb depression, instead of at 180° dry bulb with a 9° wet-bulb depression as for the specimens at 12 percent moisture content. Sufficient lead shot was placed in the load box to produce the desired stress on the specimen, the tare weight of the box and all hardware supported by the specimen being included in this load. For tests in the drying chamber at 180° F. it was then necessary to allow about an hour for the proper test conditions to be reestablished and stabilized.

The strain gages were read before load was applied. Load was then transmitted to the specimens by turning the hand screw at the top of each sawhorse. An electric light bulb connected to the time clock circuit was lighted when the microswitch under the load box switched on, indicating that the load box was free of the supporting blocks. A strain reading was made and a stop watch was started when the light turned on. Strain readings were taken at 3, 6, 12, 18, and 30 minutes, and thereafter at gradually increasing intervals of time for a 3-day period. Some of the 180° specimens at high stress levels deformed and failed so rapidly that readings were also taken at 1, 2, and 9 minutes. At the end of the 3-day loading period, specimens that had not failed were unloaded by returning the hand screw at the top of the sawhorse to its original position. Recovery readings were taken in the same manner as the creep readings, starting at the time when the electric light bulb connected to the microswitch was turned off, indicating that the load box had returned to position on the supporting blocks. A few extra turns of the screw were then made to allow sufficient slack for free recovery of the specimens. At the end of the 3-day recovery period, specimens were removed from the apparatus and reweighed to detect possible weight loss during test. The central 2 inches of tension specimens and the entire compression specimens were then weighed and ovendried for determination of moisture content. Specific gravity in the ovendry condition was determined by water immersion after dipping in a paraffin carbon tetrachloride solution.

Results

Curves showing the relationship of creep and recovery to time for tension and compression perpendicular to the grain at 0° to the growth rings are presented in figures 37 through 40. These curves are an average of the two curves obtained for each stress level at each combination of temperature and moisture content conditions from the specimens from each of two logs. When creep and recovery data from these curves were plotted against time on logarithmic paper, the resulting curves were nearly linear, suggesting that the relationship of creep and recovery to time might be described by a power function of the form

$$y = ax^b$$

Since, for the present purpose, $\underline{y}$ represents strain in creep or recovery, it may be expressed as the difference between total strain, $\underline{e}$, and the strain developed immediately upon application or removal of load, $\underline{e_o}$. The creep or recovery would then be $e - e_o$. For stresses less than the proportional limit stress, $\underline{e_o}$ represents elastic strain. In the present application the independent variable, $\underline{x}$, in the general equation above represents time. This variable can then be called $\underline{t}$. The result of this transformation is a general equation

$$e - e_o = mt^n$$

or, in terms of total strain in either creep or recovery,

$$e = e_o + mt^n \qquad (8)$$

where $\underline{m}$ and $\underline{n}$ are parameters that are constant for any one curve. Since it is difficult, however, to determine the exact moment when load is fully applied to or removed from the specimen in this type of test, it is useful to consider $\underline{e_o}$ itself as another parameter that may be calculated from the data for any particular condition of loading as a function of stress.

The first step in the calculation of parameters was the plotting of creep and recovery against time on logarithmic paper. For this purpose an estimate of e_o was made by setting e_o equal to half of the total strain at 1 hour, as suggested by Boller (7) for reinforced plastic laminates. This proved to be a close enough approximation to give straight lines on the logarithmic plot. Straight lines were drawn through the data points and extended to t = 100 hours. Separate values of e_o and resulting straight lines were determined for creep and for recovery. Values of creep or recovery strain were then taken from the line at points corresponding to 1, 10, and 100 hours (t_1, t_2, and t_3) and designated as e_1, e_2, and e_3, respectively. From the three simultaneous equations

$$e_1 = e_o + mt_1^n \qquad (9)$$

$$e_2 = e_o + mt_2^n$$

$$e_3 = e_o + mt_3^n$$

can be derived the relationships

$$e_1 - e_2 = m\ (t_1^n - t_2^n)$$

$$e_2 - e_3 = m\ (t_2^n - t_3^n)$$

From this it is apparent that

$$\frac{e_1 - e_2}{t_1^n - t_2^n} = \frac{e_2 - e_3}{t_2^n - t_3^n}$$

and $$\frac{e_1 - e_2}{e_2 - e_3} = \frac{t_1^n - t_2^n}{t_2^n - t_3^n}$$

Since the values of t_1, t_2, and t_3 are chosen such that

$$t_2 = rt_1$$

and $t_3 = r^2 t_1$,

then $$\frac{e_1 - e_2}{e_2 - e_3} = \frac{t_1^n - r^n t_1^n}{r^n t_1^n - r^{2n} t_1^n} = \frac{1 - r^n}{r^n - r^{2n}} = \frac{1}{r^n} \cdot \frac{1 - r^n}{1 - r^n} = \frac{1}{r^n}$$

$$r^n = \frac{e_2 - e_3}{e_1 - e_2}$$

$$n = \frac{\log \dfrac{e_2 - e_3}{e_1 - e_2}}{\log r}$$

Since $r = 10$, $\log r = 1$, and

$$n = \log \frac{e_2 - e_3}{e_1 - e_2} \qquad (10)$$

The value of m can then be calculated from the expression derived by subtracting the first of the simultaneous equations (9) from the second, which is

$$m = \frac{e_2 - e_1}{t_2^n - t_1^n} = \frac{e_2 - e_1}{t_2^n - 1} \qquad (11)$$

Once the values for n and m have been calculated for any condition of loading it is then a simple matter to calculate e_o from the first of the three simultaneous equations as

$$e_o = e_1 - mt_1^n = e_1 - m \qquad (12)$$

In this final calculation of e_o, it is necessary to add to the result the amount $\frac{e_1}{2}$ that was originally subtracted from all values of e as an estimate of e_o.

Values of the parameters n, m, and e_o were calculated by means of equations (10), (11), and (12) for all conditions of loading for which sufficient data were available. These are presented, along with specific gravity and moisture content data, in tables 8 and 9. Also included in table 8 are values of time to failure for tensile creep specimens that failed before the 3-day period of loading was completed. Where values of n for the various stress levels at a single temperature and moisture content condition did not show any trend with respect to stress, they were averaged to give a value of $\bar{n}$ that was used in place of individual values of n for calculations of m and e_o values for the individual stress levels. The value of $\bar{n}$ for such groups is indicated in tables 8 and 9. Since n represents the slope of the line on a logarithmic plot, such groups were also characterized by approximately parallel lines for the various stress levels within the group.

Differentiation of the general equation for creep or recovery with respect to time results in an expression

$$\frac{d\,(e - e_o)}{dt} = mnt^{n - 1} \qquad (13)$$

that can be used to calculate creep rate or recovery rate at any time, t, for any condition of loading for which values of the parameters e_o, m, and n are known. Values of the creep rate and of recovery rate calculated for various conditions and times of tensile and compressive loading are presented in table 10. A representative plot of the relationship of creep rate to stress level at 10 hours is shown in figure 41.

Discussion of Results

Tables 8 and 9, which present the results of the testing in creep and recovery from creep, show several gaps in the data. These were due largely to failures of the strain measuring equipment, although erratic behavior of test specimens under the more severe temperature and moisture content conditions also contributed to this difficulty. The clip gages used for strain measurement gave considerable trouble, particularly at 180°, both from breakage of the fine lead wires during loading or unloading of specimens and from short circuits that developed as a result of penetration of moisture during the course of a test. Improvement of the strain-measuring system would undoubtedly contribute much to the greater success of future testing of this type.

In spite of these difficulties, however, many reliable data were obtained and several significant factors contributing to the perpendicular-to-grain creep behavior of red oak were discernible.

Figures 37 through 40 show that creep and recovery in both tension and compression perpendicular to the grain were increased by both increasing moisture content and increasing temperature. The effect of raising the temperature from 80° to 180° F. at the same moisture content was considerably greater than the effect of raising moisture content from 12 percent to the green condition at the same temperature. Moreover, the combined effect of high temperature and high moisture content was much greater than that for the individual temperature and moisture content effects added together, particularly in the tension creep tests; this fact indicated a strong interaction of temperature and moisture content at 180° F. in the green condition. Creep tests in shear conducted in Australia (24) also indicated this strong interaction of temperature and moisture content on creep properties. Those same tests indicated an apparent independence of the recoverable component of creep on temperatures between 0° and 50° C. and moisture content between 5 and 18 percent, although no confirmation of this has appeared in the literature. The present results cannot confirm this result because tests were conducted at but one temperature and moisture content level within the stated range of apparent independence.

The curves of figures 37 through 40 indicate that both total creep and irrecoverable creep at 80° F. were less in compression than in tension at the same levels of stress at both levels of moisture content. This difference is also clearly evident in the values of both creep rate and recovery rate for tests at 80° presented in table 10. The difference is not apparent for tests at 180°, however, either in creep-rate and recovery-rate values or in total creep and recovery. The apparent difference cannot be attributed to differences in moisture content or specific gravity of the test material because the values listed in tables 8 and 9 are very similar for tension and compression specimens tested at 80°. The rather large value of Poisson's ratio, μ_{TR}, suggests that there may have been a difference from this cause, since the cross-sectional area of the specimen would be increased during compression testing and decreased during tension testing. It is also possible that there may be a real difference between the manner in which cell wall components behave in tensile creep and their behavior in compressive creep.

It is hardly conceivable, however, that these effects alone could account for the large observed difference between tensile and compressive creep, though they may have been contributing factors. It is possible that a large part of the difference might have resulted from restraint imposed by binding of guide-pins of the compression jigs, a likely occurrence if the jigs were not perfectly alined. The fact that the values of $\underline{e_o}$ in table 9 for compression tests at 80° are generally lower than those in table 8 based on tension tests at 80° lends some weight to this suggestion, since $\underline{e_o}$ represents strain taking place immediately upon application of load, and would represent (at least for the lower stress levels) largely elastic strain. The results of the short-time mechanical tests of this investigation showed little difference between modulus of elasticity in tension and in compression under the same conditions of temperature and moisture content.

At the same time, the form of the stress-strain curves in tension and in compression were much the same up to the point at which tensile failure took place, with any slight difference favoring a greater strain in compression than in tension at the same stress level. Under normal conditions, therefore, $\underline{e_o}$ in compression would not be expected to be less than that in tension at the same level of stress. The fact that $\underline{e_o}$ was lower in compression indicates that some such restraint might very conceivably have affected the results. In testing at 180°, all contacting metal surfaces of the compression jigs were thoroughly greased to minimize corrosion; this treatment undoubtedly reduced the restraining action of the compression jig and gave compression test results closely comparable to the results of tension creep tests.

The parameters $\underline{e_o}$ and $\underline{m}$ for creep in tension and compression are generally characterized by a greater than linear increase with increasing stress (tables 8 and 9). However, the comparable parameters for recovery are characterized by a generally linear increase with increasing stress. Since $\underline{e_o}$ represents the strain developed immediately upon application or removal of load, this observed relationship to stress is entirely to be expected. The loads applied to the creep specimens were (for the most part) sufficient to produce stresses above the proportional limit stress of the material; therefore the immediate strain would be more than proportional to the applied stress. But recovery from creep upon the removal of load is elastic in nature and as such would be proportional to stress.

The parameter $\underline{n}$, in contrast to the other two calculated parameters, does not appear to be related to stress, except for the compression creep tests at 80° that were discussed previously as showing a possible influence of external restraint. For all groups of creep and recovery tests other than these, the parameter n was averaged within the group to give a value of $\bar{n}$ characteristic of the group. No comparable value of n could be found in the published literature for purpose of comparison. However, Boller (7) found a single value of n characteristic of several stress levels of reinforced plastic laminates, as did Worley and Findley (69). Earlier work done at the Forest Products Laboratory also indicated an apparent independence of n on stress for creep of wood in tension and compression.

If it is assumed that n is generally independent of stress--as seems reasonable on the basis of the present results--it then follows that at any time, t, for any given set of temperature and moisture content conditions within the range covered by this investigation, the amount of creep must increase more than proportionately with stress, and the amount of recovery must be proportional to the stress from which the material is recovering. This conclusion is based on the previous observations as to the relationship of m to stress and on the characterization of creep or recovery by the function mt^n.

While n appears to be generally independent of stress, it is not independent of either temperature or moisture content. The values of creep parameters listed in table 8 indicate that $\bar{n}$ for green material is about 1-1/2 to 1-3/4 times that for material at a nominal 12 percent moisture content, and that $\bar{n}$ for material at 180° F. is about 1-1/3 to 1-1/2 times that for material at 80° at the same moisture content. Some of the variation in ratios of $\bar{n}$ for the different conditions may be due to the fact that the nominal 12 percent moisture content material at 180° was appreciably drier than that at 80°. The data of tables 8 and 9 show that nominal 12 percent moisture content creep specimens were actually about 11 percent at 80°

and about 7 percent at 180°. The moisture content values indicated for the 180° material are probably slightly low because of drying of the hot wood between the time of removal from the test chamber and time of weighing, in spite of the precautions taken to prevent such drying; moreover, it is apparent that the specimens tested at 180° were also somewhat drier during test than those tested at 80°. That condition no doubt resulted in some reduction in creep below what would be expected at the higher moisture content. Consequently, the drier condition resulted in values of $\underline{n}$ for 180° tests that are somewhat low with respect to those calculated from 80° test data at the nominal 12 percent moisture content level.

Comparisons of values of creep rate and recovery rate listed in table 10 are most conveniently based on equivalent stress levels as percentages of maximum load, since there is little overlapping of actual stresses between the various groups. It should be remembered that such comparisons indicate effects of temperature and moisture content that are considerably less than would be indicated by comparisons of creep rate or recovery rate based on application of the same stress under different test conditions. For example, the creep rate indicated for 180° material in tension at 12 percent moisture content at the 40 percent stress level (40 percent of static tensile strength) is about twice that for 80° green material at the 40 percent stress level; while the creep rate for 180° material at 12 percent moisture content under a stress equivalent to that of the 80° green material at the 40 percent stress level is over four times as great as that for the latter material. The ratios of creep rate for tensile creep at 180° F. to that for tensile creep at 80° F. at the same percentage stress level show a general decrease with increasing stress level and an increase with time at each stress level. The decrease with increasing stress level probably reflects the greater interval of actual stress between stress levels at 80°, while the increase with increasing time indicates that creep slows down less rapidly at 180° than at 80°. For material at a nominal 12 percent moisture content the ratio at the 40 percent stress level increases from 3.9 at 2 hours to 4.7 at 50 hours. At the 80 percent stress level the ratio increased from 2.2 at 2 hours to 2.7 at 50 hours. The comparable ratios for green material are much higher, increasing at the 40 percent stress level from 6.4 at 2 hours to 9.9 at 50 hours, despite the fact that there is a much greater disparity between the actual stresses applied for the green material than for the material at 12 percent moisture content. Comparisons of creep rates in compression are subject to the limitations regarding the behavior of compression specimens at 80° that were discussed previously. Compression creep and recovery rates at 180°, however, are generally as great as or slightly greater than those for comparable stress levels in tension. There is little evidence to substantiate for red oak the greatly increased creep rates observed for beech in very limited testing by Ellwood (14).

As indicated in figure 41 for tensile creep, creep rate not only increases with increasing temperature and with increasing moisture content, but also increases more than linearly with increasing stress at all conditions of temperature and moisture content investigated.

Work done in Australia by Grossman and Kingston (24) has been designed to test the applicability of Boltzmann's superposition principle to wood. This principle states that the deformation at any instant of a body manifesting recoverable creep is due not only to the load acting at that instant but also to the entire previous loading history of the body. The assumptions of this principle are (a) that the magnitude of recoverable creep at any time is proportional to the load, and (b) that the total deformation due to a complex loading history is a simple summation of the deformations due to the separate loading effects. In this regard, the removal of load would correspond to application of negative load equal in magnitude to the load removed. Grossman and Kingston's superposition tests in shear indicated the applicability of the superposition principle for creep times of several hours or more. The chief difficulty in applying this useful principle to wood is the problem of distinguishing between recoverable and irrecoverable creep. Leaderman (32) indicated that the effect of irrecoverable creep could be removed in many high polymers by a process of mechanical conditioning, referring to a change in properties after application of stress. Grossman and Kingston (25) considered this mechanical conditioning effect in greater detail for high polymers in general, and derived a function describing mechanical conditioning that assumed proportionality of irrecoverable creep at any time to stress.

This analysis indicated, among other things, that the irrecoverable creep function can be found most easily from the difference between a creep curve and a recovery curve after a long loading time. This concept was expressed earlier in a slightly different manner by Leaderman (32), who indicated that, for bodies manifesting only recoverable creep, contraction due to removal of load--as a function of recovery time--is the same as extension as a function of creep time following long-duration creep in which creep has essentially reached completion. A similar method of separating recoverable from irrecoverable creep was developed in an analytical approach to the theory of creep deformation by Pao and Marin (47).

It seems likely that the superposition principle could be applied in this manner to determine the time rate of development of irrecoverable creep as a function of stress under various conditions of temperature and moisture content. This information would be very useful in the solution of many drying problems, since the development of irrecoverable creep (or set) is an important factor in many of these problems. This application would consist of superimposing a recovery curve on the curve for the creep that preceded it, considering the recovery as application of a negative stress producing only recoverable creep. While it is obvious from the curves of figures 37 through 40 that creep had not reached completion at the time of unloading, many of the recovery curves do begin to approach an imaginary horizontal asymptote. This latter observation indicates that in many instances in the present investigation, the recoverable creep was approaching a point that might be called essential completion, at least as a reasonable approximation. Irrecoverable creep could then be estimated as shown in figure 42, which shows a hypothetical creep curve for wood, followed by unloading, and a recovery curve. The total strain at any time, t, on the creep curve consists of three separate components: the elastic strain developed immediately upon application of load, the recoverable creep, and the irrecoverable creep. At time t after removal of load, the total recovery is represented by the strain e_r, which includes both immediate and delayed recovery and corresponds to the immediate strain and recoverable creep at time t on the creep curve.

Superimposing recovery curve ABC with a negative sign on creep curve OO'B has the effects, therefore, of subtracting portion OO'D, which represents only elastic strain and recoverable creep, and of isolating the irrecoverable creep. At time t this latter portion would be represented by e_i. The time rate of increase of e_i from the point $t = 0$ to any point $t = t_x$ would then give a reasonable estimate of the time rate of development of irrecoverable creep. To illustrate, values of irrecoverable creep were thus determined from the tensile creep and recovery curves for the 12 percent moisture content material tested at 80° and 180° F. These were the groups from which the most reliable and complete data were obtained. The relationship of this irrecoverable creep to stress at several intervals of time after loading is shown in figure 43. These curves indicate that irrecoverable creep increases several times as rapidly at 180° as at 80° at the same moisture content, though the curves have the same basic form; and that irrecoverable creep proceeds rapidly for the first few hours of loading, the rate gradually diminishing with time. The curves also point out the fact that irrecoverable creep increases more than proportionately with stress, leading to the conclusion that most of the nonproportionality of the creep curves must be due to irrecoverable creep. Grossman and Kingston (22) observed that tensile and compressive creep of several Australian species increased more than linearly with stress and that the greater part of this nonlinearity was due to irrecoverable creep. They also observed (23) that irrecoverable creep strain in wood in bending increased more than linearly with stress, while delayed recoverable creep in bending appeared to be proportional to stress.

From these observations relative to the application of Boltzmann's superposition principle to estimate rate of development of irrecoverable creep, it follows that this rate can also be estimated for the various conditions of loading by subtracting the value of recovery rate (listed in table 10) from the corresponding value of creep rate. Comparisons on this basis indicate, for example, that rate of development of irrecoverable creep at the point $\underline{t}$ = 2 hours at the 40 percent stress level for tensile creep at 12 percent moisture content was nearly 15 times greater at 180° than at 80°; while for green material this rate was nearly 19 times as great at 180° than at 80°. Likewise, the rate of irrecoverable creep at 80° was about 4 times as great for green material as for material at 12 percent moisture content; while that at 180° was about 5 times as great for material in the green condition as for material at 12 percent moisture content.

Stress Relaxation Tests

This final phase of the investigation explored the perpendicular-to-grain rheological properties of red oak in tension and compression as indicated by relaxation of stress under constant strain. The fundamental assumptions and intended applications are generally the same as described in the introduction to the section dealing with creep and recovery tests. As in the earlier section it was not possible to carry out an intensive investigation of stress relaxation properties, and the work performed must be considered exploratory in nature, pointing the way to possible intensive work in the future.

Tests and Test Conditions

This phase of the investigation was designed to include stress relaxation tests in tension and compression perpendicular to the grain at the same temperature and moisture content conditions as the creep and recovery tests, and started at the same levels of initial stress that were applied as constant loads in the earlier tests. The fact that the tests had to be conducted in a testing machine under rather closely controlled temperature and humidity conditions necessitated a slight change in plans. Since the conditioning chamber of the machine used for the short-time tests could not be controlled closely enough as to temperature and humidity at 80° F. for relatively long-time testing, and since this machine allowed testing of but one specimen at a time, it was decided to carry out the low-temperature tests in the two loading units of a fatigue machine that was installed in a room controlled at 75° F. and 64 percent humidity. It is recognized that the relaxation rate would be lower at 75° F. than at 80° F., but the possibility of better control of test conditions and of running tests two at a time rather than singly seemed to outweigh this slight disadvantage. The machine used was a 5,000-pound capacity Krause direct-stress testing machine, the two sides of which could be operated independently for carrying out stress relaxation tests. Load was determined by measuring the distance between the midpoint of a rigid dial bar and a flexible arm attached to the grips of the machine. Loads applied to specimens at 12 percent moisture content were measured in this manner by noting the indications of a dial rigidly attached to the dial bar with its stem contacting the arm of the machine (fig. 44). Loads applied to green specimens were about 60 percent as great as those applied to specimens at 12 percent moisture content. In order to measure these smaller loads with a greater degree of sensitivity, a Tuckerman extensometer, shown in figure 44, was used to measure the distance between the dial bar and the arms of the machine.

Before testing was begun, both the dial and the Tuckerman extensometer were calibrated by applying known weights to the testing head of the machine. Strain was measured between the grips of the machine by means of the dial arrangement shown in figure 45 for a tension specimen and in figure 46 for a compression specimen. Although for ordinary testing work it is generally not good practice to determine strain by measuring the head movement, in this application the only object was to maintain a constant strain at a level equal to that resulting from the application of the initial stress. Thus the specimen does not change in length during the course of the test, and the error due to measuring head movement rather than movement of the net section of the specimen itself is relatively slight. The slight change in strain distribution in the specimen during test due to nonuniformity of stress level along the length would not be expected to have any appreciable effect on the results.

Stress relaxation tests at 180° F. were conducted in the machine used for the short-time tests (fig. 4). Load was measured by the same load cell arrangement used in the earlier tests and strain was measured across a 1-1/4-inch gage length, as described for creep and recovery tests.

Testing Procedure

Specimens for stress relaxation tests were prepared for testing in essentially the same manner as were creep specimens. Specimens for testing at 75° F. at 12 percent moisture content were conditioned for at least a week in the humidity room in which the machine was located, since the equilibrium moisture content corresponding to the conditions maintained in this room was slightly lower than that of the room in which the specimens were stored. Each green specimen to be tested at 75° F. was allowed to come to room temperature in a plastic bag before measuring, and was then transferred to a thin rubber bag containing a small amount of distilled water to maintain the green condition during test without interfering with the normal strain behavior.

Specimens were then placed in the testing machine as shown in figures 45 and 46; the machine was set at zero load, and the strain-indicating dial was set at zero. Load was applied manually by means of a crank that raised or lowered the upper head of the machine until the desired load in tension or compression was attained. The strain dial was read at the instant the desired load was reached and the head of the machine was thereafter adjusted manually as necessary to keep the strain at this same value. The amount of load required to maintain this strain was noted at 3, 6, 12, 18, and 30 minutes, and thereafter at gradually increasing intervals for about 3 days. At the end of the relaxation period, specimens were unloaded and removed from the machine; their moisture content and specific gravity were then determined in the same manner as for creep and recovery specimens.

The procedure in conducting stress relaxation tests at 180° F. was similar to that for short-time tests in tension and compression, except that specimens were loaded to a predetermined stress level and held at a strain equal to that attained under the initial application of this stress. Specimens were weighed and measured before testing and were conditioned for about 1 hour in the cabinet of the testing machine before the test was begun, in order to minimize errors due to thermal expansion and change in moisture content during the course of the test. Because of the rapid relaxation and many experimental difficulties associated with testing under these conditions, many of the relaxation tests at 180° were discontinued after 1 day at constant strain. The data obtained under these conditions were not as consistent or as reliable as those obtained in comparable tests at 75° F. When each test was completed, the specimen was removed from the testing machine and its moisture content and specific gravity were determined in the same manner as were creep and recovery specimens.

Test Results

The observed stress at constant strain as a function of time is shown in figure 47 for tests conducted at 75° F. and in figure 48 for tests conducted at 180° F. Table 11 presents the physical characteristics of the test material and indicates the stress relaxation characteristics by means of the exponent b and the relaxation coefficient m; the meaning of these parameters is discussed below. Experimental difficulties and clip gage breakdowns invalidated much of the data based on tests at 180° F., whereas the complete series of tests at 75° yielded good data; therefore, values based on the tests at the lower temperature are more reliable and more complete. For these reasons, each value from tests at 75° is an average based on two tests while values from tests at 180° are largely based on one test. In testing at 180° it was rarely possible to maintain adequate control of testing conditions in the chamber of the test machine for more than 1 day and frequently the limit was about 10 hours, since these tests were particularly sensitive to slight variations in atmospheric conditions.

The relationship commonly used to describe relaxation characteristics of wood is that proposed by Kitazawa (28). That equation expresses the relationship between stress and time as

$$f = f_1(1 - m \log t) \qquad (14)$$

Where f = stress at time $\underline{t}$

f_1 = stress at unit time

m = constant designated as the relaxation coefficient.

The data of this investigation could be fitted reasonably well by an expression of this type; such a fitting would be indicated by a linear relationship between stress and the logarithm of relaxation time (hours). While Kitazawa's relationship is a very useful one in practical application, it is theoretically unsound in two ways. First, it implies that stress goes to infinity at zero time; second, it implies that stress relaxes to zero at a finite time. Boyd (8) found that stress relaxation in copper could be described by an expression of the form

$$f = f_o \left[1 - m \log (pt + 1) \right] \qquad (15)$$

Where f = stress at time $\underline{t}$

f_o = the initial stress

m and p = constants.

Boyd's equation overcomes the first objection to Kitazawa's relationship by shifting the vertical axis slightly to allow the initial stress to be represented at a finite value of $\underline{t}$. The second objection to Kitazawa's relationship is of no practical importance, since the time at which stress would reach zero is generally from several thousand to a million years.

With a suitable time scale, the data of the present investigation indicated a linear relationship between the logarithm of stress and the logarithm of relaxation time, suggesting an expression of the general form

$$f = at^b$$

Where f = stress

t = relaxation time

a and b = constants.

It was then established that a good fit of the data could be obtained by setting a equal to the initial stress f_o, and t equal to t + 1. These substitutions yield an expression for stress relaxation of the form

$$f = f_o (t + 1)^b \qquad (16)$$

Where f = stress at time t

f_o = initial stress

t = relaxation time (minutes)

b = constant indicating the slope of the straight line on a logarithmic plot.

This expression could be fitted to the data equally as well as Kitazawa's relationship, and it overcomes both objections to the latter by going to a known stress (f_o) at zero time and approaching zero stress asymptotically with increasing time. In addition it is of the same general form as equation (8), which was used to express the relationship between strain and time indicated by the creep data of this investigation. There is undoubtedly a relationship between creep and stress relaxation; and it seems likely that subsequent analyses based on the findings of this investigation will be facilitated by using expressions of the same basic form for both types of behavior.

To fit equation (16) to the data of the present investigation, the stress values obtained by test were plotted against time in minutes plus one minute on a logarithmic plot. Straight lines were fitted to the plotted points and the parameter b for each line was then calculated as the slope of the line. Values of b thus calculated are listed for each test condition in table 11.

In order to provide stress relaxation coefficients comparable to those obtained in previous studies of stress relaxation in wood, values of the parameter m were calculated on the basis of Kitazawa's equation. From equation (14) it follows that the value of m can be calculated by substituting the proper values in the expression

$$m = \frac{1 - \frac{f}{f_1}}{\log t}$$

To apply this type of analysis to the present data, the stress values for each test were plotted against time on a logarithmic scale, and a straight line was drawn through the data points. Values of f were then picked off at 0.1 hour and at 100 hours for the 75° tests, and at 0.1 hour and 10 hours for the 180° tests. The value of m was then calculated as

$$m = \frac{1 - \frac{f_{100}}{f_{.1}}}{3} \quad \text{for } 75^\circ \text{ tests} \tag{17}$$

$$m = \frac{1 - \frac{f_{10}}{f_{.1}}}{2} \quad \text{for } 180^\circ \text{ tests} \tag{18}$$

Values derived from the linear plots on semilogarithmic paper were used to calculate m by means of equation (17) or (18). These values are presented in table 11 for all conditions of loading for which adequate data were available. Average and standard deviation values for each group are also presented where applicable.

Individual values of m calculated from the data of each test at 75° were analyzed statistically by means of an analysis of variance. Data based on tests at 180° were too incomplete to lend themselves readily to such analysis. The analysis-of-variance table is presented in the appendix.

Discussion of Results

As was true of the creep tests described in the previous section, there are several gaps in the data for tests at 180° F. These were largely due to failures of the strain-measuring equipment and to failure of the conditioning chamber of the testing machine to maintain the high degree of uniformity of test conditions over the long periods of time required for this type of testing. Adding to the difficulty was the fact that test specimens could not be thoroughly conditioned at the test conditions before testing was begun, since this would have resulted in serious thermal degradation, as described in the section dealing with duration of heating effects. Nevertheless, the data do give information on relaxation properties at the higher temperatures that will be very useful in understanding problems involving perpendicular-to-grain rheological behavior of wood.

The curves of figures 47 and 48 show that stress relaxation follows the same general relationship to time that has been observed previously for wood by Kitazawa (28) and by Grossman (21), and for other materials such as copper (8) and textile fibers (32).

The analysis of variance of the relaxation coefficient for the tests at 75° F. indicates that there was no significant difference between the two logs. There were, however, very significant differences between values derived from compression testing and those derived from tension testing. The average value of m derived from compression tests at 12 percent moisture content is about 64 percent of the value derived from tension tests at the same moisture content, while the value from compression tests of green material is about 78 percent of the value from tension tests of green material. Moisture content had a very pronounced effect on the relaxation coefficient; the ratio of the average value at 12 percent moisture content to that based on green material was about 0.77 for tension tests and about 0.63 for compression tests.

An outstanding fact to be observed from the analysis of variance is the very significant linear component of the stress level effect, indicating that the relaxation coefficient increases linearly with increasing stress. A supplementary analysis of the slopes of the regression lines for the individual groups indicated that the combined slope is a better estimate of the regression than the individual slopes; this combined slope amounts to 4.15×10^{-4} per 1 percent change in stress level. Kitazawa (28) observed that the relaxation coefficient did not vary with stress below about 1/4 to 1/3 of the proportional limit stress, which indicates that the upper limit of initial stress from which normal relaxation results is in that range. Presumably, this normal relaxation is a manifestation of recoverable creep only, and does not involve permanent plastic deformation (irrecoverable creep). In view of the fact that all stress levels in the present investigation were well above the limit observed by Kitazawa, it is not surprising that m increases with increasing stress levels. Grossman (21) also observed that Kitazawa's formula involving a constant m did not hold over a wide range of stress, and he suggested that the force could be better represented by the sum of exponential terms with various relaxation times.

Although the parameter b was not analyzed by means of an overall analysis of variance, statistical analysis based on ranking procedures indicates that b, like m, is significantly lower in compression than in tension at 75° for both green and dry material, and is significantly lower for material at 12 percent moisture content than for green material in both tension and compression. The values of b listed in table 11 also indicate an increase in b with increasing initial stress for all groups tested at 75° except that group tested in tension at 12 percent moisture content.

The observed difference in b and m between tension and compression tests indicates that there may be a real difference in rheological characteristics determined by the two types of test. A comparable effect observed in creep tests was thought to be at least partially attributable to restraints imposed by the compression jig; in the 75° relaxation tests, however, no such restraint was possible. This suggests the possibility (as mentioned in the discussion of creep test results) that there is a basic difference in the behavior of the cell wall components under the two types of loading, at least as regards plastic flow. Microscopic investigation at high magnification during loading might shed some light on this possibility. The relatively high values of Poisson's ratio, μ_{TR}, suggest the further possibility that the actual increase in cross-sectional area of the specimen resulting from compression in the tangential direction and the decrease in cross-sectional area resulting from tension might result in measurable differences in the rheological characteristics.

The values of b and m presented in table 11 indicate that relaxation takes place much more rapidly at 180° F. than at 75° F. at the same level of moisture content in both tension and compression. These values do not, however, indicate the marked temperature-moisture content interaction that was characteristic of creep test results. Neither do the values based on tests at 180° indicate a marked increase of b or m with increasing stress, as would be expected from the previous observations as to the large amount of irrecoverable creep taking place under these conditions. The average value of m derived from tension relaxation tests at 180° on the dry material is about 3 times that of the comparable value from tests at 75°.

In compression tests at the same moisture content--for which the data are more variable and incomplete than in tension testing--the average value of m is more than 5 times as great for tests at 180° as for tests at 75°. In both tension and compression testing at 180° the actual moisture content of test specimens at the nominal 12 percent level was lower than that of comparable specimens tested at 75°; this probably reduced the difference between values of m at the two temperatures to a point below what would be expected if the specimens were at exactly the same level of moisture content. Values of m for green material do not indicate as great an effect of temperature as do the values based on dry material, but the scatter and incompleteness of the data on green specimens at 180° lend considerable uncertainty to any conclusion as to the actual effect of these conditions on the relaxation characteristics. Boyd (8) observed a marked effect of temperature on relaxation of copper, in which the relaxation increased quite rapidly above 80° C.

Since stress relaxation is but one form of the general creep phenomenon, there must be a relationship between data derived from creep tests and data derived from stress relaxation tests under the same conditions. This relationship is a relatively simple one for the case of a body manifesting a small amount of creep with respect to its instantaneous elastic deformation; but it becomes quite complex when the amount of creep is large with respect to the instantaneous deformation, particularly when irrecoverable as well as recoverable creep is involved. Fundamental mathematical relationships underlying creep and relaxation and their interrelationship are presented in a series of papers by Gross (18,19), and by Gross and Pelzer (20). No attempt has been made in the present investigation to develop any specific relationship between creep data and stress relaxation data, since such analysis is beyond the scope of this work.

Conclusions

The perpendicular-to-grain mechanical properties of northern red oak (Quercus rubra L.) within the temperature range 80° to 180° F. and the moisture content range 6 percent to green are significantly affected by temperature and moisture content, both independently and in combination. The temperature effect on most properties tends to increase percentagewise with increasing moisture content. The relationship to moisture content is generally curvilinear and that to temperature is generally linear. The relationship of all properties to temperature and moisture content within the range investigated can be described by an expression of the general form

$$Y = a + bT + cM + dM^2 + eTM + fTM^2$$

Where Y = the property in question

T = temperature in °F.

M = moisture content expressed as a percent of ovendry weight

a, b, c, d, e, and f = constants for each property.

The properties characteristic of tensile loading at 0° to the growth rings are generally similar to those characteristic of loading at 45° to the growth rings. Properties characteristic of loading at 90° to the growth rings show generally similar trends with respect to temperature and moisture content but differ markedly in magnitude from those characteristic of 0° or 45° loading. The observed intersection points for both tensile and compressive properties are generally below the 25 percent moisture content value ordinarily applied to properties of this species, and show a tendency to decrease with increasing temperature. However, some of the intersection points are so low as to raise considerable doubt as to their accuracy.

Modulus of elasticity in both tension and compression decreases with increasing moisture content up to the intersection point and with increasing temperature. The relationship to both temperature and moisture content for loading at 0° to the growth rings is generally similar in tension and compression. The modulus of elasticity for tensile loading at 45° to the growth rings is very nearly the same as that for 0° loading. For loading at 90° to the growth rings, however, the modulus of elasticity is about twice as great as that for 0° or 45° loading, and is affected markedly less by increasing temperature at low levels of moisture content.

Proportional limit stress in tension perpendicular to the grain is decreased by increasing temperature and moisture content; it is increased by increasing the angle of loading with respect to the growth rings, although the increase with angle of loading is generally less than for modulus of elasticity.

Proportional limit stress in compression at intermediate moisture content levels is very nearly the same as that in tension, but is slightly higher at 6 percent moisture content and appreciably higher in the green condition. The effect of temperature on proportional limit stress in compression is about the same as that on the comparable property in tension, except for green material where the temperature effect in compression is less than that in tension.

Maximum stress in tension is decreased by increasing temperature and moisture content and is considerably greater under 90° loading than under either 0° or 45° loading. The ratio of the maximum tensile stress under 90° to that under 0° or 45° loading varies from about 1.4 at 6 percent moisture content to about 2 for green material. The percentage-wise reduction of this property with increasing temperature increases with increasing moisture content and decreases with increasing angle of loading.

Maximum strain in tension perpendicular to the grain appears to be strongly affected by both temperature and moisture content but not significantly affected by angle of loading, although there is a tendency for this property to be somewhat lower under 90° loading than under 0° or 45° loading at moisture content levels below the intersection point. Maximum tensile strain at 130° and 180° F. appears to reach a maximum in the vicinity of 12 to 16 percent moisture content and to recede with further increase in moisture content up to the fiber saturation point; above this level the maximum strain appears to be almost independent of temperature. At 80° F. maximum strain increases almost linearly with increasing moisture content up to the fiber saturation point.

Compressive stress at 2.5 percent strain--which was evaluated in lieu of a maximum stress in compression perpendicular to the grain--decreases with increasing temperature and increasing moisture content;

the moisture content relationship conforms fairly well to the generally assumed exponential form. The effect of temperature on this property appears to be less at 6 percent moisture content than at any of the higher levels of moisture content, and about the same at 12 and 18 percent moisture content as in green material.

Modulus of rigidity and maximum shearing strength associated with strain in the TR plane (as determined by calculations based on tension data) decrease with increasing moisture content and increasing temperature over the range investigated, and the effect of moisture content increases markedly with increasing temperature. Modulus of rigidity is about 1/3 the modulus of elasticity, and maximum shearing stress is about 1/2 the maximum tensile stress under comparable conditions of temperature and moisture content at 0° to the growth rings.

Perpendicular-to-grain mechanical properties of red oak appear to be somewhat more sensitive to duration of heating effects than are the parallel-to-grain properties previously investigated with a view toward structural applications. Except for maximum tensile stress, these duration of heating effects are insignificant at 130° F. for both green material and material at 12 percent moisture content but are significant for many properties at 180° F., particularly in green material. Significant duration of heating effects can be characterized by a linear relationship between percent of control value and the logarithm of exposure time.

Of the properties investigated, maximum stress in tension appears to be most affected, followed in order by compressive stress at 2.5 percent strain, modulus of elasticity, proportional limit stress in compression, and proportional limit stress in tension, and maximum strain in tension. All properties except maximum strain in tension appear to be permanently reduced in value by heating for periods of 30 days or less at 180° in the green condition; and maximum tensile stress, compressive stress at 2.5 percent strain, and tensile modulus of elasticity appear to be permanently reduced in value by heating at 180° at 12 percent moisture content. Most of the reduction in strength due to thermal degradation is permanent, not recoverable by reconditioning to room temperature. The ratio of strength at exposure conditions to that for material reconditioned after the same exposure tends to remain nearly constant over the exposure time investigated at a value about equal to the ratio for the control material.

Creep in tension and compression perpendicular to the grain follows a pattern similar to that observed parallel to the grain in wood, and can be characterized by a general expression of the form

$$e - e_o = mt^n$$

Where e = total strain

e_o = instantaneous strain

t = creep time

m and n = constants.

For any one set of temperature and moisture conditions, _m_ increases more than linearly with stress, and _n_ is generally independent of stress but is dependent on temperature and moisture content.

Recoverable creep appears to increase linearly and irrecoverable creep more than linearly with increasing stress under the same conditions of temperature and moisture content.

Creep in tension and compression perpendicular to the grain is increased by increasing temperature and by increasing moisture content; the effect of heating from 80° to 180° F. at the same moisture content is much greater than that of raising moisture content from 12 percent to green at the same temperature. A large part of the increase in creep with increasing temperature and moisture content is apparently due to irrecoverable creep.

Relaxation of stress at constant strain is increased by increasing temperature and by increasing moisture content. Perpendicular-to-grain stress relaxation from initial stresses between the proportional limit stress and the maximum stress in tension can be characterized by a linear relationship of stress to the logarithm of relaxation time.

The commonly applied stress relaxation formula

$$f = f_1 (1 - m \log t)$$

Where f = stress at any time $\underline{t}$

f_1 = stress at unit time

m = a constant

can be applied to stress relaxation under the conditions of this investigation. The parameter $\underline{m}$, however, is not independent of stress; at 75° F. it increases linearly with increasing stress.

The stress relaxation characteristics can be represented somewhat more satisfactorily by a hyperbolic relationship of the form

$$f = f_o (t + 1)^b$$

Where f = stress at time t

f_o = the initial stress

t = relaxation time in minutes

b = a constant.

This expression is sounder from a theoretical standpoint than is the commonly applied formula and has the added advantage of being similar in form to the strain-time function applied to the creep data of this investigation. The parameter b varies with test conditions in a manner similar to that of the relaxation coefficient m. In both instances the increase in the parameter with increasing initial stress is probably attributable largely to irrecoverable creep.

An apparent difference between perpendicular-to-grain rheological properties indicated in tension testing and those indicated in compression testing was observed in both creep and stress relaxation tests at room temperature, but was not observed in similar tests at 180° F. In each case creep was less in compression than in tension. This may be due to a fundamental difference in the rheological behavior of the individual cell wall components under the two types of loading, although the data of the present investigation do not allow the establishment of any substantial conclusions relative to this observation.

Some Applications of the Results

The results of this investigation provide considerable fundamental information on the perpendicular-to-grain strength, elastic, and rheological properties of northern red oak under normal kiln-drying conditions. The first and most direct application of this information will be, of course, to gain a better understanding of the drying behavior of the particular species concerned, a major part of which will consist of correlating these results with information on drying stresses gathered by McMillen (39,40). The results of this investigation should also be applicable--at least in a general way--to a better understanding of the drying behavior of other refractory hardwoods. Investigations similar to this will be conducted on at least one softwood and on at least one nonrefractory hardwood; on the basis of past experience, it is known that both the drying behavior and the mechanical properties of these broad groups differ in some of their fundamental aspects from the same behavior and properties of northern red oak.

It is also likely that the results of this work may find general application to problems involving the effects of temperature, moisture content, and duration of heating and loading in structural members. One outstanding example of this would be the structural elements of cooling towers, which are subjected to continuous heating by hot water in normal use and have been observed to fail at stresses considerably below the usual design stresses after periods of a few months.

The application of these results to a fundamental understanding of the drying behavior of northern red oak and similar species will be a rather comprehensive piece of work in itself, as currently envisioned, and should follow as a logical extension of the present investigation. A few implications of the present results in terms of that problem are immediately apparent and bear mentioning at this time.

The key operation in the slicing technique of drying strain analysis is the measurement of instantaneous elastic strain resulting from the unloading of each slice by freeing it from restraints imposed by the adjacent wood. The observed instantaneous strain is related to stress by means of the modulus of elasticity; the stress is equal to the product of the observed elastic recovery strain and the modulus of elasticity of the wood comprising the slice under the conditions of temperature and moisture content at which the instantaneous recovery takes place. Since the modulus of elasticity decreases markedly with increasing temperature and moisture content, it is readily apparent that the same amount of recovery strain at 180° as at 80° will indicate considerably less stress at the higher temperature. Likewise, the same amount of recovery strain for green material as for material at 6 percent moisture content will indicate considerably less stress for the green material. The same amount of recovery strain observed in a slice cut across the width of a quartersawed red oak board as in a slice cut across the width of a flat-sawed board under the same conditions of temperature and moisture content would indicate about twice as great a stress in the quartersawed board, since the modulus of elasticity is about twice as great for 90° loading as for 0° loading. It is assumed in these applications that modulus of elasticity in recovery from load is the same as that in loading, which has been shown to be approximately (though not strictly) the case. It is generally observed that the stress-strain relationship in a cycle of loading and unloading forms a hysteresis loop, so that the apparent modulus of elasticity in unloading would be slightly greater than that in loading (9). It is extremely unlikely, however, that the error resulting from this effect would be sufficient to have any marked influence on drying stress determinations.

Some of McMillen's data (40) on the effect of temperature on drying stress development will serve as an example of this application. These data indicate a maximum instantaneous recovery strain in the outside slices of 0.0031 inch per inch at 80° F., 0.0040 inch per inch at 110° F., and 0.0046 inch per inch at 140° F. In each case the average moisture content of the slices was above the intersection point indicated in the present study. The modulus of elasticity values for green material indicated in figure 14B are 62,000 p.s.i. at 80°, 45,000 p.s.i. at 110°, and 29,000 p.s.i. at 140°. The stresses calculated from these observed recovery strains would then be 205 p.s.i. at 80°, 180 p.s.i. at 110°, and 133 p.s.i. at 140°, indicating that the maximum average tensile stress attained early in the drying process in the outside slices decreases with increasing temperature; this is true in spite of the fact that the observed recovery strains, when considered alone, would indicate the reverse.

The stresses thus calculated are all well below the maximum tensile stress indicated for these temperatures in figure 19. These are average stresses for the outside slices, however, and the tensile stress would undoubtedly be considerably greater near the surface in each case; this is because the first few layers of cells near the surface of the board approach the equilibrium moisture content of the drying atmosphere and undergo the greatest amount of shrinkage. It is apparent, therefore, that a means of estimating stress at the surface of the board early in drying must be developed, since the tensile failure known as surface checking is related to the stress at that point in the drying board.

It is probable that the difference between average stress of the outside slices and tensile stress at the surface will be found to increase as the steepness of the moisture gradient increases. Since McMillen's data indicate that steepness of the moisture gradient at the time of maximum tensile recovery increases with increasing temperature, it may very well be that surface tensile stress at 140° approaches the maximum tensile stress more closely than at 80° or 110°, even though the average stress of the outside slices is lower at the higher temperature. It should be remembered in this regard that the maximum tensile stress at 140° would be about 40 percent less than that at 80°, as indicated by figure 19 and by the values given in table 5.

Properties other than modulus of elasticity and maximum tensile stress will also have a bearing on the tensile stress attained at the surface of a drying board. Since drying stresses are developed as a result of self-imposed restraints of shrinkage in adjacent portions of the wood, the modulus of rigidity associated with strain in the TR plane must be a determining factor in their development. The relationships shown in figure 29 indicate that modulus of rigidity is about 43 percent less at 140° than at 80° under the moisture content conditions likely to be established in the outer layers of the wood early in drying; from this it is apparent that adjacent layers of the wood can move much more readily with respect to each other at the higher temperature, thus reducing the amount of stress resulting from any specified shearing deformation.

The fact that both recoverable and irrecoverable creep occur more rapidly as temperature is increased would serve to decrease the amount of stress developed at increased temperatures by permitting stress relaxation. This same creep would lead to tensile failure at stress levels well below the maximum tensile stress as determined by short-time tension tests. Also, the irrecoverable plastic deformation of the surface layers of the wood early in drying results in increased tensile stress in the interior of the wood as it attempts to shrink against the restraint of the outer layers.

It does not appear that duration of heating effects will have any appreciable effect on the likelihood of tensile failure at the surface of a drying board early in the drying process, since currently available data indicate that the time at which the greatest tensile stress is developed in the outer layers of the wood decreases with increasing temperature. Duration of heating effects will have an important bearing on likelihood of tensile failure in the interior of the wood, however. Results of the present study indicate that the temperatures employed in normal kiln drying of northern red oak can reduce perpendicular-to-grain tensile strength considerably during the course of a kiln-drying run. Duration of heating effects will also have considerable bearing on the evaluation of drying stresses, particularly during the final part of the drying run at relatively high temperatures. The decrease in modulus of elasticity with duration of heating will decrease the magnitude of stress represented by an observed recovery strain.

Thus it becomes apparent that the perpendicular-to-grain properties investigated have a bearing on all phases of the development, effects, and evaluation of drying stresses. The present study has not been complete enough to make possible the precise evaluation of the effects of all aspects of normal drying behavior. Much of the work has been only exploratory, since each phase of the present work could profitably be the subject of a rather comprehensive investigation. The results of this research, together with the results of its application to an understanding of drying behavior, should indicate more effective approaches to similar future investigations.

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Table 1.--Results of tests in tension perpendicular to grain of northern red oak at three angles to the growth rings under various conditions of temperature and moisture content (averages based on eight tests).

Angle of loading	Temperature	Moisture content: Nominal	Moisture content: Actual	Modulus of elasticity	Proportional limit: Strain	Proportional limit: Stress	Maximum load: Strain	Maximum load: Stress
Degrees	°F.	Percent	Percent	1,000 p.s.i.	Inches per inch	P.s.i.	Inches per inch	P.s.i.
0	80	6	5.4	123.4	0.0054	675	0.0100	1,062
		12	11.3	112.8	.0044	499	.0152	1,018
		18	19.6	65.3	.0051	305	.0246	752
		Green	88.3	63.8	.0056	355	.0185	678
	130	6	5.5	98.7	.0043	386	.0200	1,042
		12	11.4	49.5	.0068	317	.0349	795
		18	20.6	19.4	.0119	210	.0297	437
		Green	85.0	31.5	.0033	99	.0230	297
	180	6	5.7	45.0	.0060	274	.0356	770
		12	11.9	17.1	.0065	100	.0353	336
		18	23.3	9.8	.0079	68	.0290	178
		Green	85.4	10.0	.0044	45	.0213	157
45	80	6	5.6	123.7	.0069	806	.0094	1,060
		12	11.5	111.4	.0044	437	.0159	1,058
		18	19.9	69.5	.0052	344	.0188	748
		Green	86.0	61.1	.0059	354	.0208	681
	130	6	5.9	89.5	.0065	534	.0181	974
		12	11.5	59.0	.0064	340	.0306	792
		18	19.0	34.3	.0056	141	.0346	474
		Green	83.4	35.4	.0043	121	.0239	307
	180	6	5.6	52.4	.0066	330	.0310	810
		12	12.6	21.2	.0086	130	.0484	425
		18	21.4	13.1	.0065	60	.0356	225
		Green	81.9	8.4	.0094	59	.0321	144
90	80	6	5.7	248.5	.0036	849	.0064	1,404
		12	11.6	180.8	.0052	900	.0095	1,403
		18	19.9	134.4	.0038	480	.0139	1,198
		Green	84.4	110.5	.0056	616	.0139	1,116
	130	6	5.9	171.0	.0046	763	.0092	1,308
		12	11.8	105.7	.0044	430	.0231	1,152
		18	20.1	50.6	.0075	378	.0248	796
		Green	84.9	66.8	.0042	247	.0227	586
	180	6	6.1	133.2	.0035	458	.0169	1,123
		12	13.4	31.8	.0086	225	.0393	639
		18	20.5	46.0	.0044	141	.0246	483
		Green	83.8	22.8	.0044	86	.0241	322

Table 2.--Results of tests in compression perpendicular to grain of northern red oak at 0° to the growth rings under various conditions of temperature and moisture content (averages based on eight tests).

Temperature	Moisture content: Nominal	Moisture content: Actual	Modulus of elasticity	Proportional limit: Strain	Proportional limit: Stress	Stress at 2.5 percent strain
°F.	Percent	Percent	1,000 p.s.i.	Inches per inch	P.s.i.	P.s.i.
80	6	5.4	123.7	0.0067	806	1,504
	12	10.1	100.8	.0058	574	1,130
	18	19.6	65.4	.0060	383	765
	Green	94.4	64.8	.0075	460	716
130	6	5.3	85.1	.0053	434	1,121
	12	10.3	52.9	.0046	263	602
	18	17.8	29.6	.0082	223	457
	Green	94.9	34.9	.0064	198	404
180	6	5.4	41.8	.0087	344	714
	12	11.3	22.3	.0051	117	286
	18	18.5	9.7	.0102	96	177
	Green	91.6	9.7	.0110	99	163

Table 3.--Theoretical values of modulus of rigidity and maximum shear strength calculated on the basis of perpendicular-to-grain tension tests at 0°, 90°, and 45° to the growth rings.

Temperature	Moisture content: Assumed	Moisture content: Actual	Modulus of rigidity G_{TR}	Maximum shear strength F_{sux}
°F.	Percent	Percent	1,000 p.s.i.	P.s.i.
80	6	5.6	39.87	595
	12	11.5	37.27	598
	18	19.8	22.74	416
	Green	86.2	19.94	379
130	6	5.8	28.74	538
	12	11.6	19.90	442
	18	19.9	13.12	268
	Green	84.4	11.72	172
180	6	5.8	16.68	458
	12	12.6	7.47	253
	18	21.7	4.12	135
	Green	83.7	2.55	79

Table 4.--Parameters of the general equation $Y = a + bT + cM + dM^2 + eTM + fTM^2$, expressing the relationship of perpendicular-to-grain mechanical properties of red oak to temperature and moisture content within the moisture content range of 6 to 18 percent and the temperature range of 80° to 180° F. (T = temperature, °F.; M = moisture content, percent).

Property (Y)	Angle to growth rings	a	b	c	d	e	f
	Degrees						
		Tension					
Modulus of elasticity (1,000 p.s.i.)	0	162.368	-0.3070	+8.0180	-0.5518	-0.11180	+0.00496
	45	153.967	-.2914	+7.7434	-.4944	-.09918	+.00428
	90	344.592	-.3317	-1.6142	-.2910	-.16766	+.00690
Stress at proportional limit (p.s.i.)	0	1047.523	-3.3252	-13.5036	-.6430	-.15898	+.00980
	45	1964.587	-8.0597	-167.2456	+4.8232	+.71772	-.02294
	90	550.300	+2.4286	+151.0492	-7.0344	-1.39944	+.05567
Stress at maximum load (p.s.i.)	0	716.765	+3.8876	+141.9336	-5.8476	-1.47602	+.04922
	45	616.904	+3.6490	+153.5176	-6.4030	-1.35562	+.04600
	90	853.345	+4.8832	+168.1688	-6.1652	-1.56046	+.04805
Strain at maximum load (in./in. x 10^4)	0	-247.197	+2.7612	+21.7310	-.1158	+.01301	-.00464
	45	-10.779	-.0340	-20.1716	+1.1132	+.50182	-.01965
	90	309.640	-3.4415	-72.3148	+2.9706	+.95077	-.03572
		Compression					
Modulus of elasticity (1,000 p.s.i.)	0	232.140	-.8752	-8.4238	+.1066	+.00836	+.00038
Stress at proportional limit (p.s.i.)	0	1489.006	-4.6753	-75.6448	+1.5108	-.02024	+.00654
Stress at 2.5 percent strain (p.s.i.)	0	2775.883	-7.1865	-132.2162	+2.7498	-.21226	+.01484
		Tension and Compression					
Modulus of elasticity (1,000 p.s.i.)	0	194.732	-.5692	+.4012	-.2496	-.05704	+.00292
		Shear					
Modulus of rigidity, G_{TR} (p.s.i.)	....	41.128	-.0430	+3.8651	-.1994	-.03979	+.00162
Maximum shear strength, F_{TR} (p.s.i.)	....	321.8	+2.26	+89.283	-3.7638	-.79167	+.02778

Table 5.--Effect of temperature on perpendicular-to-grain properties of northern red oak within the range 80° to 180° F. at various levels of moisture content. Reduction expressed as percentage of 80° value per °F. (based on mathematically fitted curves shown in figures 9 through 26).

Property	Angle to growth rings	Reduction: 6 percent moisture content	12 percent moisture content	18 percent moisture content	Green
	Degrees	Percent	Percent	Percent	Percent
Tension					
Modulus of elasticity	0	0.63	0.88	0.85	0.86
	45	.60	.81	.88	.86
	90	.46	.77	.80	.78
Stress at proportional limit	0	.62	.78	.85	.97
	45	.60	.63	.86	.92
	90	.45	.76	.80	.91
Stress at maximum load	0	.28	.65	.82	.82
	45	.23	.57	.70	.86
	90	.19	.48	.61	.76
Strain at maximum load	0	-2.79	-1.43	-.49	[1]-.14
	45	-2.56	-1.89	-1.28	-.54
	90	-1.78	-2.96	-1.54	-.65
Compression					
Modulus of elasticity	0	.67	.81	.86	.86
Stress at proportional limit	0	.63	.83	.83	.83
Stress at 2.5 percent strain	0	.53	.75	.79	.79
Modulus of elasticity (combined tension and compression)	0	.65	.86	.86	.86
Shear					
Modulus of rigidity (G_{TR})	....	.57	.81	.88	.87
Maximum strength (F_{TR})	....	.25	.54	.61	.83

[1] A negative reduction indicates an increase with increasing temperature.

Table 6.--Results of tests in tension perpendicular to the grain after various durations of exposure to 130° and 180° F. at 12 percent moisture content and in the green condition. (Values for 0 hours are based on four tests; other values are based on two tests. Control values are underlined.)

Exposure time	Tested at exposure conditions: Modulus of elasticity	Tested at exposure conditions: Stress at proportional limit	Tested at exposure conditions: Stress at maximum load	Tested at exposure conditions: Strain at maximum load	Reconditioned and tested at 80° F.: Modulus of elasticity	Reconditioned and tested at 80° F.: Stress at proportional limit	Reconditioned and tested at 80° F.: Stress at maximum load	Reconditioned and tested at 80° F.: Strain at maximum load
Hours	1,000 p.s.i.	P.s.i.	P.s.i.	Inches per inch	1,000 p.s.i.	P.s.i.	P.s.i.	Inches per inch
				130° Material at 12 Percent Moisture Content				
0	53.4	245	834	0.0369	105.9	454	978	0.0150
42	68.6	218	724	.0215	147.2	698	1044	.0121
75	45.2	263	800	.0342	101.0	531	916	.0106
132	42.0	329	790	.0279	145.9	521	979	.0088
232	81.1	310	908	.0302	83.7	662	832	.0108
408	70.0	286	823	.0274	86.2	829	832	.0099
720	60.8	229	713	.0232	117.2	678	904	.0091
Significance of regression[1]	NS	NS	NS	NS	NS	NS	S	S
Regression coefficient[2]							11.60	21.21
				130° Green Material				
0	32.2	106	308	.0248	67.8	382	733	.0181
42	49.5	136	384	.0194	67.7	290	614	.0160
75	20.0	124	345	.0297	65.3	308	642	.0160
132	31.3	148	376	.0193	58.2	310	531	.0114
232	35.0	190	435	.0236	60.2	370	674	.0164
408	28.8	162	379	.0238	55.6	248	551	.0182
720	23.3	177	408	.0220	67.8	341	562	.0119
Significance of regression[1]	NS	NS	NS	NS	NS	NS	S	NS
Regression coefficient[2]							11.60	

(Sheet 1 of 2)

Table 6.--Results of tests in tension perpendicular to the grain after various durations of exposure to 130° and 180° F. at 12 percent moisture content and in the green condition. (Values for 0 hours are based on four tests; other values are based on two tests. Control values are underlined.)--continued

Exposure time	Tested at exposure conditions: Modulus of elasticity	Tested at exposure conditions: Stress at proportional limit	Tested at exposure conditions: Stress at maximum load	Tested at exposure conditions: Strain at maximum load	Reconditioned and tested at 80° F.: Modulus of elasticity	Reconditioned and tested at 80° F.: Stress at proportional limit	Reconditioned and tested at 80° F.: Stress at maximum load	Reconditioned and tested at 80° F.: Strain at maximum load
Hours	1,000 p.s.i.	P.s.i.	P.s.i.	Inches per inch	1,000 p.s.i.	P.s.i.	P.s.i.	Inches per inch
180° Material at 12 Percent Moisture Content								
0	19.8	106	346	0.0337	105.9	454	978	0.0150
42	19.4	173	437	.0543	98.2	724	1,034	.0125
75	15.1	125	362	.0376	110.6	423	1,048	.0168
132	15.3	127	330	.0349	102.4	296	930	.0098
232	12.3	104	245	.0341	98.6	568	1,023	.0151
408	17.2	72	299	.0425	100.1	406	698	.0064
720	14.8	147	314	.0541	89.0	532	690	.0073
Significance of regression[1]	VS	NS	S	NS	VS	NS	VS	NS
Regression coefficient[2]	6.63	....	9.22	....	6.63	....	23.08	....
180° Green Material								
0	11.9	50	184	.0198	67.8	382	733	.0181
42	11.6	62	130	.0148	72.6	209	506	.0146
75	9.1	90	155	.0155	62.8	200	520	.0250
132	8.4	43	113	.0189	50.8	260	526	.0252
232	4.8	62	82	.0262	56.8	155	432	.0176
408	4.2	35	117	.0572	32.4	110	284	.0324
720	4.6	36	52	.0155	32.1	125	141	.0043
Significance of regression[1]	VS	NS	S	NS	VS	S	VS	NS
Regression coefficient[2]	6.63	....	9.22	....	41.50	37.18	45.70	....

[1]NS = not statistically significant; S = significant at 5 percent level of probability; VS = significant at 1 percent level of probability.

[2]Reduction in property (percent of control per log day).

(Sheet 2 of 2)

Table 7.--Results of tests in compression perpendicular to the grain after various durations of exposure to 130° F. and 180° F. at 12 percent moisture content and in the green condition (0 hour values are based on four tests; other values are based on two tests. Control values are underlined).

Exposure time	Tested at exposure conditions			Reconditioned and tested at 80° F.		
	Modulus of elasticity	Stress at proportional limit	Stress at 2.5 percent strain	Modulus of elasticity	Stress at proportional limit	Stress at 2.5 percent strain
Hours	1,000 p.s.i.	P.s.i.	P.s.i.	1,000 p.s.i.	P.s.i.	P.s.i.
130° Material at 12 Percent Moisture Content						
0	46.8	290	588	95.1	593	1,085
42	39.0	181	457	113.9	410	1,223
75	59.8	178	562	116.1	416	1,253
132	51.9	450	707	124.9	539	1,307
232	58.7	264	664	173.6	306	1,202
408	67.0	370	783	114.1	700	1,261
720	73.8	287	682	106.9	737	1,390
Significance of regression[1]	NS	NS	NS	NS	NS	NS
Regression coefficient[2]	....	....	....	....	....	....
130° Green Material						
0	32.9	177	374	59.4	492	742
42	29.5	162	338	68.2	247	618
75	32.6	151	336	70.3	248	621
132	28.2	207	380	79.5	322	642
232	44.4	170	444	104.8	274	683
408	29.9	178	404	71.0	248	584
720	29.6	170	382	105.6	232	618
Significance of regression[1]	NS	NS	NS	NS	NS	NS
Regression coefficient[2]	....	....	....	....	....	....

(Sheet 1 of 2)

Table 7.--Results of tests in compression perpendicular to the grain after various durations of exposure to 130° F. and 180° F. at 12 percent moisture content and in the green condition (0 hour values are based on four tests; other values are based on two tests. Control values are underlined).--continued

Exposure time	Tested at exposure conditions			Reconditioned and tested at 80° F.		
	Modulus of elasticity	Stress at proportional limit	Stress at 2.5 percent strain	Modulus of elasticity	Stress at proportional limit	Stress at 2.5 percent strain
Hours	1,000 p.s.i.	P.s.i.	P.s.i.	1,000 p.s.i.	P.s.i.	P.s.i.
			180° Material at 12 Percent Moisture Content			
0	22.9	132	301	95.1	593	1,085
42	33.2	84	234	102.3	462	1,219
75	23.5	68	197	118.8	581	1,277
132	31.4	76	249	117.0	719	1,248
232	29.0	79	260	91.4	629	1,174
408	19.2	68	206	114.3	586	1,163
720	17.0	69	82	114.5	398	1,137
Significance of regression[1]	NS	VS	VS	NS	NS	VS
Regression coefficient[2]	....	7.04	6.78	....	....	6.78
			180° Green Material			
0	10.6	100	170	59.4	492	742
42	10.8	54	149	44.1	200	514
75	17.4	47	157	50.4	260	559
132	7.5	40	114	45.4	170	483
232	6.9	36	96	29.8	209	430
408	13.4	24	88	26.2	118	322
720	5.4	20	42	24.1	108	217
Significance of regression[1]	NS	VS	VS	VS	VS	VS
Regression coefficient[2]	....	7.04	6.78	39.50	40.38	40.95

[1] NS = not statistically significant; S = significant at 5 percent level of probability; VS = significant at 1 percent level of probability.

[2] Reduction in property with time of exposure (percent of control per log day).

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Table 8.--Results of creep and recovery tests in tension perpendicular to the grain.

Temperature	Nominal moisture content	Stress level	Stress	Moisture content	Specific gravity (ovendry)	Parameters of equation $e = e_o + mt^{n^1}$						Time to failure
						Creep			Recovery			
						e_o	m	n	e_o	m	n	
°F.	Percent	Percent	P.s.i.	Percent								Hours
80	12	40	387	10.7	0.585	0.0025	0.0013	0.140	0.0021	0.0018	0.060	....
		50	486	10.6	.585	.0031	.0019	.194	.0024	.0018	.147	....
		60	586	10.4	.558	.0037	.0029	.156	.0041	.0023	.091	....
		70	684	10.7	.565	.0045	.0033	.177	.0048	.0021	.124	....
		80	780	10.6	.552	.0048	.0055	.180	.0050	.0036	.114	....
		90	880	10.6	.588	.0052	.0064	.182	....	....	....	8.85
								$\bar{n}$ = .171			$\bar{n}$ = .107	
80	Green	40	242	70.9	.577	.0033	.0015	.226	.0021	.0023	.138	....
		50	304	72.5	.581	.0041	.0029	.274	.0035	.0034	.124	....
		60	361	75.0	.562	.0046	.0040	.280	.0053	.0040	.134	....
		70	422	85.0	.554	.0055	.0055	.286	....	....	....	20.05
		80	483	85.0	.542	.0068	.0077	.300	....	....	....	6.45
		90	560	87.6	.562	....	....	....	....	....	....	.09
								$\bar{n}$ = .273			$\bar{n}$ = .132	
180	12	40	127	7.0	.535	.0023	.0036	.254	.0010	.0010	.322	....
		50	159	7.5	.554	.0049	.0049	.224	.0019	.0013	.284	....
		60	191	7.0	.527	.0056	.0062	.247	.0009	.0015	.352	....
		70	223	7.8	.568	.0089	.0057	.191	.0024	.0025	.300	....
		80	254	6.5	.559	.0096	.0087	.231	.0029	.0021	.300	....
		90	286	7.0	.549	.0139	.0120	.234	.0038	.0030	.314	....
								$\bar{n}$ = .230			$\bar{n}$ = .312	

(Sheet 1 of 2)

Table 8.--Results of creep and recovery tests in tension perpendicular to the grain.--continued

Temperature	Nominal moisture content	Stress level	Stress	Moisture content	Specific gravity (ovendry)	Parameters of equation $e = e_o + mt^n$[1]						Time to failure
						Creep			Recovery			
						e_o	m	n	e_o	m	n	
°F.	Percent	Percent	P.s.i.	Percent								Hours
180	Green	40	62	120.9	0.558	0.0024	0.0058	0.540	0.0043	0.0008	0.204	......
		50	78	86.1	.608	.0151	.0055	.277	......	......	......	51.85
		60	94	76.1	.583	......	......	......	......	......	......	6.65
		70	110	116.4	.549	......	......	......	......	......	......	.98
		80	126	108.1	.600	......	......	......	......	......	......	.10
								$\bar{n}$ = .408				

[1] e represents total strain (inches per inch); t represents time (hours).

(Sheet 2 of 2)

Table 9.--Results of creep and recovery tests in compression perpendicular to the grain.

Temperature	Nominal moisture content	Stress level	Stress	Moisture content	Specific gravity (ovendry)	Creep e_o	Creep m	Creep n	Recovery e_o	Recovery m	Recovery n
						Parameters of equation $e = e_o + mt^{\frac{1}{n}}$					
°F.	Percent	Percent	P.s.i.	Percent							
80	12	40	387	10.8	0.582	0.0012	0.0010	0.040	0.0004	0.0012	0.020
		50	485	10.9	.592	.0026	.0006	.147	.0005	.0023	.020
		60	586	10.8	.567	.0038	.0020	.095	.0025	.0023	.020
		70	680	11.0	.570	.0031	.0037	.101	.0047	.0023	.020
		80	785	10.9	.565	.0047	.0037	.153	.0063	.0025	.107
		90	880	10.8	.586	.0046	.0032	.185	.0067	.0025	.107
											$\bar{n}$ = .049
80	Green	40	239	77.9	.552	-.0035	.0064	.020	....	....	....
		50	301	71.0	.624	.0011	.0024	.080	.0021	.0017	.124
		60	358	73.6	.583	.0025	.0027	.186	....	....	....
		70	421	71.2	.571	.0038	.0033	.350	.0080	.0034	.070
		80	480	79.3	.544	.0035	.0029	.284	.0088	.0023	.020
		90	542	61.1	.577	.0052	.0044	.336	....	....	....
											$\bar{n}$ = .071
180	12	40	127	7.1	.549	.0014	.0026	.382	.0018	.0012	.282
		50	159	8.7	.573	.0025	.0029	.328	.0016	.0016	.336
		60	191	6.6	.553	.0055	.0045	.287	.0017	.0035	.400
		70	223	6.6	.581	.0060	.0062	.314	.0035	.0041	.357
		80	254	6.0	.551	.0094	.0052	.259	.0038	.0032	.324
		90	286	5.8	.572	.0086	.0124	.356	.0078	.0044	.254
								$\bar{n}$ = .312			$\bar{n}$ = .325

(Sheet 1 of 2)

Table 9.--Results of creep and recovery tests in compression perpendicular to the grain.--continued

Temperature	Nominal moisture content	Stress level	Stress	Moisture content	Specific gravity (ovendry)	Parameters of equation $e = e_o + mt^n$[1] Creep e_o	Creep m	Creep n	Recovery e_o	Recovery m	Recovery n
°F.	Percent	Percent	P.s.i.	Percent							
180	Green	40	62	135.8	0.565	0.0038	0.0023	0.409	....	....	....
		50	78	129.2	.592	....	....	....	....	....	....
		60	94	142.7	.556	.0048	.0037	.488	....	....	....
		70	110	135.9	.575	.0061	.0160	.496	....	....	....
								$\bar{n}$ = .464			

[1] e represents total strain (inches per inch); t represents time (hours).

(Sheet 2 of 2)

Table 10.--Rate of creep and recovery from creep under constant load in tension and compression at 2, 10, and 50 hours after application or removal of load (values calculated from parameters listed in tables 8 and 9).

Nominal moisture content	Stress level	Time	Tension				Compression			
			Creep rate[1]		Recovery rate[1]		Creep rate[1]		Recovery rate[1]	
			80°	180°	80°	180°	80°	180°	80°	180°
	Percent	Hours	Inches per inch per hour x 10^5	Inches per inch per hour x 10^5	Inches per inch per hour x 10^5	Inches per inch per hour x 10^5	Inches per inch per hour x 10^5	Inches per inch per hour x 10^5	Inches per inch per hour x 10^5	Inches per inch per hour x 10^5
12 percent	40	2	12.5	48.6	10.4	19.3	2.05	50.4	1.22	24.4
		10	3.31	14.1	2.47	6.42	.44	16.6	.25	8.25
		50	.87	4.08	.59	2.11	.09	5.49	.05	2.78
	50	2	18.2	66.1	10.4	25.1	4.88	56.1	2.33	32.6
		10	4.82	19.2	2.47	8.33	1.24	18.6	.98	11.0
		50	1.27	5.56	.59	2.74	.31	6.12	.10	3.71
	60	2	27.9	83.6	13.3	29.0	10.1	87.1	2.33	71.3
		10	7.40	24.3	3.16	9.62	2.36	28.8	.98	24.0
		50	1.94	7.03	.75	3.16	.55	9.50	.10	8.10
	70	2	31.7	71.9	12.1	48.4	20.0	120.0	2.33	83.5
		10	8.36	22.3	2.88	16.0	4.70	39.7	.98	28.2
		50	2.20	6.46	.69	5.26	1.11	13.1	.10	9.49
	80	2	53.0	117.2	20.7	40.6	31.4	100.5	14.4	65.2
		10	14.0	34.1	4.94	13.4	8.05	33.3	3.44	22.0
		50	3.67	9.85	1.17	4.42	2.06	11.0	.77	7.41
	90	2	61.5	162.0	....	58.0	33.6	218.0	14.4	89.5
		10	16.2	47.8	....	19.2	9.07	72.3	3.44	30.2
		50	4.28	13.6	....	6.33	2.44	23.8	.77	10.2

(Sheet 1 of 2)

Table 10.--Rate of creep and recovery from creep under constant load in tension and compression at 2, 10, and 50 hours after application or removal of load (Values calculated from parameters listed in tables 8 and 9).

Nominal moisture content	Stress level	Time	Tension: Creep rate[1] 80°	Tension: Creep rate[1] 180°	Tension: Recovery rate[1] 80°	Tension: Recovery rate[1] 180°	Compression: Creep rate[1] 80°	Compression: Creep rate[1] 180°	Compression: Recovery rate[1] 80°	Compression: Recovery rate[1] 180°
	Percent	Hours	Inches per inch per hour x 10^5	Inches per inch per hour x 10^5	Inches per inch per hour x 10^5	Inches per inch per hour x 10^5	Inches per inch per hour x 10^5	Inches per inch per hour x 10^5	Inches per inch per hour x 10^5	Inches per inch per hour x 10^5
Green	40	2	24.7	157.0	16.6	9.41	6.50	73.6	....	....
		10	7.68	60.7	4.13	2.61	1.34	31.1	....	....
		50	2.38	23.5	1.01	.73	.28	13.1	....	....
	50	2	47.9	149.0	24.6	....	10.16	....	6.34	....
		10	14.9	57.5	6.10	....	2.31	....	1.42	....
		50	4.60	22.3	1.50	....	.52	....	.32	....
	60	2	66.0	....	28.9	....	28.6	118.2	....	....
		10	20.5	....	7.18	....	7.71	50.0	....	....
		50	6.35	....	1.76	....	2.08	21.1	....	....
	70	2	90.7	....	....	....	73.8	513.0	12.67	....
		10	28.2	....	....	....	25.9	216.0	2.84	....
		50	8.74	....	....	....	9.10	91.4	.64	....
	80	2	127.0	....	....	....	50.2	....	8.58	....
		10	39.4	....	....	....	15.9	....	1.93	....
		50	12.2	....	....	....	4.99	....	.43	....
	90	2	....	....	....	....	93.3	....	....	....
		10	....	....	....	....	32.1	....	....	....
		50	....	....	....	....	11.0	....	....	....

[1] Rate of creep or recovery = mnt^{n-1}.

(Sheet 2 of 2)

Table 11.--Results of stress relaxation tests in tension and compression perpendicular to the grain.

Temperature	Nominal moisture content	Initial stress: Actual stress (f_o)	Initial stress: Percent of maximum	Tension: Moisture content	Tension: Specific gravity[1]	Tension: b[2]	Tension: m[3]	Compression: Moisture content	Compression: Specific gravity[1]	Compression: b[2]	Compression: m[3]
°F.		P.s.i.	Percent	Percent				Percent			
75	12 percent	425	40	10.8	0.584	-0.0453	0.108	11.1	0.590	-0.0265	0.050
		531	50	10.6	.570	-.0372	.084	11.0	.567	-.0321	.058
		637	60	10.9	.567	-.0452	.092	11.4	.577	-.0444	.050
		744	70	11.0	.568	-.0522	.100	11.0	.572	-.0334	.062
		850	80	11.0	.544	-.0503	.096	11.2	.548	-.0457	.074
		955	90	11.3	.562	-.0478	.100	11.1	.584	-.0478	.079
	Average			10.9	.566	-.0463	.097	11.1	.573	-.0383	.062
	Standard deviation			.23	.0126	.0053	.0084	.16	.0155	.0091	.0139
75	Green	271	40	91.1	.574	-.0539	.106	107.8	.550	-.0487	.095
		339	50	109.7	.544	-.0520	.119	114.5	.552	-.0556	.100
		407	60	100.2	.564	-.0605	.128	102.5	.552	-.0555	.089
		475	70	109.9	.525	-.0718	.139	106.2	.599	-.0617	.100
		542	80	92.0	.554	-.0725	.130	104.9	.566	-.0690	.102
		610	90	90.4	.560	-.0741	.134	101.0	.574	-.0700	.105
	Average			98.9	.554	-.0641	.126	106.2	.566	-.0600	.098
	Standard deviation			9.98	.0170	.0107	.0126	4.93	.0186	.0091	.0060

Table 11.--Results of stress relaxation tests in tension and compression perpendicular to the grain.--continued

Temperature	Nominal moisture content	Initial stress: Actual stress: (f_o)	Initial stress: Percent of maximum	Tension: Moisture content	Tension: Specific gravity[1]	Tension: b[2]	Tension: m[3]	Compression: Moisture content	Compression: Specific gravity[1]	Compression: b[2]	Compression: m[3]
°F.		P.s.i.	Percent	Percent				Percent			
180	12 percent	127	40	8.7	0.554	-0.2538	0.315	8.2	0.550	-0.3541	0.386
		159	50	8.7	.564	-.1511	.219	10.0	.614	-.0890	.196
		191	60	8.8	.541	-.1999	.300	....	....	....	....
		223	70	9.3	.601	-.1807	.297	....	....	....	....
		254	80	9.1	.556	-.1619	.254	8.9	.551	-.4683	.472
		286	90	8.9	.535	-.1997	.321	....	....	....	....
	Average			8.9	.558	-.1912	.284	9.0	.572	-.3038	.351
	Standard deviation			.26	.0233	.0369	.0427	1.06	.0378	.2241	.1631
180	Green	62	40	....	....	....	....	....	....	....	....
		78	50	59.6	.571	-.1832	.350	....	.625	-.0506	.141
		94	60	104.8	.564	....	....	....	....	....	....
		110	70	....	.610	-.0877	.235	110.1	.535	-.0654	.144
		126	80	91.1	.590	-.0790	.182	115.1	.577	-.0520	.122
		142	90	....	....	....	....	105.3	.596	-.0376	.080
	Average			85.2	.584	-.1166	.256	110.2	.583	-.0514	.122
	Standard deviation			26.71	.0224	.0616	.0993	5.79	.0437	.0135	.0311

[1] Based on ovendry weight and volume.

[2] Parameter of equation $f = f_o (t + 1)^b$; t represents time (minutes).

[3] Parameter of equation $f = f_1 (1 - m \log t)$; t represents time (hours).

Table 12.--Tension perpendicular to grain, modulus of elasticity

Effect[1]	Component	Degrees of freedom	Sum of squares	Mean square	Variance ratio (F)	Significance[2]	Basis of comparison
L	....	3	31.9809	10.6603	2.589	NQS	R
M	Gr. v. Others	1	717.0445	....	152.013	VS	LM
M	Others - l	1	1842.5556	....	390.620	VS	LM
M	Others - q	1	32.6150	....	6.914	S	LM
T	l	1	3290.9688	....	365.265	VS	LT
T	q	1	41.6563	....	4.623	NS	LT
A	l	1	1428.4463	....	795.349	VS	LA
A	q	1	387.2696	....	215.629	VS	LA
LxM	....	9	42.4529	4.7170	1.146	NS	R
LxT	....	6	54.0585	9.0098	2.188	S	R
LxA	....	6	10.7761	1.7960	....	NS	R
MxT	Total	6	217.6843	36.2807	5.439	VS	LMT
MxT	Others - l-l	1	....	27.9504	4.19	NS	LMT
MxT	Others - q-l	1	....	91.8012	13.76	VS	LMT
MxT	Others - l-q	1	....	32.8050	4.92	S	LMT
MxT	Others - q-q	1	....	1.4670	0.22	NS	LMT
MxA	Total	6	400.0677	66.6780	8.234	VS	LMA
MxA	Others - l-l	1	....	147.7584	18.25	VS	LMA
MxA	Others - q-l	1	....	45.8403	5.66	S	LMA
MxA	Others - l-q	1	....	86.7903	10.72	VS	LMA
MxA	Others - q-q	1	....	16.6389	2.05	NS	LMA
TxA	Total	4	195.1457	48.7864	15.590	VS	LTA
TxA	l-l	1	....	124.0314	39.63	VS	LTA
TxA	q-l	1	....	7.9926	2.55	NS	LTA
TxA	l-q	1	....	55.0551	17.59	VS	LTA
TxA	q-q	1	....	8.0667	2.58	NS	LTA
LxMxT	....	18	120.0598	6.6700	1.620	S	R
LxMxA	....	18	145.7680	8.0982	1.967	S	R
LxTxA	....	12	37.5523	3.1294	....	NS	R
MxTxA	....	12	62.0733	5.1728	....	NS	LMTA
LxMxTxA	....	36	189.5177	5.2644	1.278	NS	R
Residual	....	144	592.9367	4.1176	....	....	....
Total	....	287	9840.6300	....	....	....	....
Correction	....	1	1526.7417	....	....	....	....

[1]L = logs; M = moisture content; T = temperature; A = angle of loading.

[2]NS = not statistically significant; S = significant at 5 percent level of probability; VS = significant at 1 or 0.1 percent level of probability; NQS = approaching significance at the 5 percent level of probability.

Table 13--Compression perpendicular to grain, modulus of elasticity

Effect[1]	Component	Degrees of freedom	Sum of squares	Mean square	Variance ratio (F)	Significance[2]	Basis of comparison
L	....	3	3.0503	1.0168	1.04	NS	R
M	Gr. v. Others	1	93.0475	....	79.76	VS	LM
M	Others - l	1	283.2408	....	242.79	VS	LM
M	Others - q	1	0.0278	....	0.02	NS	LM
T	l	1	733.7327	....	1003.88	VS	LT
T	q	1	3.6576	....	5.00	NS	LT
LxM	....	9	10.4993	1.1666	1.19	NS	R
LxT	....	6	4.3856	0.7309	0.74	NS	R
MxT	Total	6	29.0472	4.8412	6.24	VS	LMT
MxT	Others - l-l	1	....	13.6503	17.60	VS	LMT
MxT	Others - q-l	1	....	2.7000	3.48	NS	LMT
MxT	Others - l-q	1	....	2.7675	3.57	NS	LMT
MxT	Others - q-q	1	....	1.2933	1.67	NS	LMT
LxMxT	....	18	13.9636	0.7758	0.79	NS	R
Residual	....	48	47.0950	0.9811	....	....	....
Total	....	95	1221.7474	....	....	....	....
Correction	....	1	11.0026	....	....	....	....

[1] L = logs; M = moisture content; T = temperature.

[2] NS = not statistically significant; VS = significant at 1 or 0.1 percent level of probability.

Table 14--Tension perpendicular to grain, stress at proportional limit

Effect[1]	Component	Degrees of freedom	Sum of squares	Mean square	Variance ratio (F)	Significance[2]	Basis of comparison
L		3	65.41	21.80		NS	R
M	Gr. v. Others	1	15930.67		157.08	VS	LM
M	Others - 1	1	38743.36		382.01	VS	LM
M	Others - q	1	283.56		2.80	NS	LM
T	1	1	71379.19		580.32	VS	LT
T	q	1	495.06		4.02	NS	LT
A	1	1	16539.19		87.05	VS	LA
A	q	1	2835.56		14.92	VS	LA
LxM		9	912.77	101.42	1.12	NS	R
LxT		6	737.97	123.00	1.36	NS	R
LxA		6	1139.97	190.00	2.10	S	R
MxT	Total	6	3033.70	505.62	4.90	VS	LMT
MxT	Others - 1-1	1		1120.67	10.85	VS	LMT
MxT	Others - q-1	1		868.05	8.41	VS	LMT
MxT	Others - 1-q	1		14.22	0.14	NS	LMT
MxT	Others - q-q	1		50.07	0.48	NS	LMT
MxA	Total	6	1792.62	298.77	2.61	NS	LMA
MxA	Others - 1-1	1		777.00	6.79	S	LMA
MxA	Others - q-1	1		32.67	0.29	NS	LMA
MxA	Others - 1-q	1		389.67	3.40	NS	LMA
MxA	Others - q-q	1		426.45	3.73	NS	LMA
TxA	Total	4	2277.25	569.31	4.24	S	LTA
TxA	1-1	1		1718.45	12.79	VS	LTA
TxA	q-1	1		47.46	0.35	NS	LTA
TxA	1-q	1		506.46	3.77	NS	LTA
TxA	q-q	1		4.88	0.04	NS	LTA
LxMxT		18	1858.85	103.27	1.14	NS	R
LxMxA		18	2060.44	114.47	1.26	NS	R
LxTxA		12	1612.03	134.34	1.48	NS	R
MxTxA		12	5110.97	425.91	3.74	VS	LMTA
LxMxTxA		36	4103.31	113.98	1.26	NS	R
Residual		144	13037.00	90.53			
Total		287	183948.88				
Correction		1	6903.12				

[1]L = logs; M = moisture content; T = temperature; A = angle of loading.

[2]NS = not statistically significant; S = significant at 5 percent level of probability; VS = significant at 1 or 0.1 percent level of probability.

Table 15--Compression perpendicular to grain, stress at proportional limit

Effect[1]	Component	Degrees of freedom	Sum of squares	Mean square	Variance ratio (F)	Significance[2]	Basis of comparison
L	....	3	876.58	292.19	4.77	VS	R
M	Gr. v. Others	1	2077.98	....	17.24	VS	LM
M	Others - l	1	10410.58	....	86.35	VS	LM
M	Others - q	1	637.14	....	5.28	S	LM
T	l	1	24605.84	....	131.74	VS	LT
T	q	1	1375.49	....	7.36	S	LT
LxM	....	9	1085.04	120.56	1.97	NS	R
LxT	....	6	1120.60	186.77	3.05	S	R
MxT	Total	6	1258.28	209.71	4.00	S	LMT
MxT	Others - l-l	1	....	615.13	11.73	VS	LMT
MxT	Others - q-l	1	....	182.33	3.48	NS	LMT
MxT	Others - l-q	1	....	411.27	7.84	S	LMT
MxT	Others - q-q	1	....	0.56	0.01	NS	LMT
LxMxT	....	18	944.35	52.46	0.86	NS	R
Residual	....	48	2938.68	61.22	....	....	....
Total	....	95	47330.56	....	....	....	....
Correction	....	1	1045.44	....	....	....	....

[1] L = logs; M = moisture content; T = temperature.

[2] NS = not statistically significant; S = significant at 5 percent level of probability; VS = significant at 1 or 0.1 percent level of probability.

Table 16.--Tension perpendicular to grain, maximum stress

Effect[1]	Component	Degrees of freedom	Sum of squares	Mean square	Variance ratio (F)	Significance[2]	Basis of comparison
L		3	3775.32	1258.44	15.06	VS	R
M	Gr. v. Others	1	68035.75		705.85	VS	LM
M	Others - l	1	80750.69		834.20	VS	LM
M	Others - q	1	230.98		2.39	NS	LM
T	l	1	143937.76		544.68	VS	LT
T	q	1	19.87		0.08	NS	LT
A	l	1	53633.76		150.32	VS	LA
A	q	1	14894.17		41.74	VS	LA
LxM		9	871.16	96.80	1.16	NS	R
LxT		6	1585.59	264.26	3.16	VS	R
LxA		6	2140.79	356.80	4.27	VS	R
LxA	LxA_l	3	1726.51	575.50	6.89	VS	R
LxA	LxA_q	3	414.28	138.09	1.65	NS	R
MxT	Total	6	17239.31	2873.22	31.24	VS	LMT
MxT	Others - l-l	1		6501.03	70.69	VS	LMT
MxT	Others - q-l	1		2595.27	28.22	VS	LMT
MxT	Others - l-q	1		773.55	8.41	VS	LMT
MxT	Others - q-q	1		654.51	7.12	S	LMT
MxA	Total	6	491.51	81.92	1.01	NS	LMA
MxA	Others - l-l	1		150.00	1.85	NS	LMA
MxA	Others - q-l	1		1.04	0.01	NS	LMA
MxA	Others - l-q	1		6.72	0.08	NS	LMA
MxA	Others - q-q	1		118.52	1.46	NS	LMA
TxA	Total	4	2211.91	552.98	3.01	NS	LTA
TxA	l-l	1		1170.06	6.36	S	LTA
TxA	q-l	1		62.58	0.34	NS	LTA
TxA	l-q	1		921.93	5.01	S	LTA
TxA	q-q	1		57.33	0.31	NS	LTA
LxMxT		18	1655.47	91.97	1.10	NS	R
LxMxA		18	1462.11	81.23	0.97	NS	R
LxTxA		12	2207.70	183.98	2.20	S	R
MxTxA		12	1319.24	109.94	1.06	NS	LMTA
LxMxTxA		36	3747.48	104.10	1.25	NS	R
Residual		144	12029.50	83.54			
Total		287	412240.25				
Correction		1	170284.75				

[1]L = logs; M = moisture content; T = temperature; A = angle of loading.

[2]NS = not statistically significant; S = significant at 5 percent level of probability; VS = significant at 1 or 0.1 percent level of probability.

Table 17.--Tension perpendicular to grain, maximum strain

Effect[1]	Component	Degrees of freedom	Sum of squares	Mean square	Variance ratio (F)	Significance[2]	Basis of comparison
L	....	3	511.70	170.57	2.35	NS	R
M	Gr. v. Others	1	24.33	....	0.24	NS	LM
M	Others - l	1	2686.69	....	26.42	VS	LM
M	Others - q	1	1833.56	....	18.03	VS	LM
T	l	1	14145.33	....	106.62	VS	LT
T	q	1	101.67	....	0.77	NS	LT
A	l	1	1190.02	....	3.08	NS	LA
A	q	1	1213.36	....	3.14	NS	LA
LxM	....	9	915.30	101.70	1.40	NS	R
LxT	....	6	796.00	132.67	1.83	NS	R
LxA	....	6	2316.38	386.06	5.32	VS	R
MxT	Total	6	2865.62	477.60	5.78	VS	LMT
MxT	Others - l-l	1	....	472.59	5.72	S	LMT
MxT	Others - q-l	1	....	1270.92	15.39	VS	LMT
MxT	Others - l-q	1	....	493.50	5.97	S	LMT
MxT	Others - q-q	1	....	7.23	0.09	NS	LMT
MxA	Total	6	1157.58	192.93	1.65	NS	LMA
MxA	Others - l-l	1	....	104.17	0.89	NS	LMA
MxA	Others - q-l	1	....	162.00	1.38	NS	LMA
MxA	Others - l-q	1	....	37.56	0.37	NS	LMA
MxA	Others - q-q	1	....	17.80	0.15	NS	LMA
TxA	Total	4	560.23	140.06	2.05	NS	LTA
TxA	l-l	1	....	138.20	2.02	NS	LTA
TxA	q-l	1	....	83.44	1.22	NS	LTA
TxA	l-q	1	....	302.82	4.43	NS	LTA
TxA	q-q	1	....	35.77	0.52	NS	LTA
LxMxT	....	18	1486.71	82.60	1.14	NS	R
LxMxA	....	18	2106.99	117.06	1.61	S	R
LxTxA	....	12	820.77	68.40	0.94	NS	R
MxTxA	....	12	1656.31	138.02	1.76	S	LMTA
LxMxTxA	....	36	2827.03	78.53	1.08	S	....
Residual	....	144	10452.50	72.59	....	....	....
Total	....	287	49668.08	....	....	....	....
Correction	....	1	161927.92	....	....	....	....

[1]L = logs; M = moisture content; T = temperature; A = angle of loading.

[2]NS = not statistically significant; S = significant at 5 percent level of probability; VS = significant at 1 or 0.1 percent level of probability.

Table 18.--Compression perpendicular to grain, stress at 2.5 percent strain

Effect[1]	Component	Degrees of freedom	Sum of squares	Mean square	Variance ratio (F)	Significance[2]	Basis of comparison
L	....	3	1089.54	363.18	14.64	S	R
M	Gr. v. Others	1	19045.01	....	488.96	VS	LM
M	Others - l	1	50181.33	....	1288.35	VS	LM
M	Others - q	1	1950.69	....	50.08	VS	LM
T	l	1	75831.39	....	1178.24	VS	LT
T	q	1	312.63	....	4.86	NS	LT
LxM	....	9	350.56	38.95	1.57	NS	R
LxT	....	6	386.15	64.36	2.59	S	R
MxT	Total	6	2767.41	461.24	10.30	VS	LMT
MxT	Others - l-l	1	820.14	....	18.31	VS	LMT
MxT	Others - q-l	1	504.17	....	11.26	VS	LMT
MxT	Others - l-q	1	15.03	....	0.34	NS	LMT
MxT	Others - q-q	1	460.05	....	10.27	VS	LMT
LxMxT	....	18	806.25	44.79	1.80	NS	R
Residual	....	48	1191.00	24.81	....	....	....
Total	....	95	153911.96	....	....	....	....
Correction	....	1	28222.04	....	....	....	....

[1]L = logs; M = moisture content; T = temperature; A = angle of loading.

[2]NS = not statistically significant; S = significant at 5 percent level of probability; VS = significant at 1 or 0.1 percent level of probability.

Table 19.--Analysis of variance of the relaxation coefficient, m, at 75° F.

Effect[1]	Degrees of freedom	Sum of squares	Mean square	Variance ratio (F)[2]	Significance[3]
L	1	204.2	204.2	1.18	NS
T	1	11439.2	11439.2	66.12	S
M	1	12838.0	12838.0	74.21	S
S_l	1	1547.7	1547.7	8.95	S
S_q	1	37.1	37.1	0.21	NS
S_{sc}	3	244.0	81.3	0.47	NS
LxT	1	713.0	713.0	4.12	NS
LxM	1	305.1	305.1	1.76	NS
LxS_l	1	84.1	84.1	0.49	NS
LxS_q	1	17.4	17.4	0.10	NS
LxS_{sc}	3	610.2	203.4	1.18	NS
TxM	1	165.1	165.1	0.95	NS
TxS_l	1	54.7	54.7	0.32	NS
TxS_q	1	118.3	118.3	0.68	NS
TxS_{sc}	3	448.7	149.6	0.86	NS
MxS_l	1	125.4	125.4	0.72	NS
MxS_q	1	0.9	0.9	0.01	NS
MxS_{sc}	3	335.2	111.7	0.65	NS
Pooled error	21	3632.2	173.0	....	....
Total	47	32820.5	....	....	....
Correction factor	1	441408.5	....	....	....

[1] L = logs; T = type of test; M = moisture content; S = stress level; S_l = linear; S_q = quadratic; S_{sc} = scatter.

[2] All variance ratios based on pooled error with 21 degrees of freedom.

[3] NS = not statistically significant; S = significant at 1 percent level of probability.

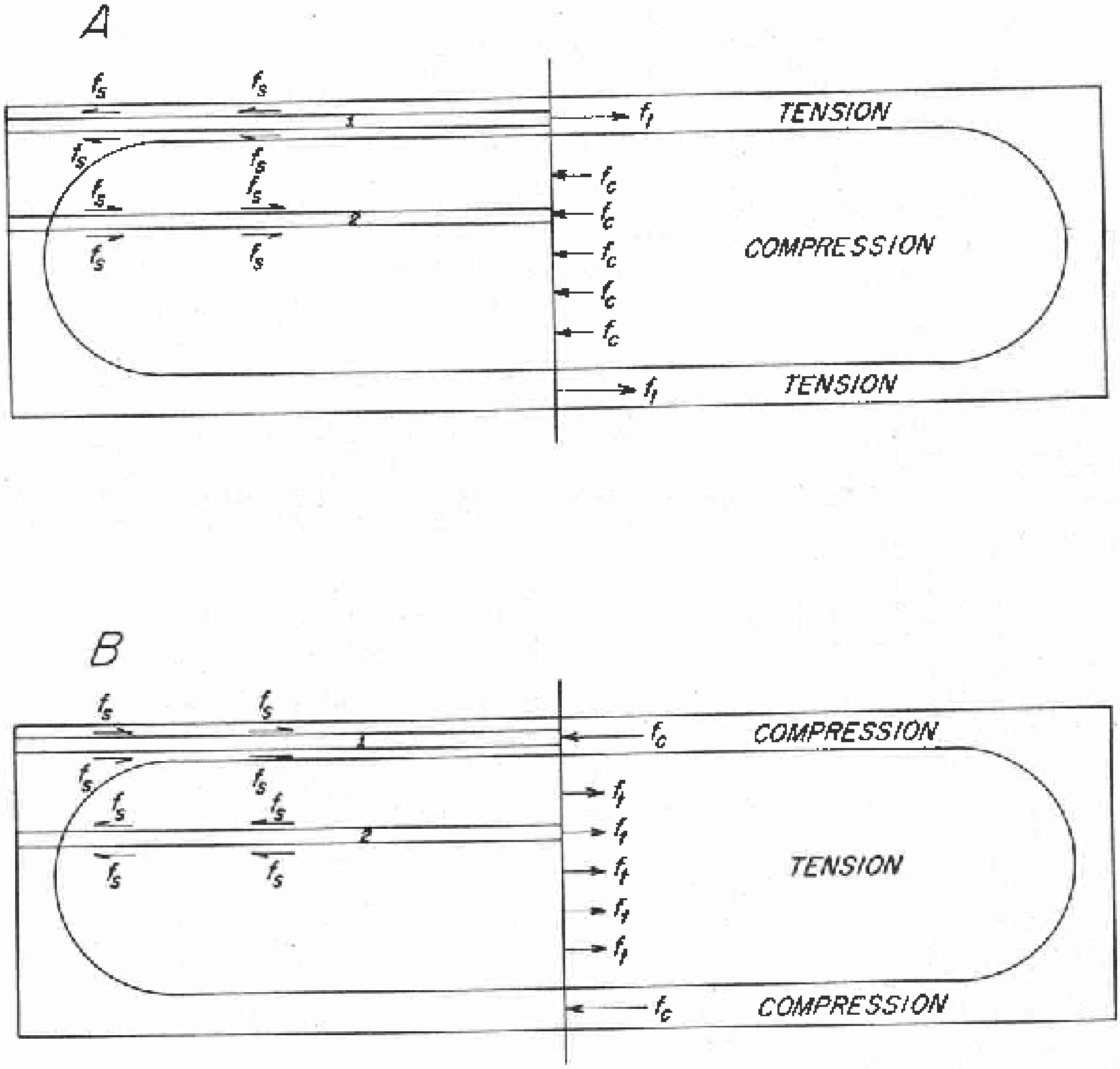
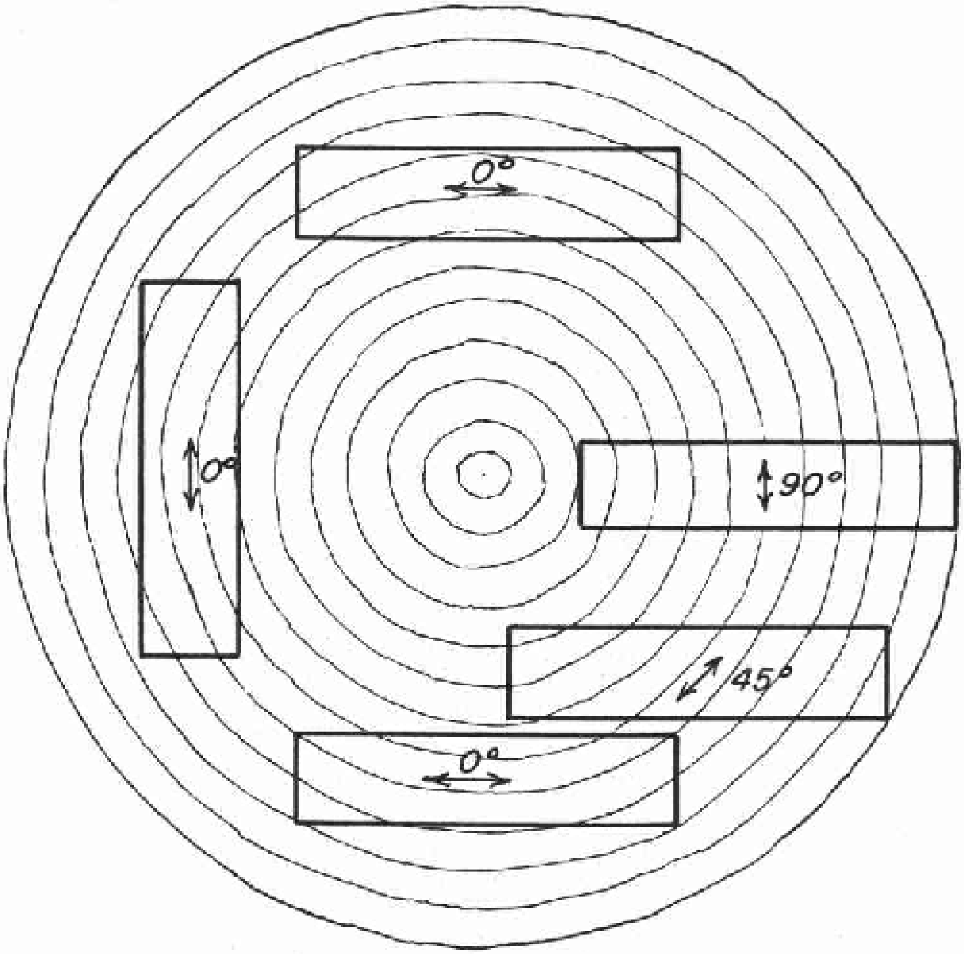
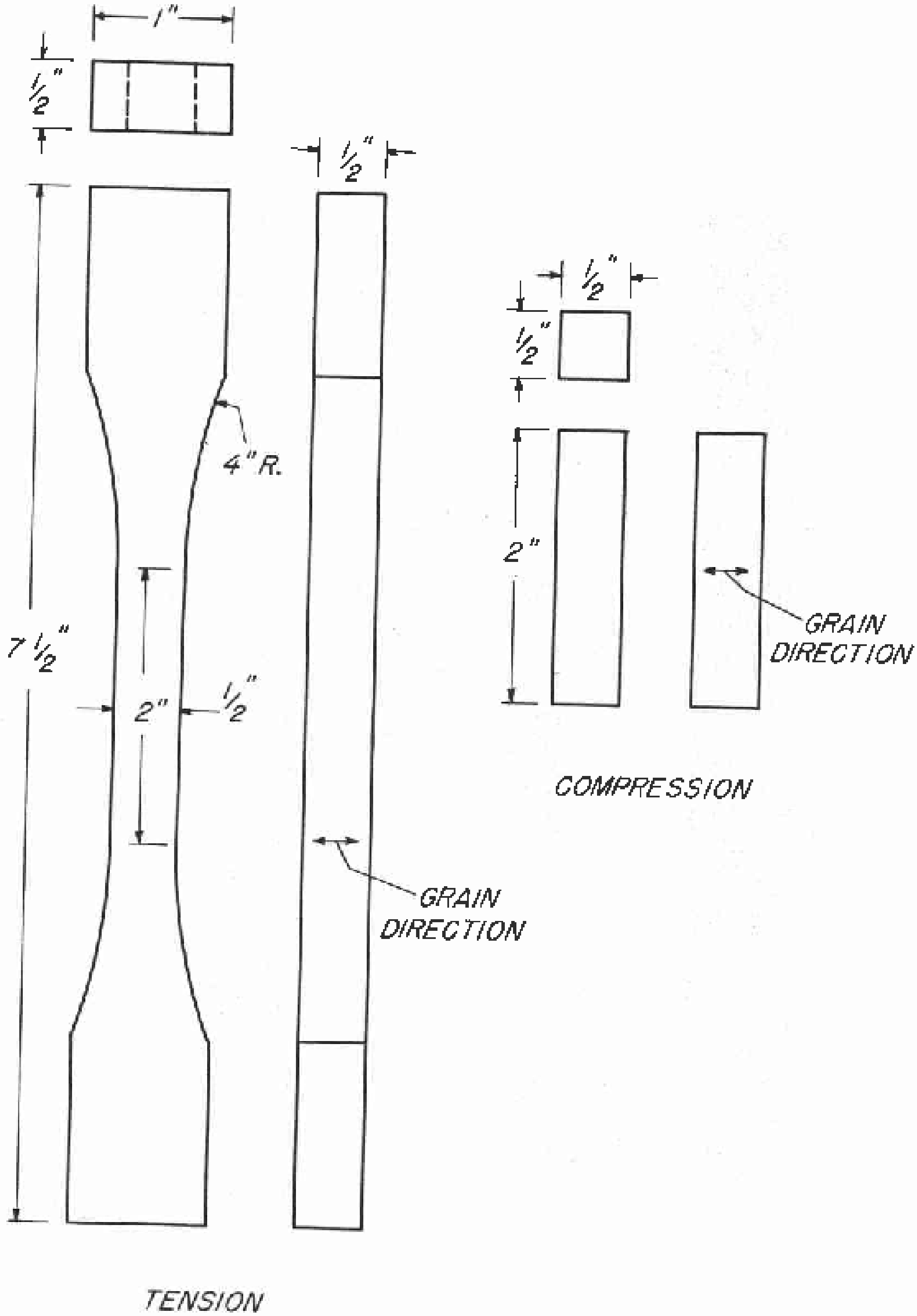


Figure 1. --Schematic diagram of stresses developed perpendicular to the grain in a drying board (A) early in drying and (B) late in drying after stress reversal.



Z M 110 665

Figure 2. --Arrangement of planks cut from each of four logs.



Z M 110 666

Figure 3. --Form and dimensions of specimens for tension and compression tests.

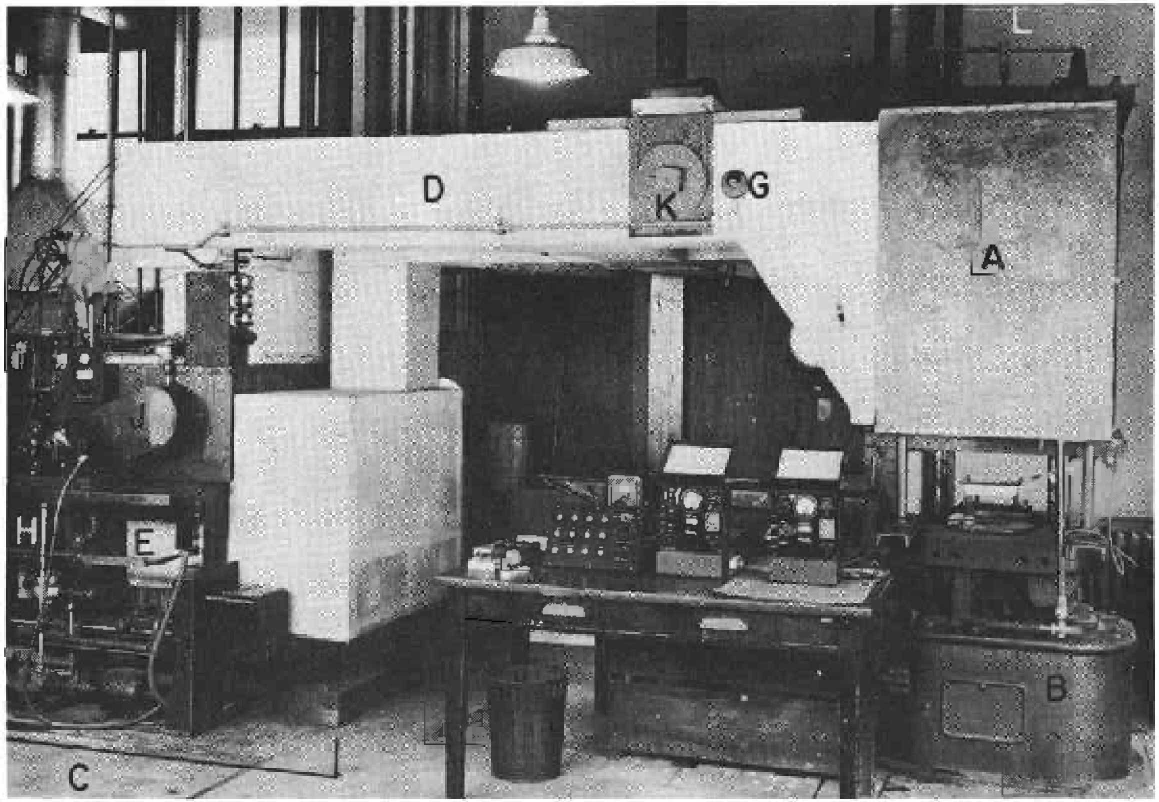


Figure 4. --Apparatus used for short-time tension and compression tests. (A) testing chamber, (B) testing machine, (C) air-conditioning equipment, (D) ducts, (E) steam heating coil, (F) electrical resistance heaters, (G) control bulb for resistance heaters, (H) steam spray, (J) variable-speed blower, (K) dampers, and (L) load bar.

Z M 106 817 F

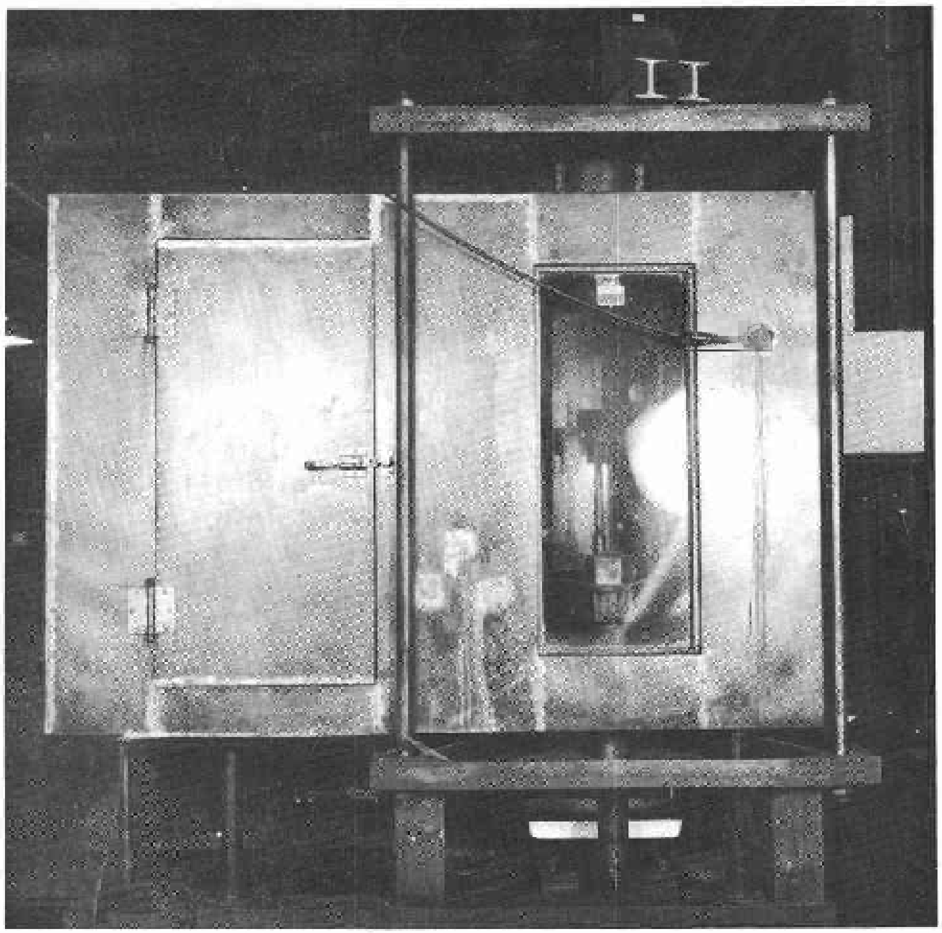


Figure 5. --End view of cabinet in which short-time tension and compression tests were conducted.

Z M 106 816

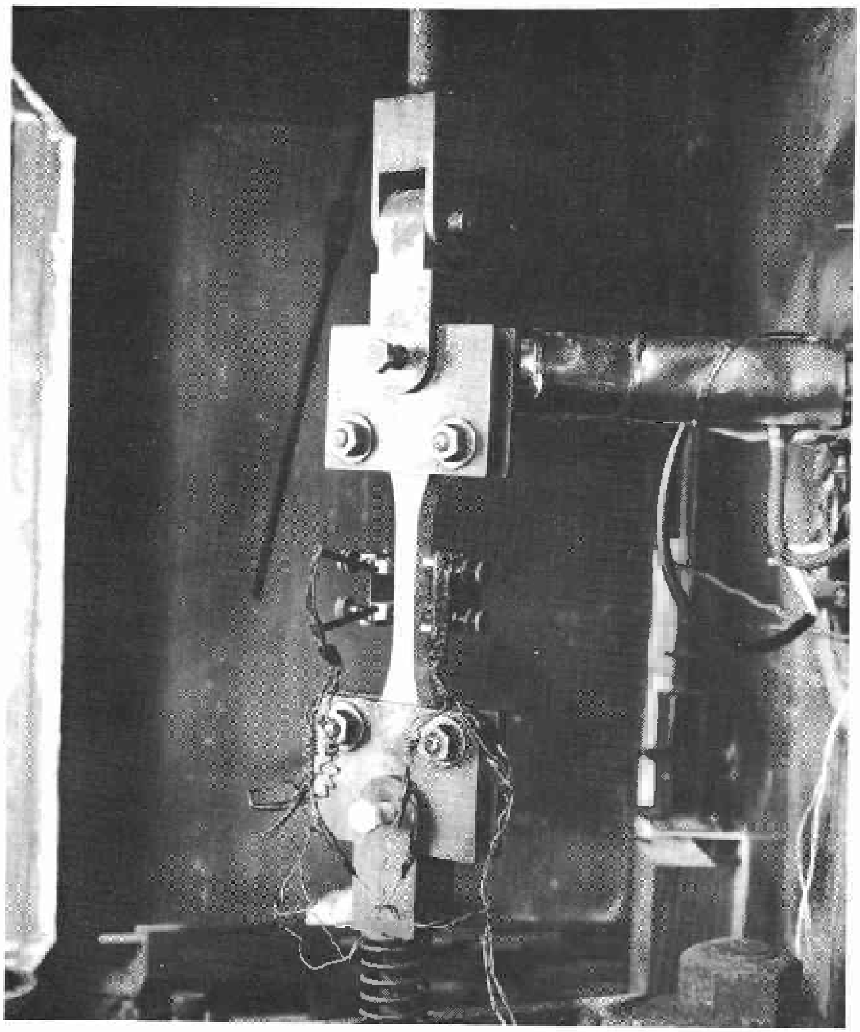


Figure 6. --Apparatus for short-time tension tests at moisture content levels below the fiber saturation point.

Z M 108 875

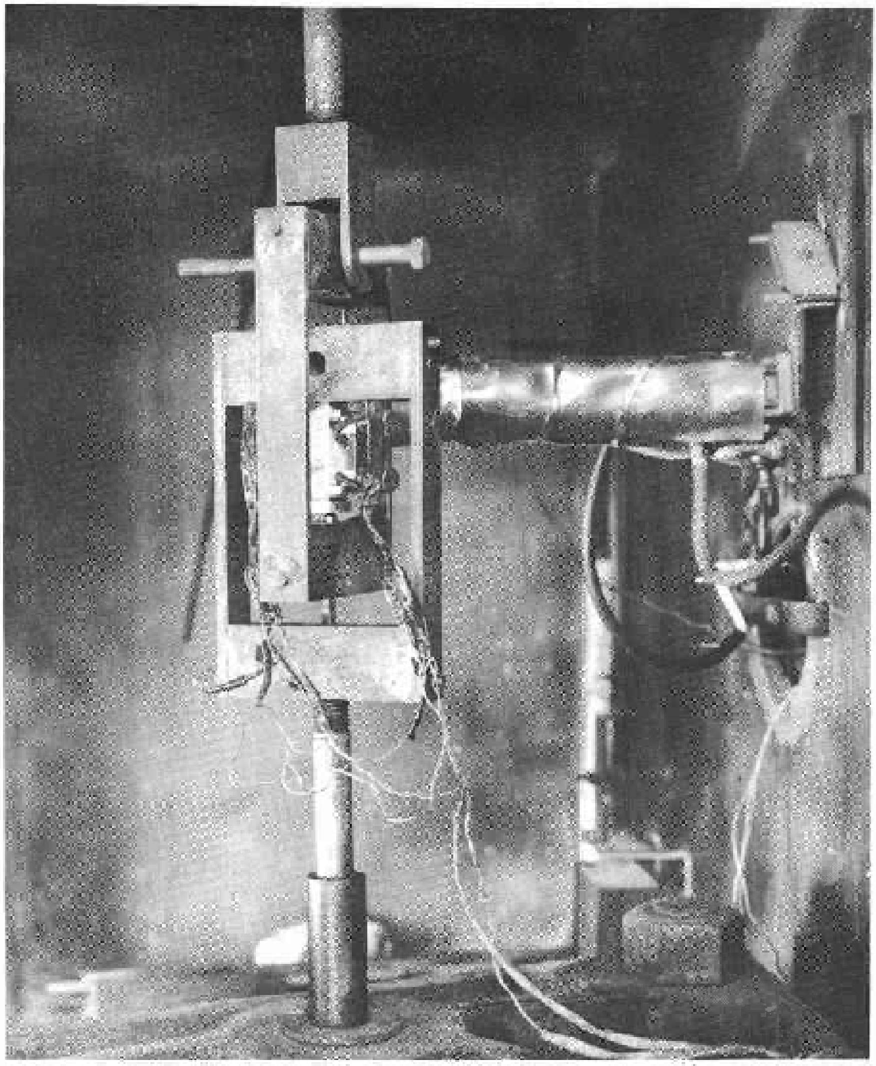


Figure 7. --Apparatus for short-time compression tests at moisture content levels below the fiber saturation point.

Z M 108 876 E

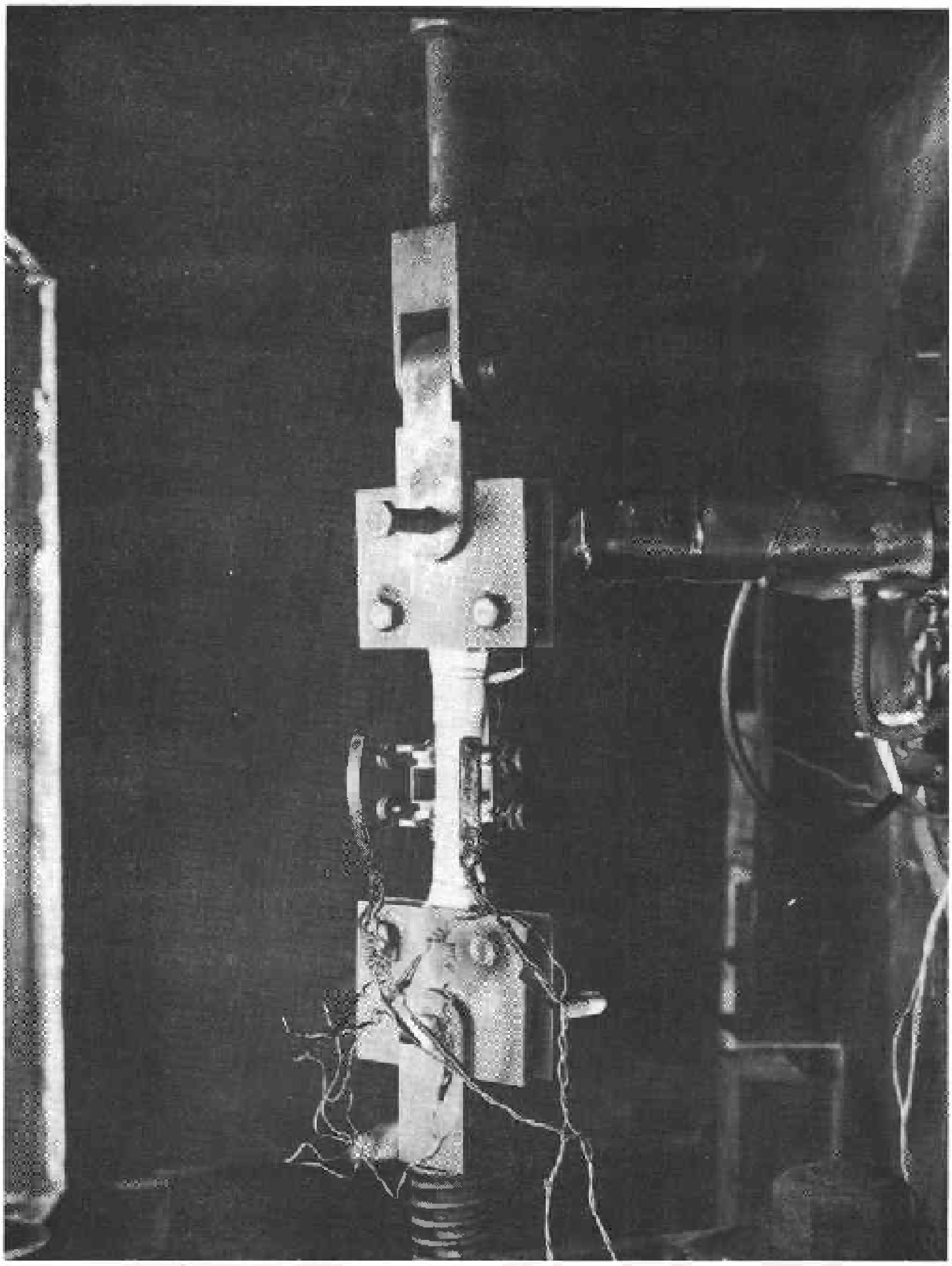
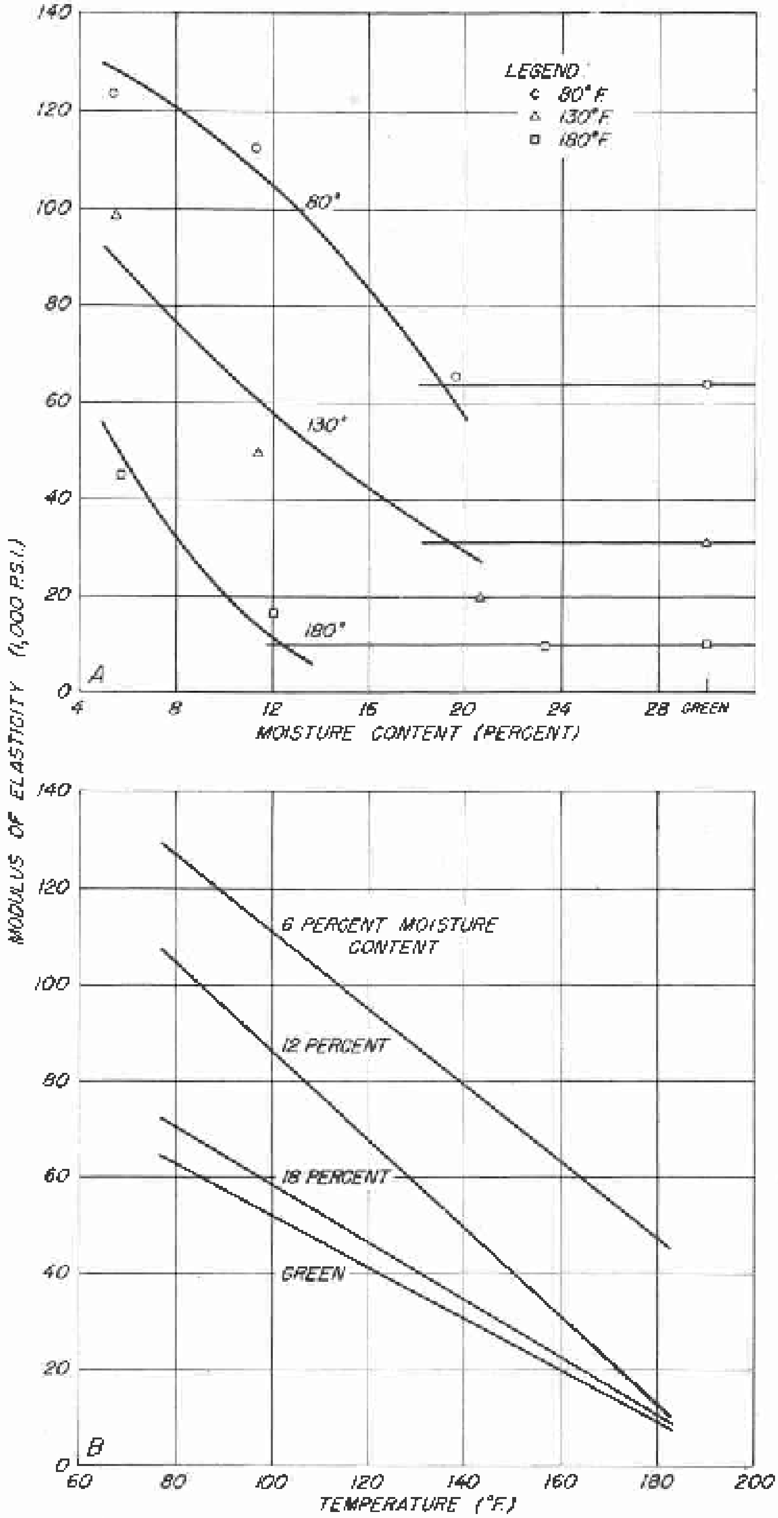


Figure 8. --Apparatus for short-time tension tests of green specimens.

Z M 108 874



Z M 110 667

Figure 9. --Relationship of modulus of elasticity in tension perpendicular to the grain at 0° to the growth rings to (A) moisture content and (B) temperature.

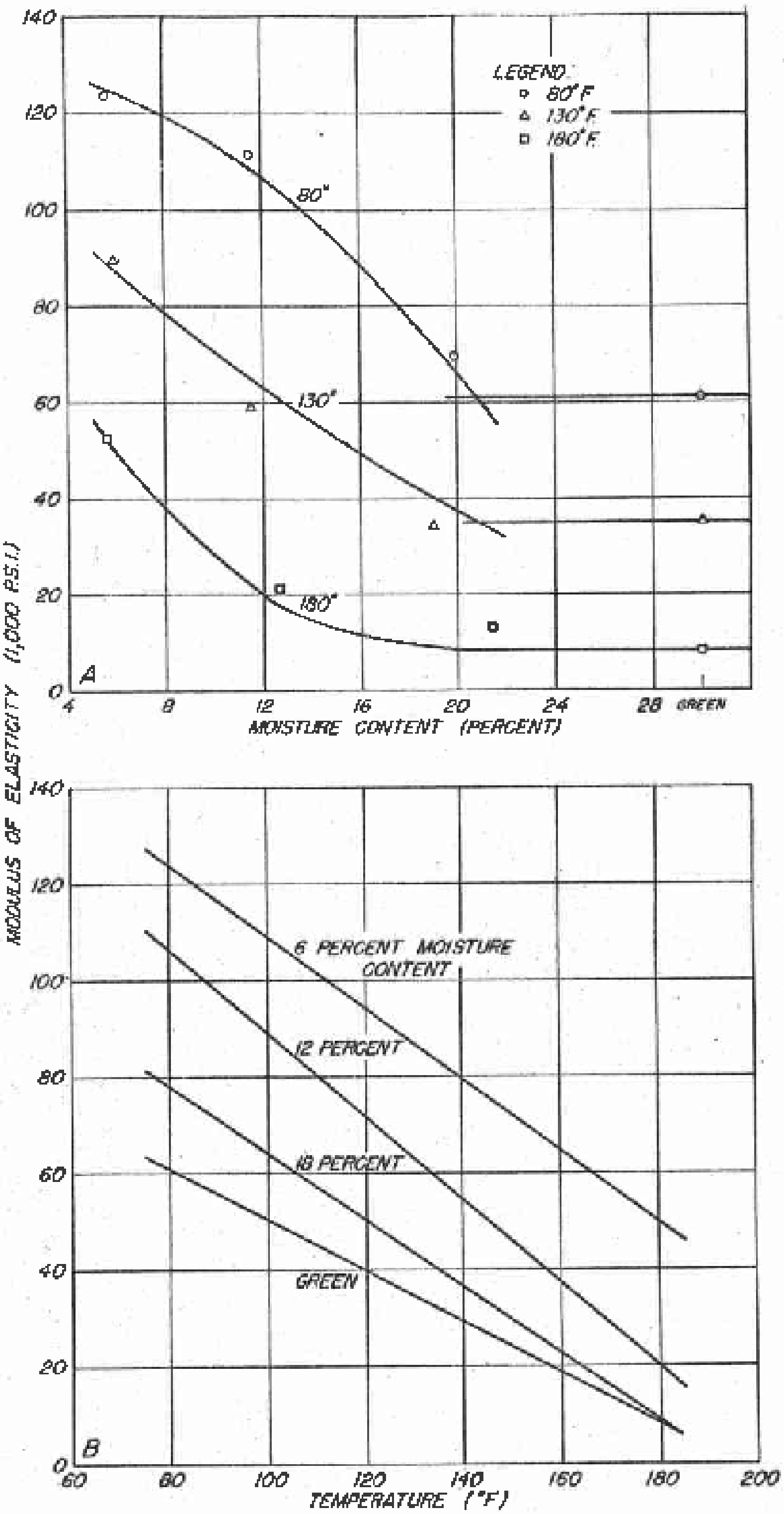
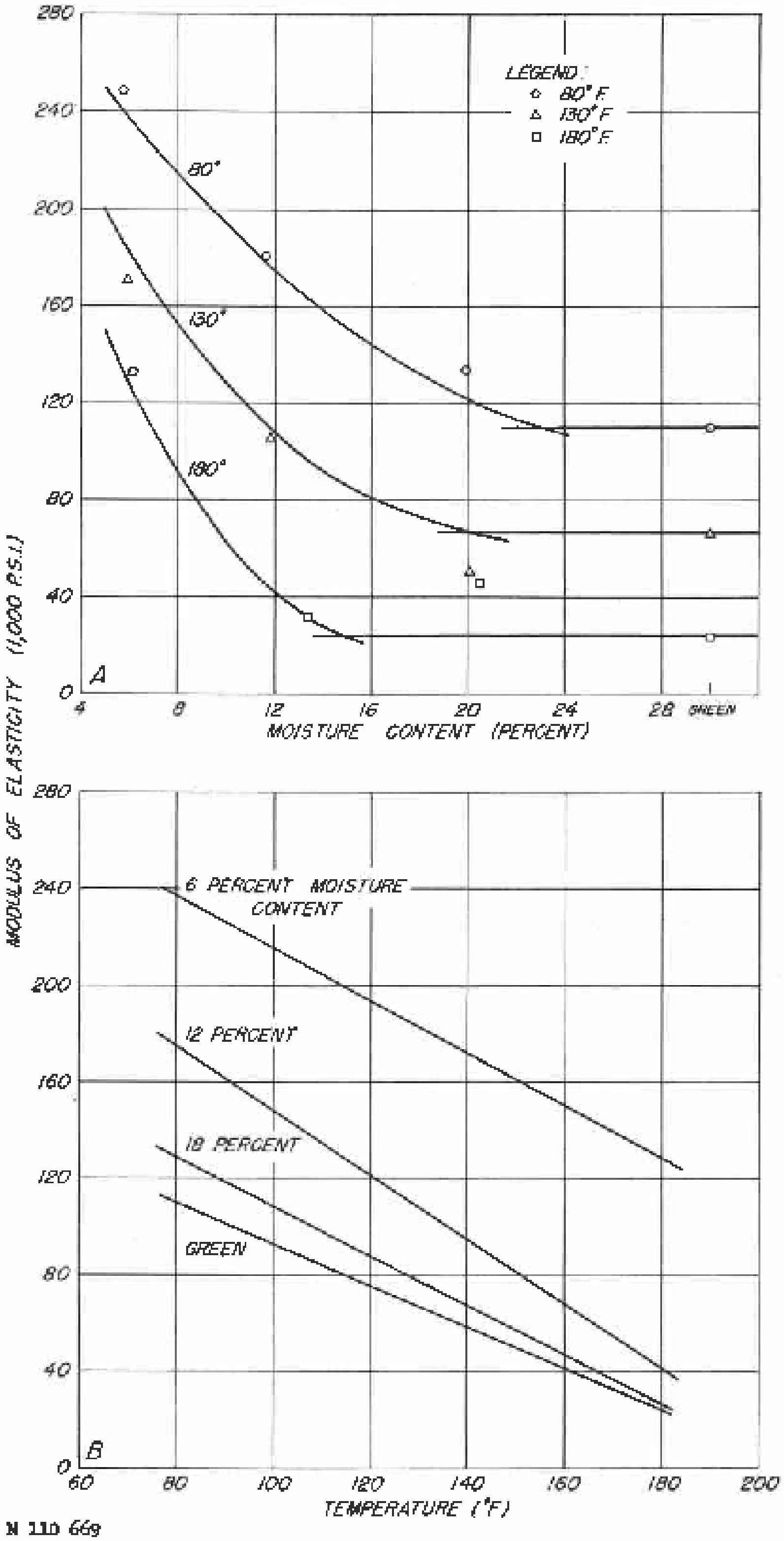


Figure 10.--Relationship of modulus of elasticity in tension perpendicular to the grain at 45° to the growth rings to (A) moisture content and (B) temperature.



Z M 110 669

Figure 11. --Relationship of modulus of elasticity in tension perpendicular to the grain at 90° to the growth rings to (A) moisture content and (B) temperature.

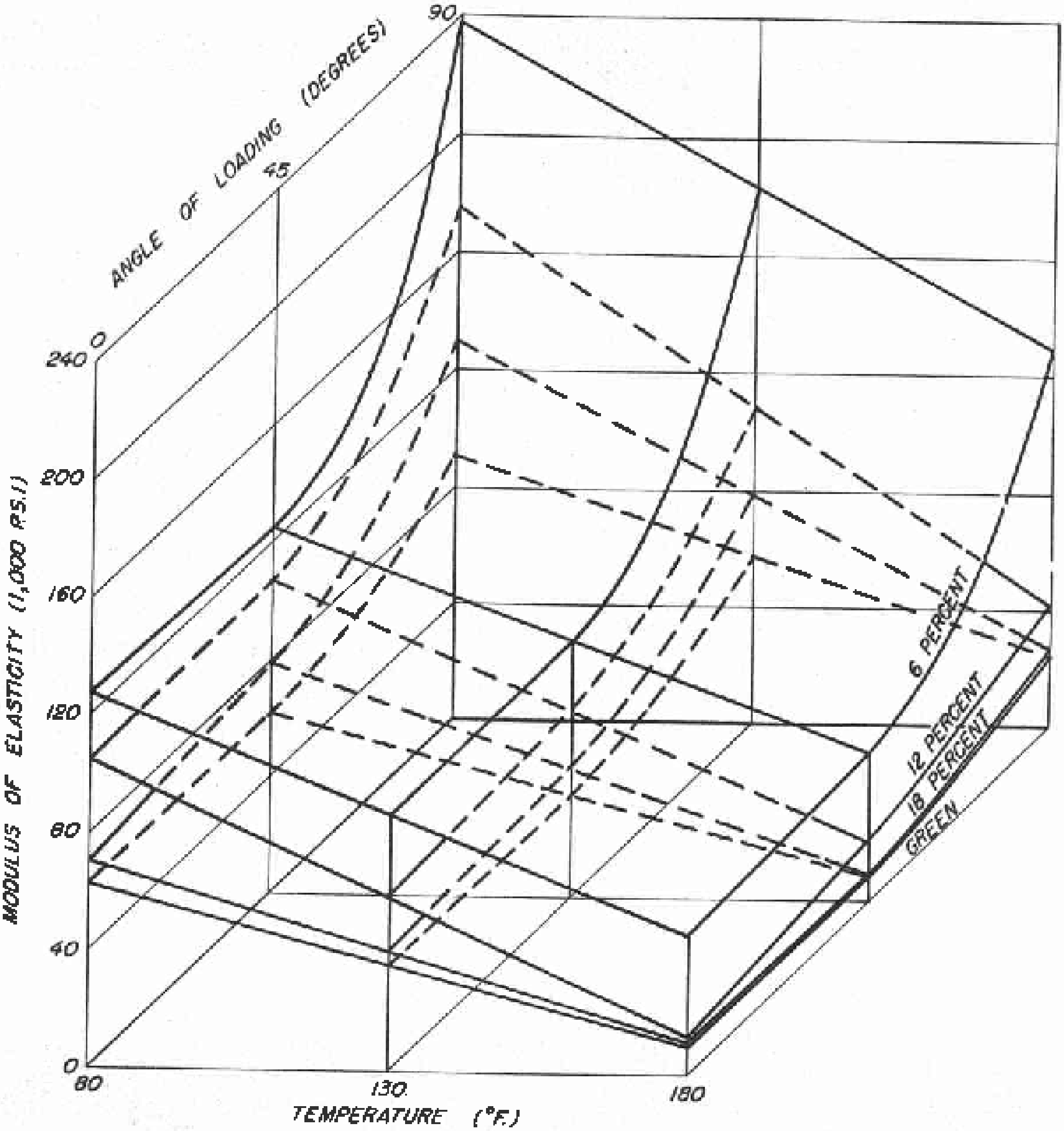
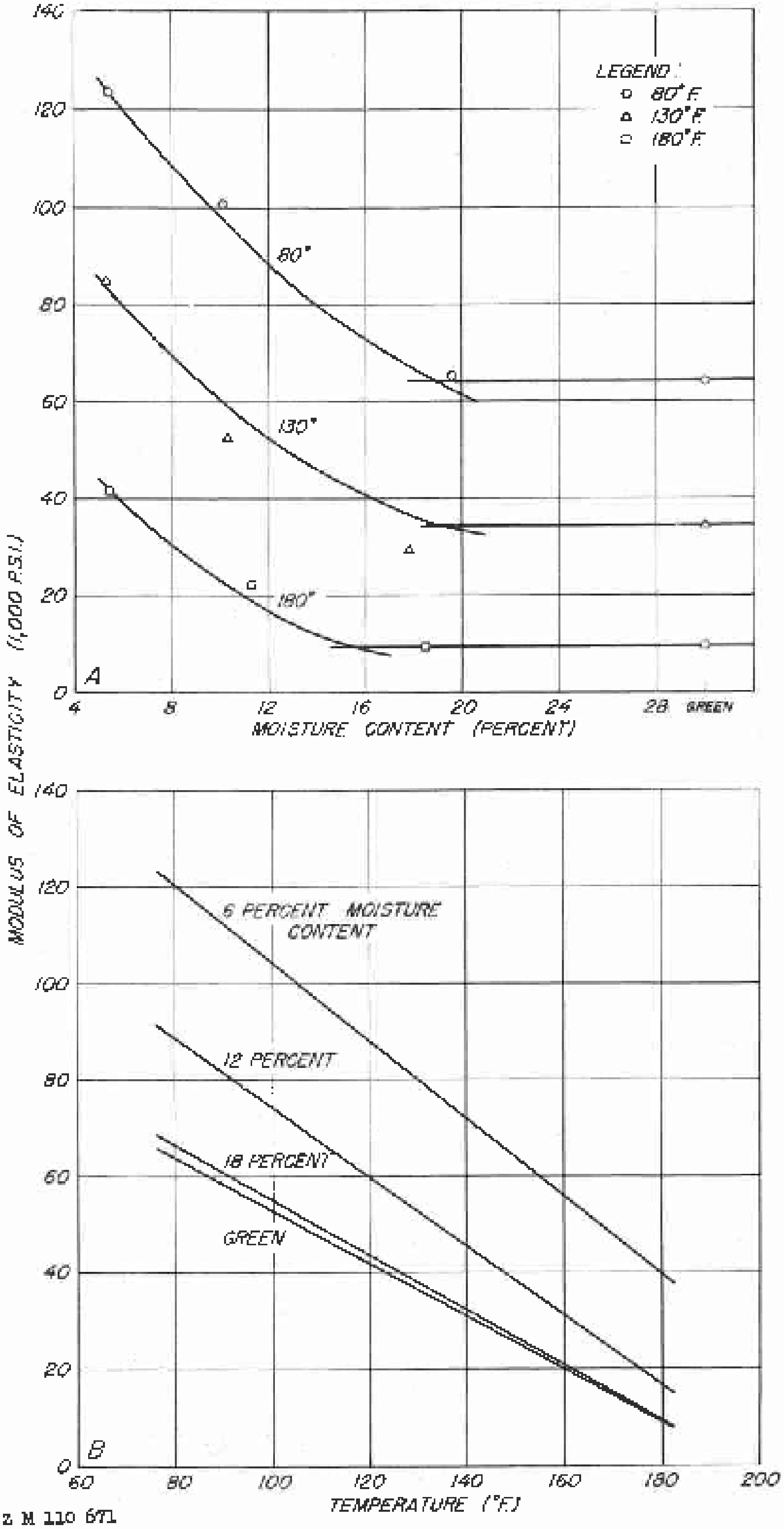
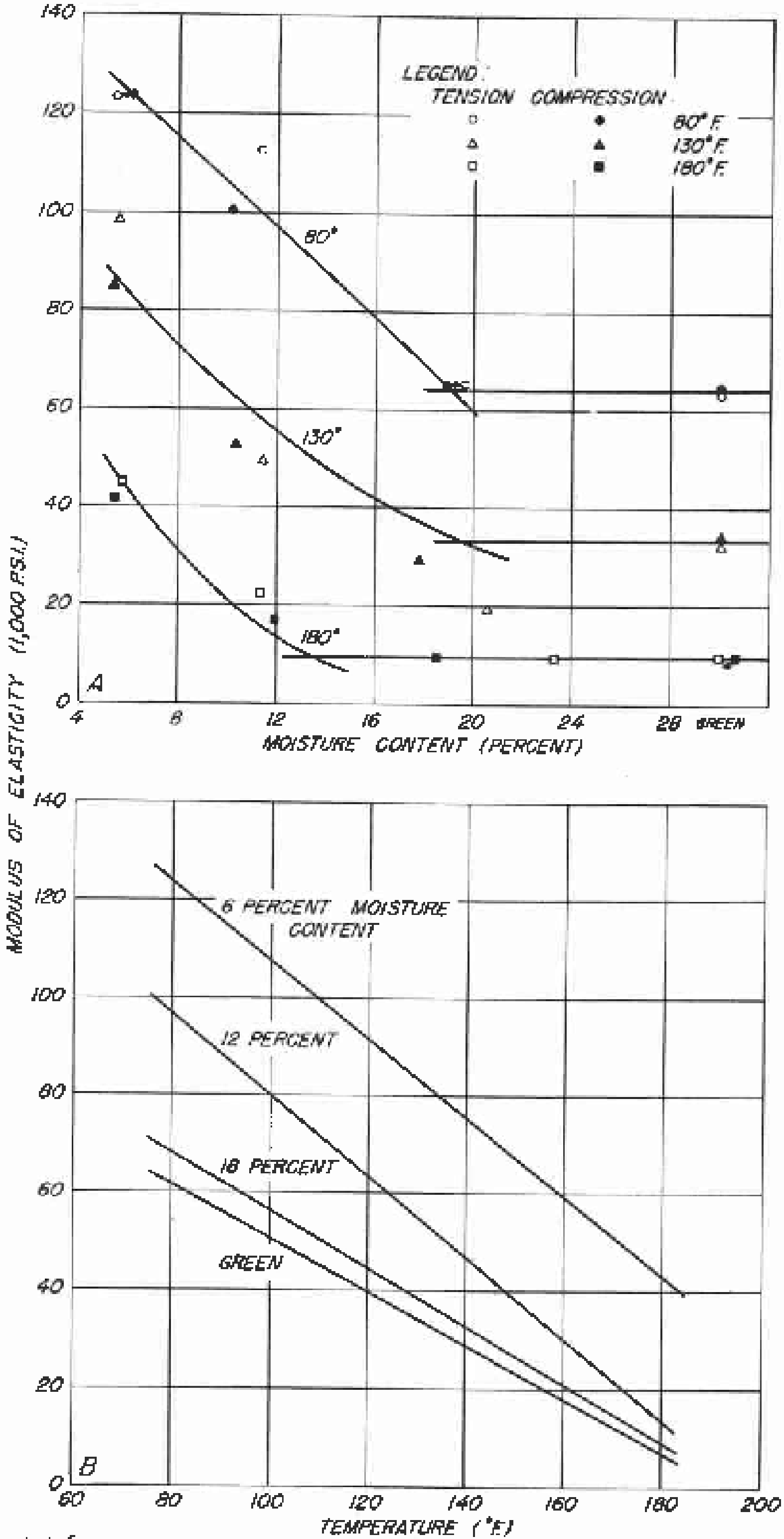


Figure 12. --Relationship of modulus of elasticity in tension perpendicular to the grain to temperature and angle of loading at four levels of moisture content.



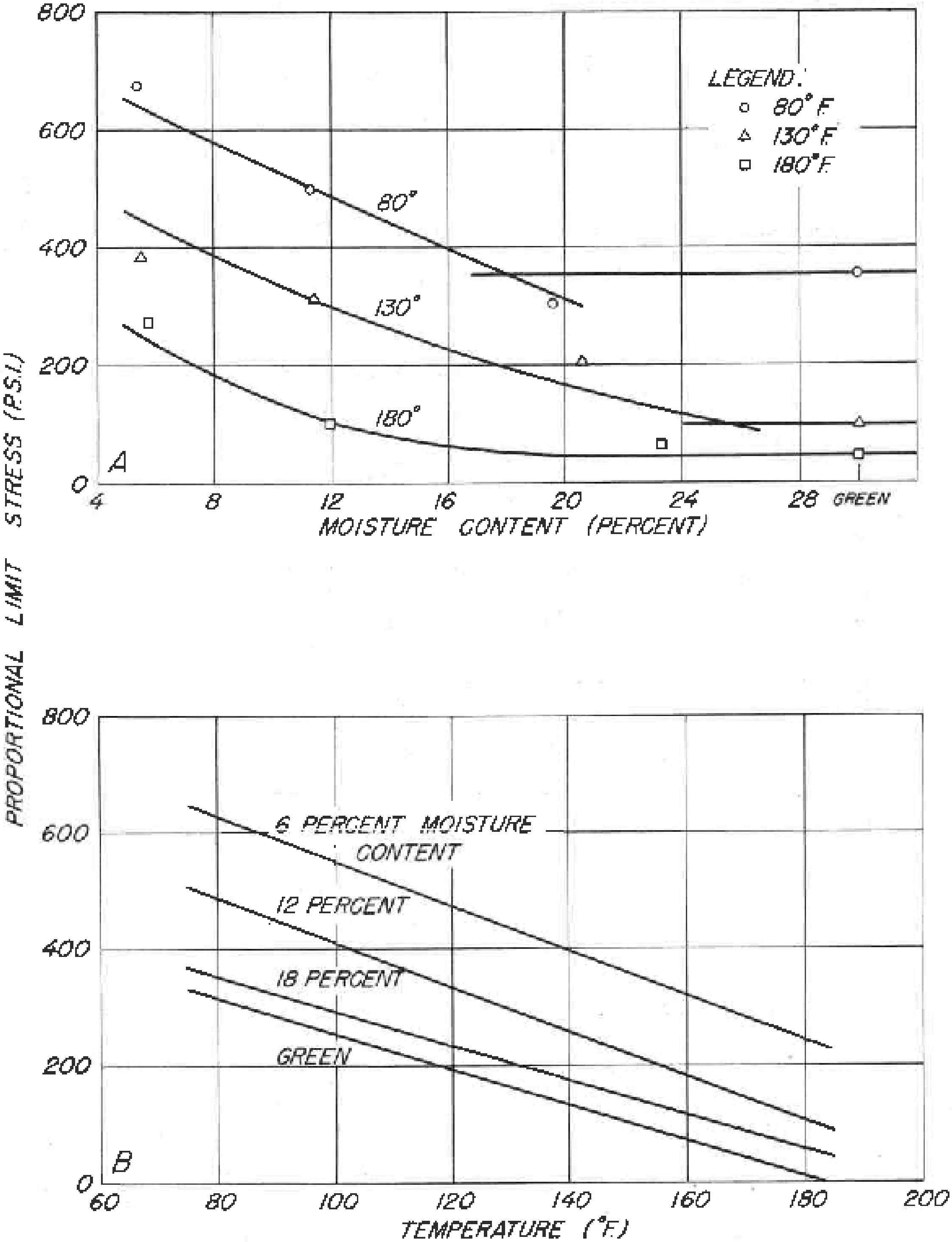
Z M 110 671

Figure 13. --Relationship of modulus of elasticity in compression perpendicular to the grain at 0° to the growth rings to (A) moisture content and (B) temperature.



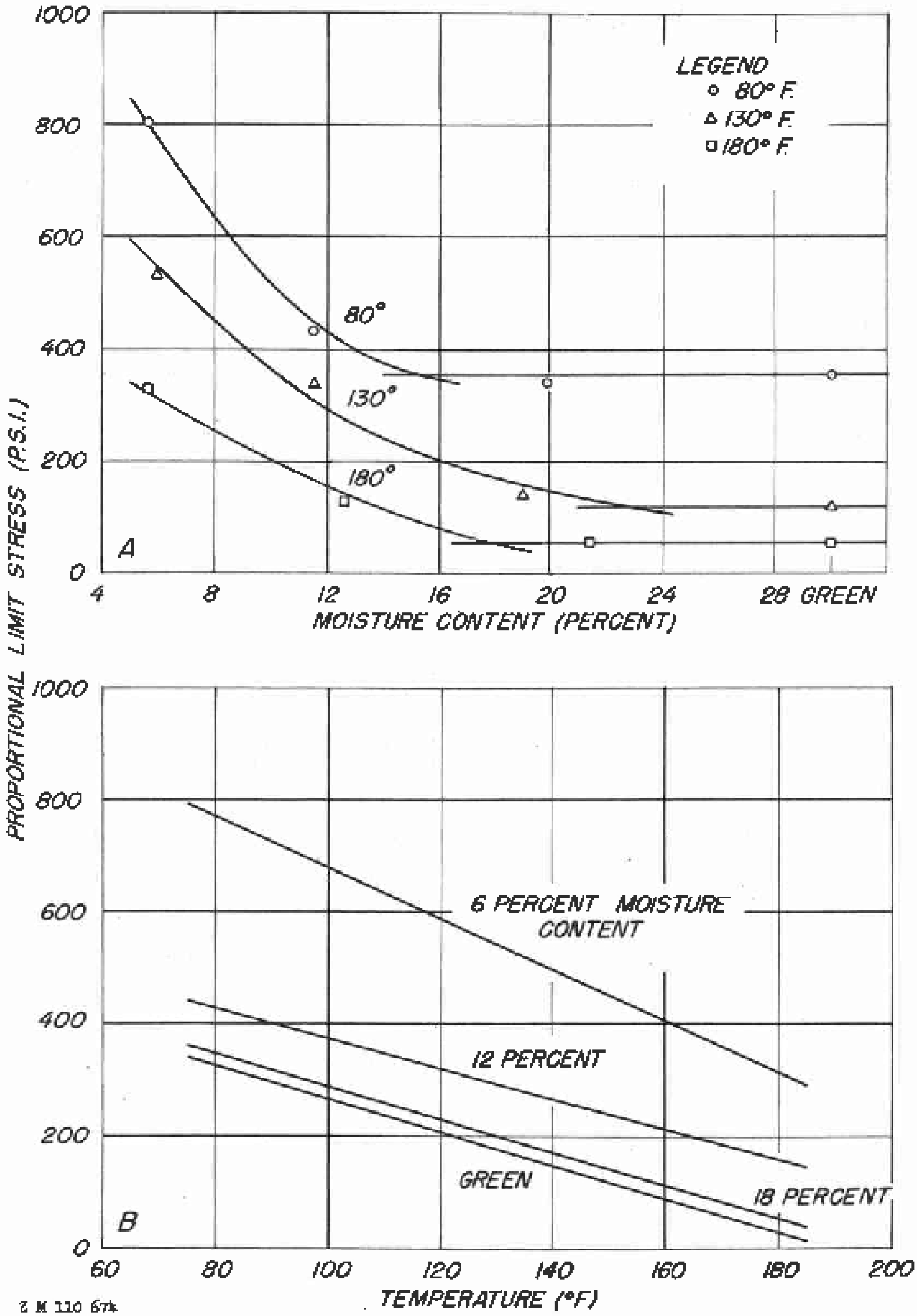
Z M 110 672

Figure 14. --Relationship of modulus of elasticity in tension and compression perpendicular to the grain at 0° to the growth rings to (A) moisture content and (B) temperature.



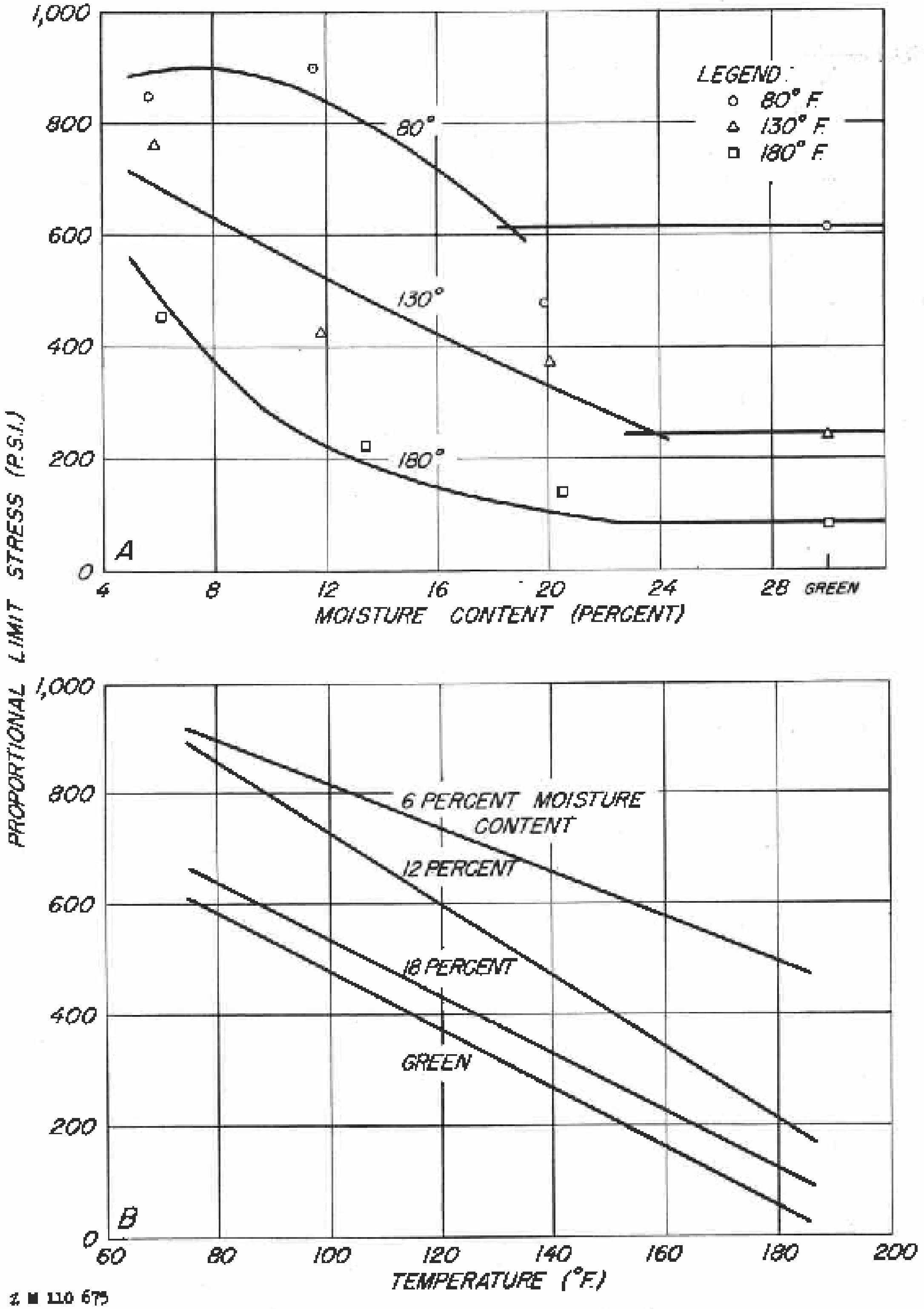
Z M 110 673

Figure 15. --Relationship of proportional limit stress in tension perpendicular to the grain at 0° to the growth rings to (A) moisture content and (B) temperature.



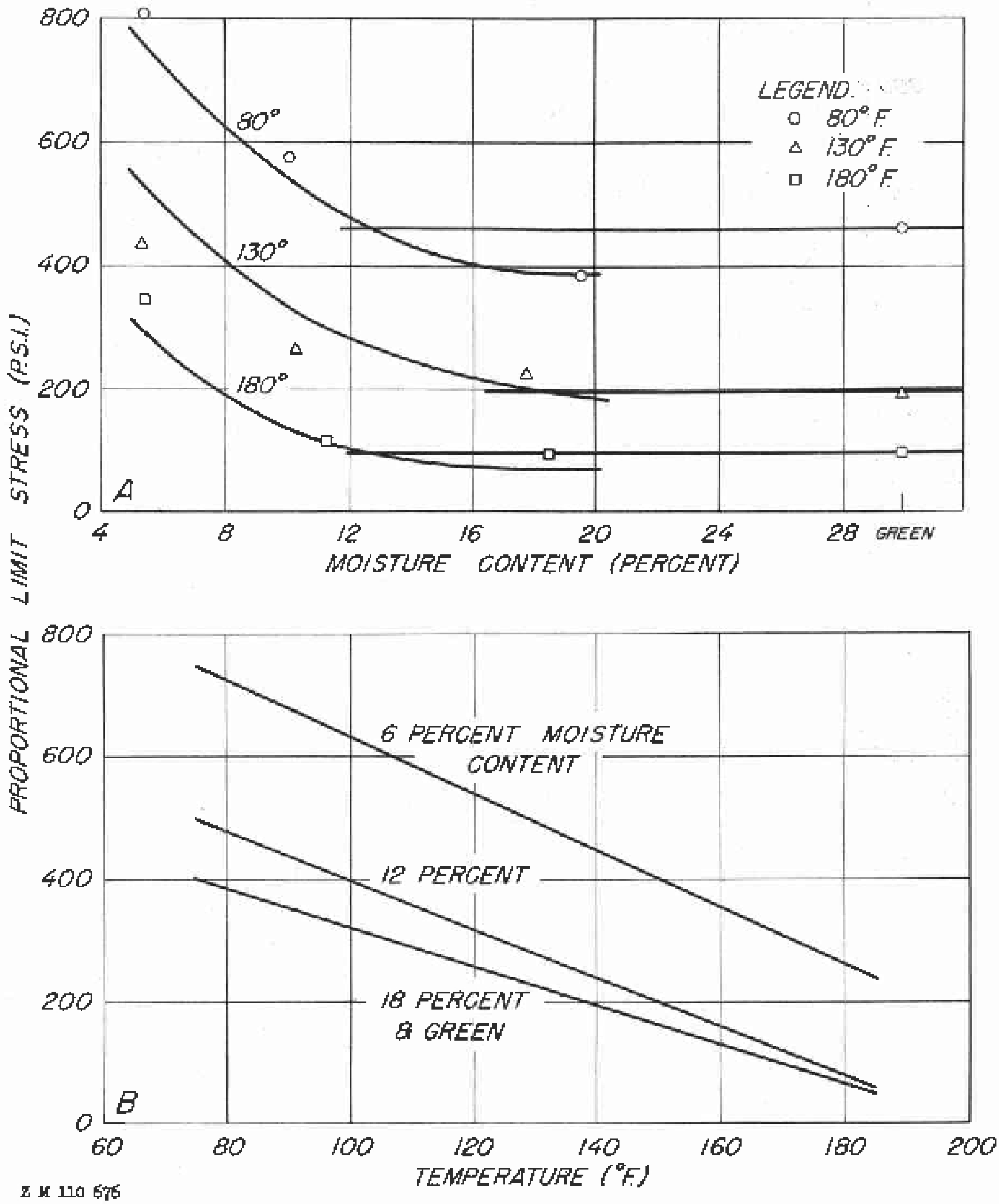
Z M 110 67k

Figure 16. --Relationship of proportional limit stress in tension perpendicular to the grain at 45° to the growth rings to (A) moisture content and (B) temperature.



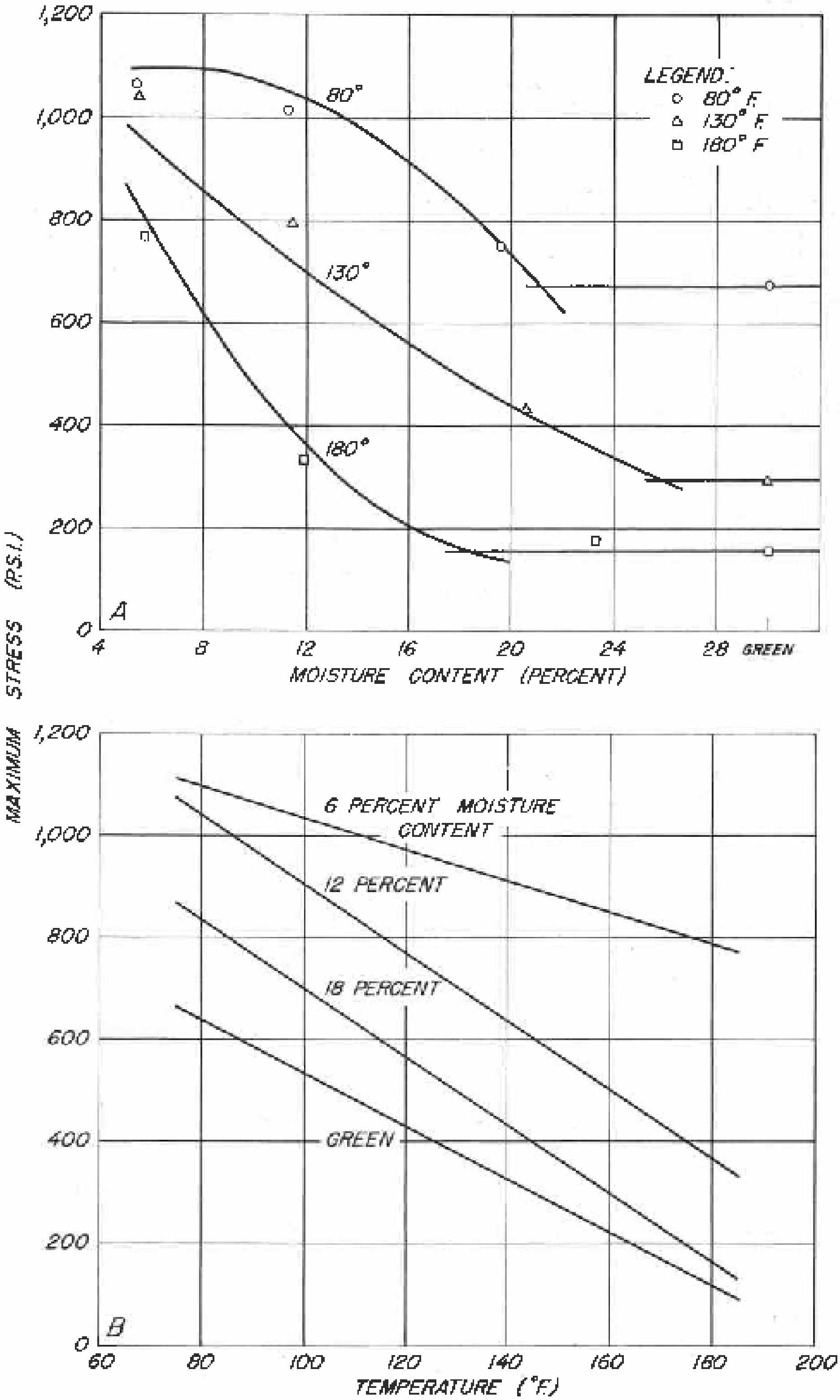
Z M 110 675

Figure 17. --Relationship of proportional limit stress in tension perpendicular to the grain at 90° to the growth rings to (A) moisture content and (B) temperature.



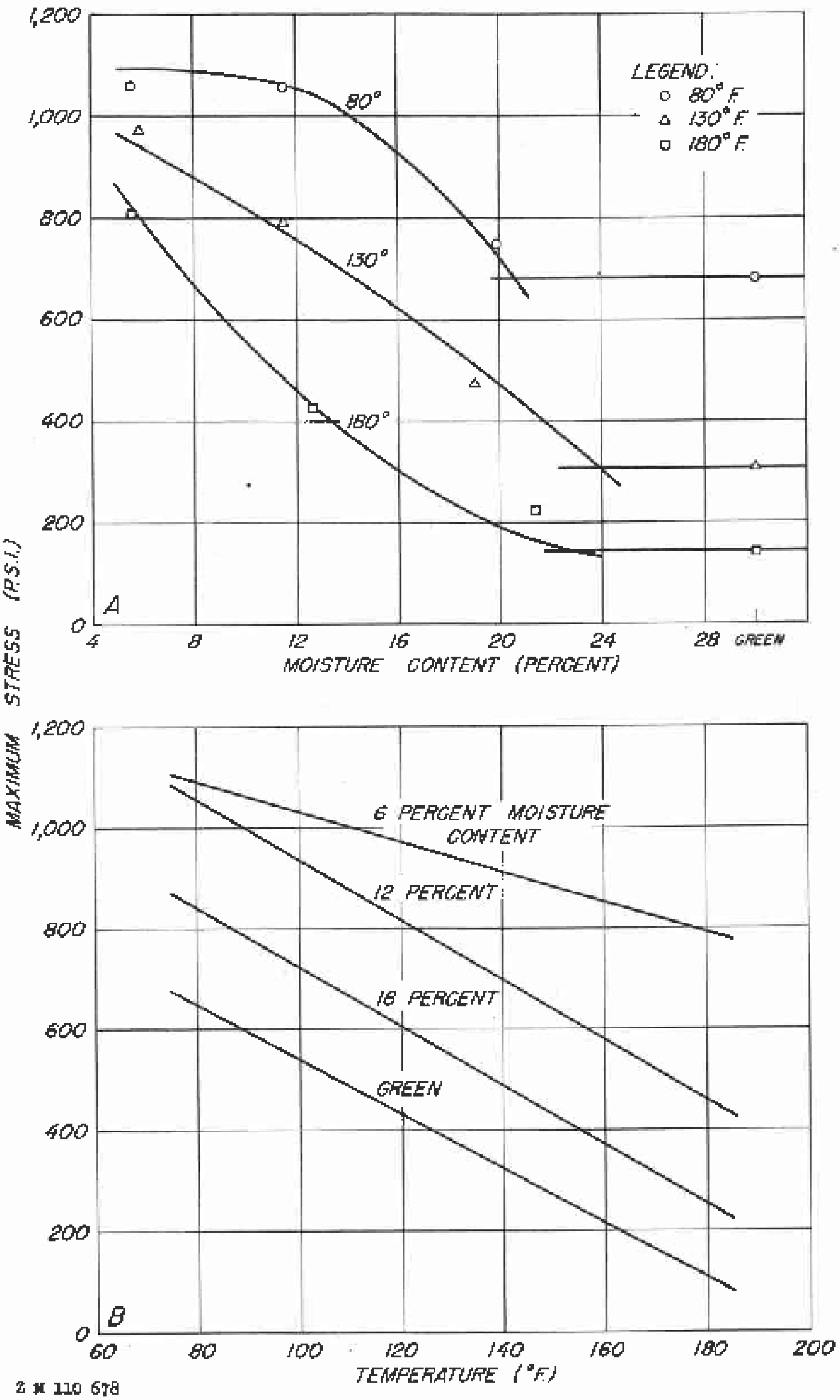
Z M 110 676

Figure 18.--Relationship of proportional limit stress in compression perpendicular to the grain at 0° to the growth rings to (A) moisture content and (B) temperature.



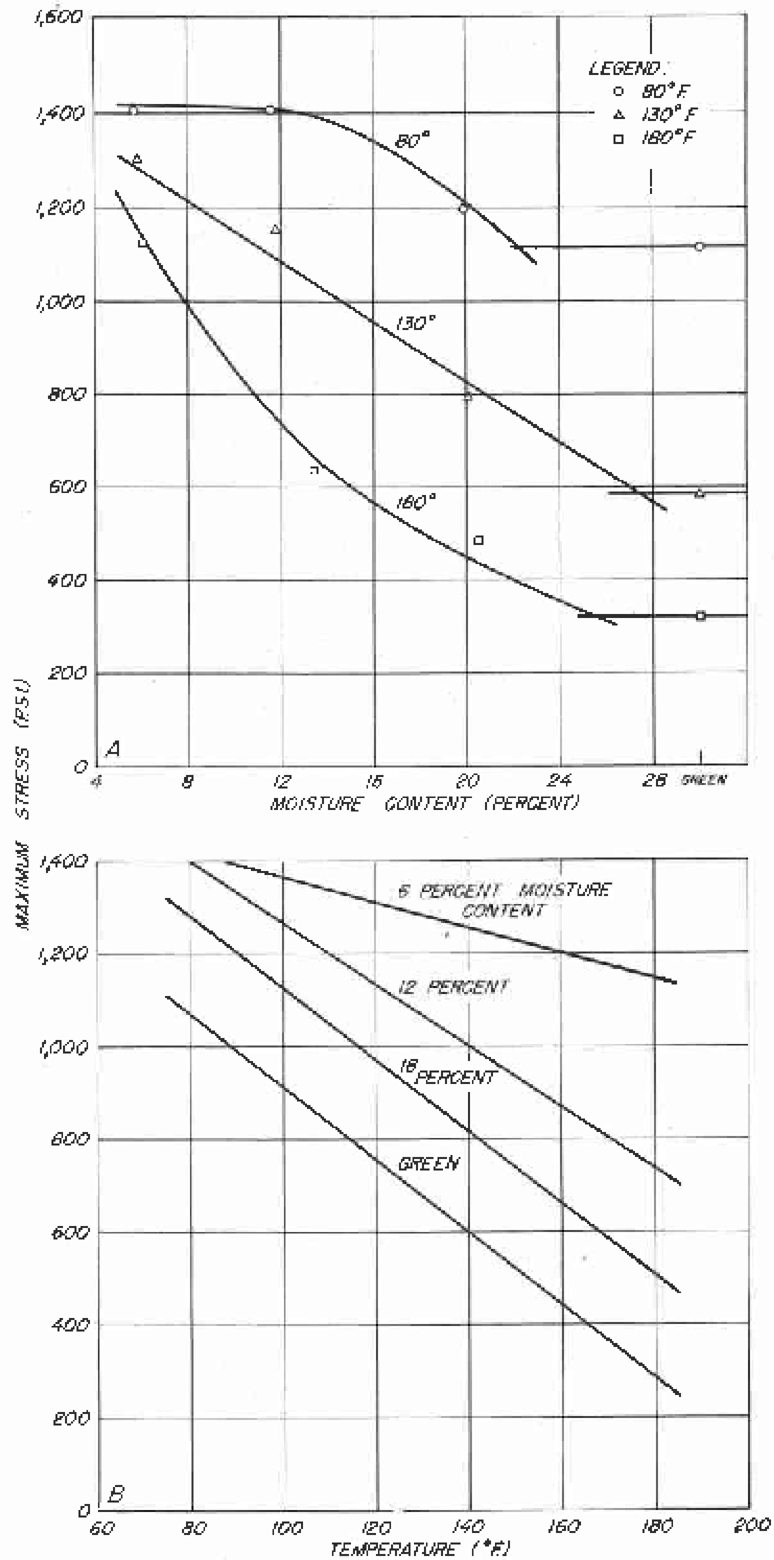
Z M 110 671

Figure 19. --Relationship of maximum stress in tension perpendicular to the grain at 0° to the growth rings to (A) moisture content and (B) temperature.



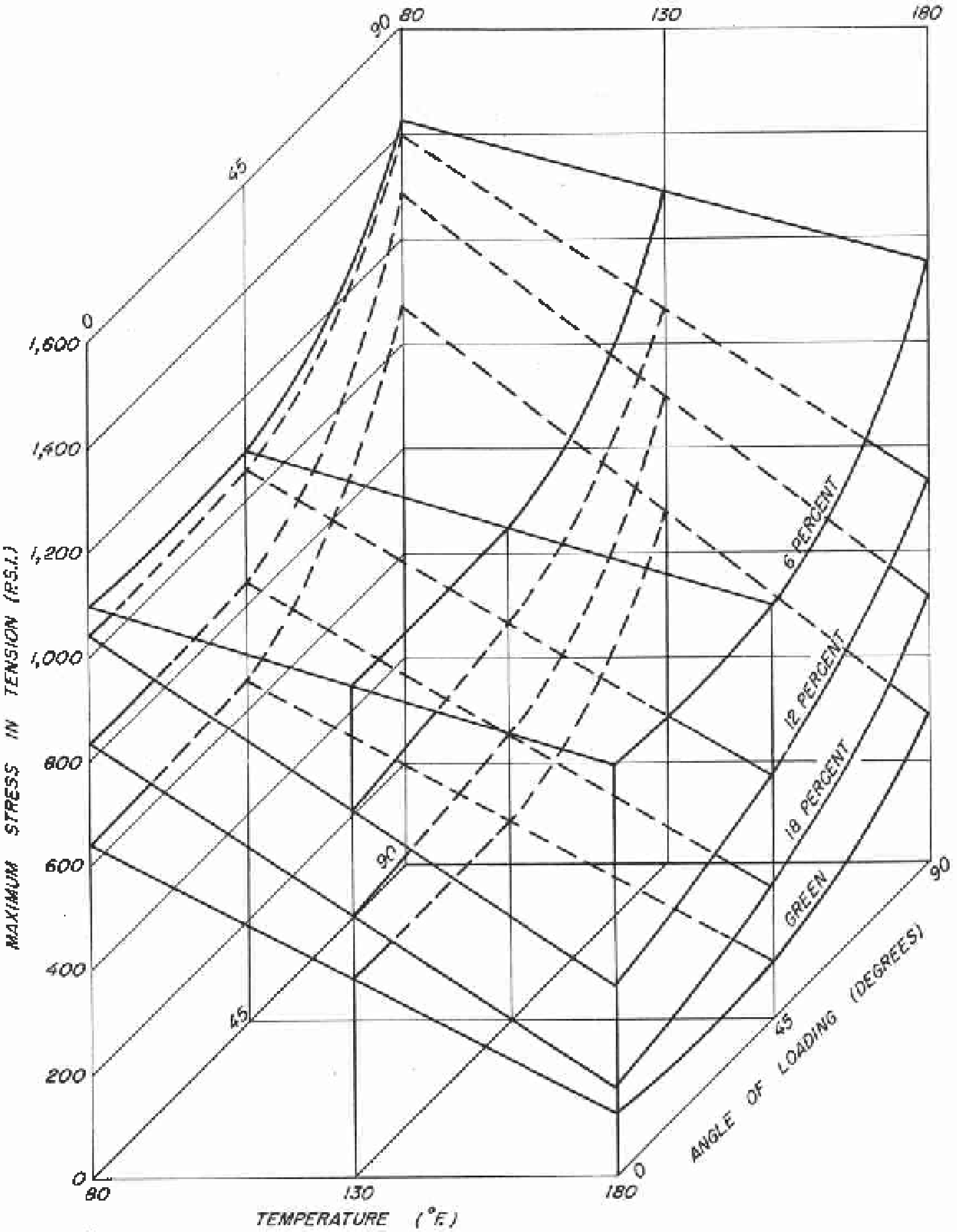
Z M 110 678

Figure 20. --Relationship of maximum stress in tension perpendicular to the grain at 45° to the growth rings to (A) moisture content and (B) temperature.



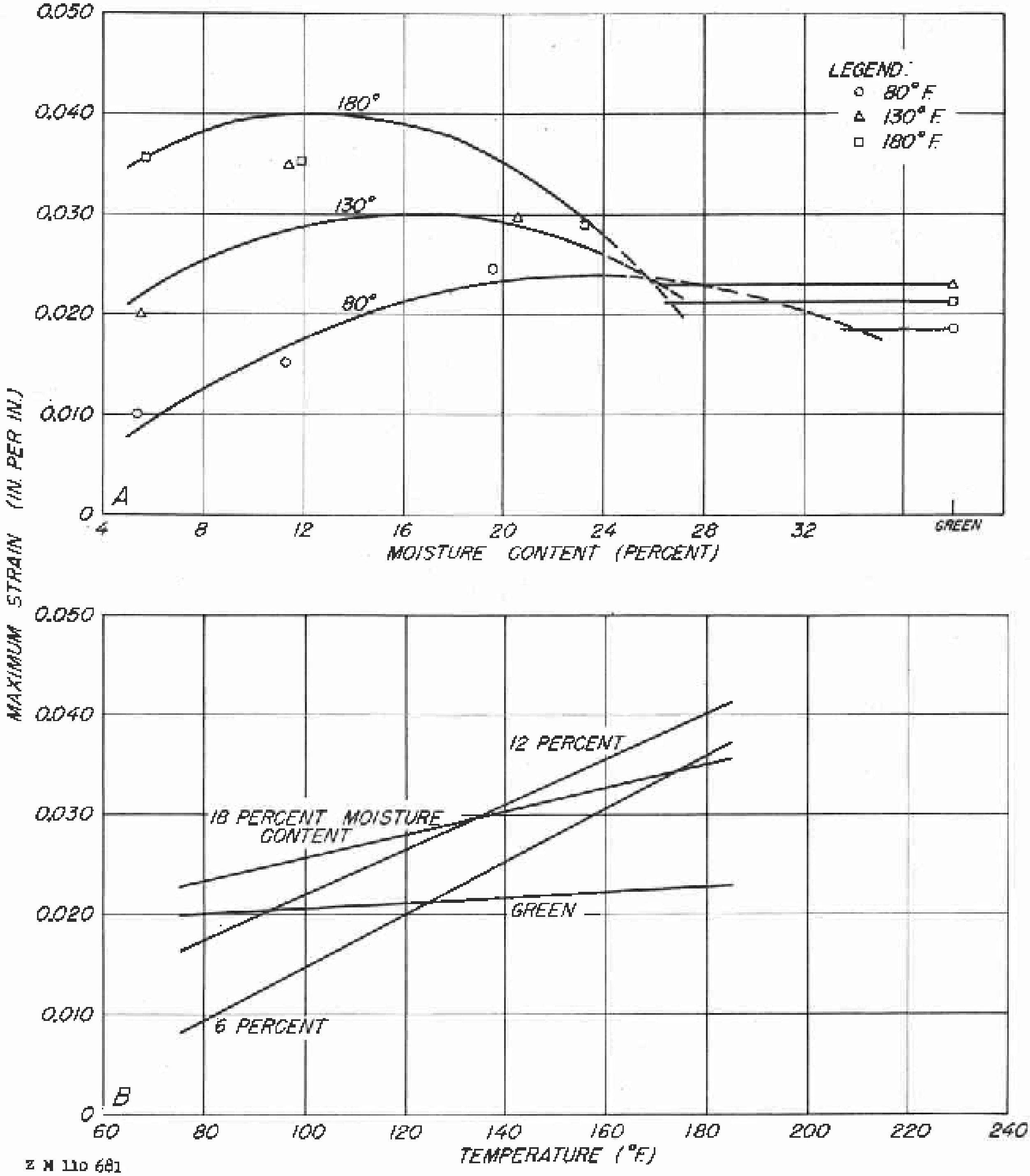
Z M 110 679

Figure 21. --Relationship of maximum stress in tension perpendicular to the grain at 90° to the growth rings to (A) moisture content and (B) temperature.



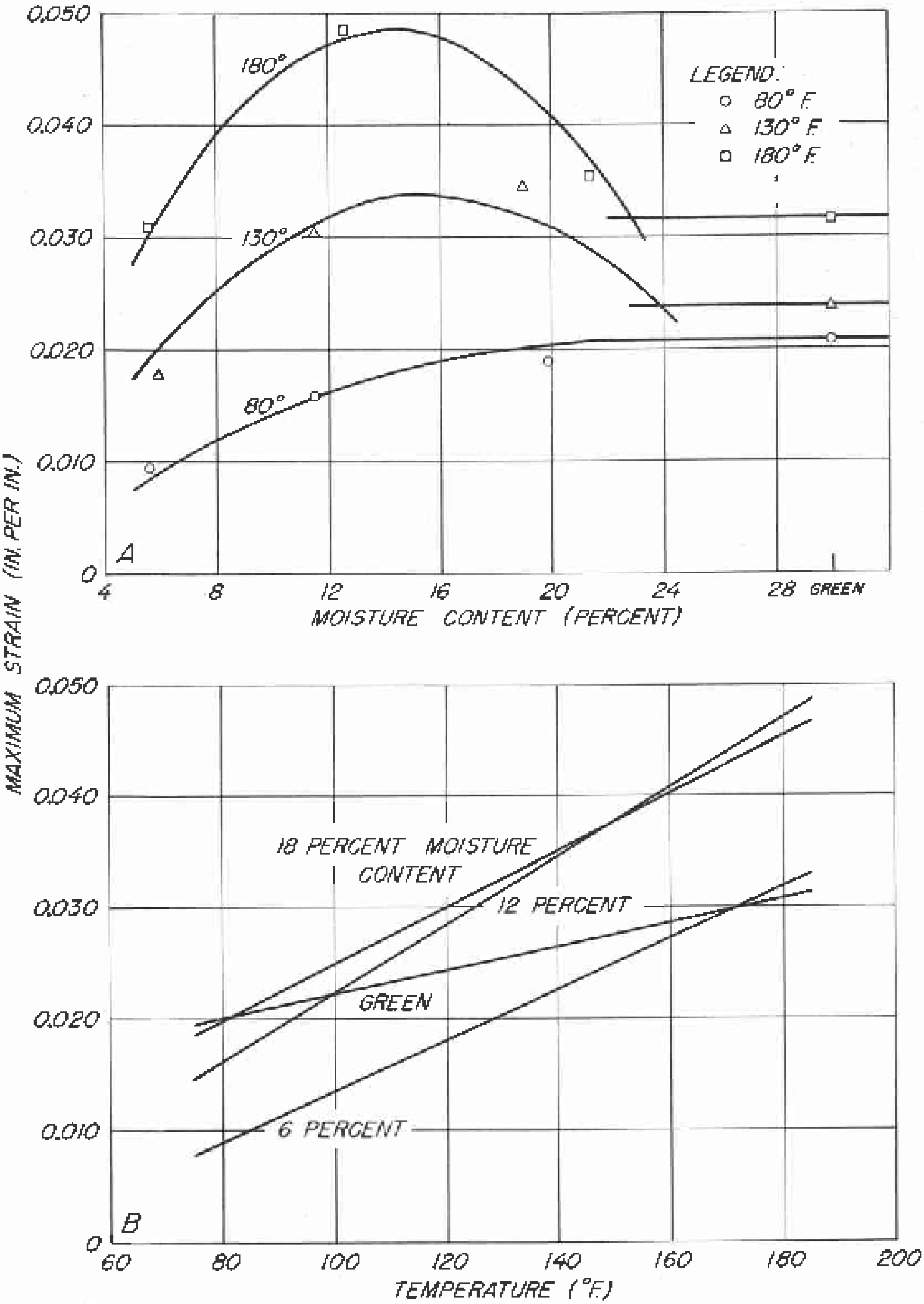
Z M 110 680

Figure 22. --Relationship of maximum stress in tension perpendicular to the grain to temperature and angle of loading at four levels of moisture content.



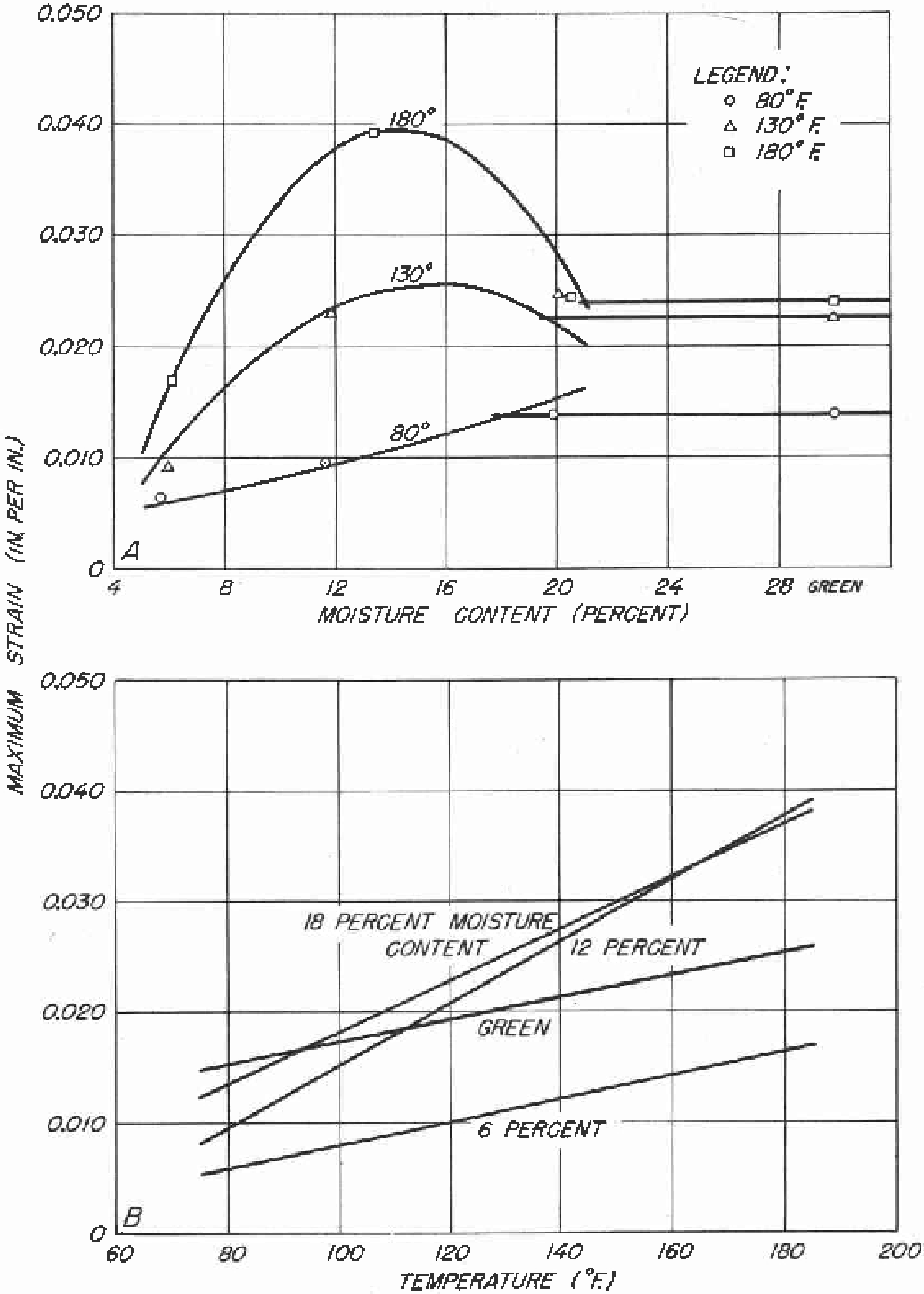
Z M 110 681

Figure 23. --Relationship of maximum strain in tension perpendicular to the grain at 0° to the growth rings to (A) moisture content and (B) temperature.



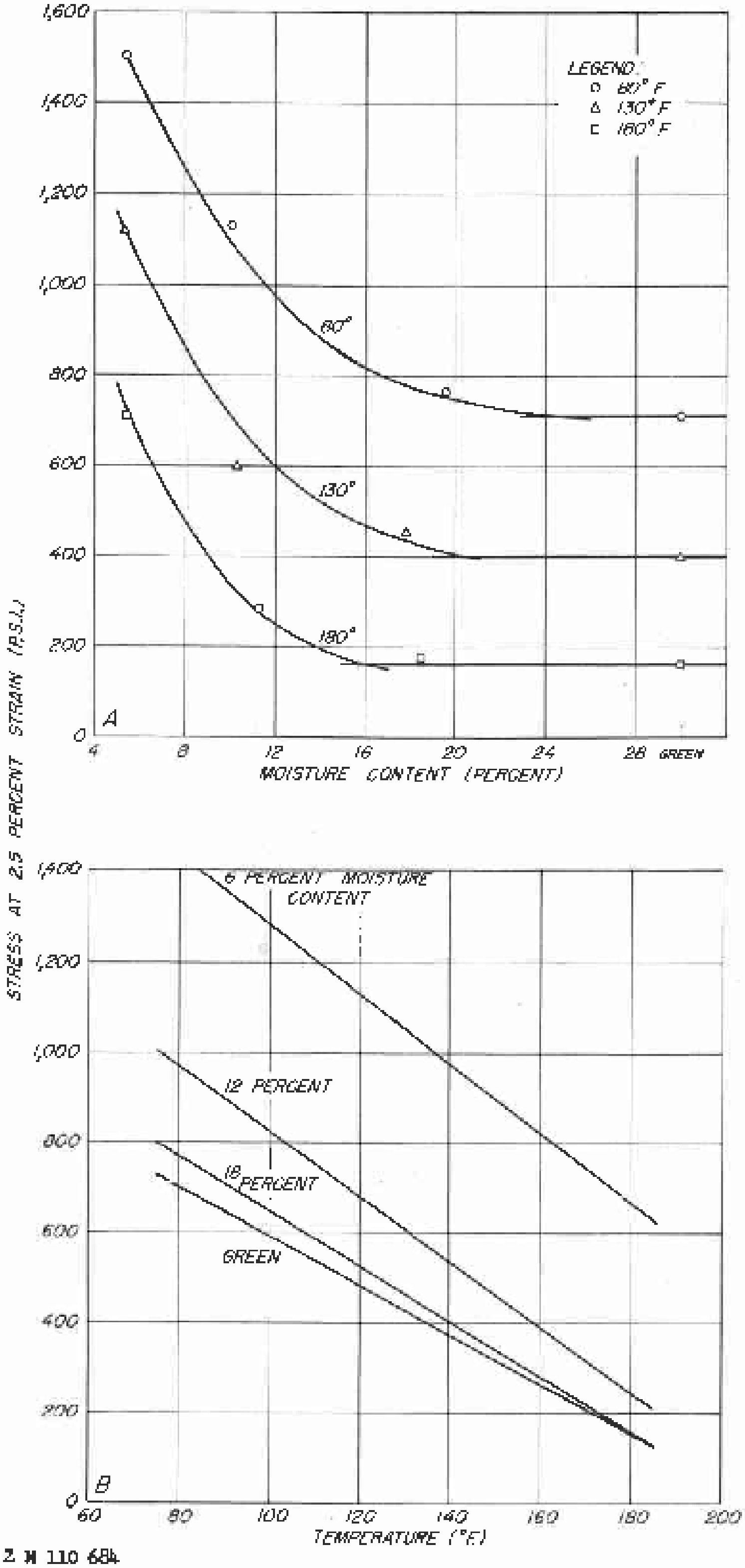
Z M 110 682

Figure 24. --Relationship of maximum strain in tension perpendicular to the grain at 45° to the growth rings to (A) moisture content and (B) temperature.



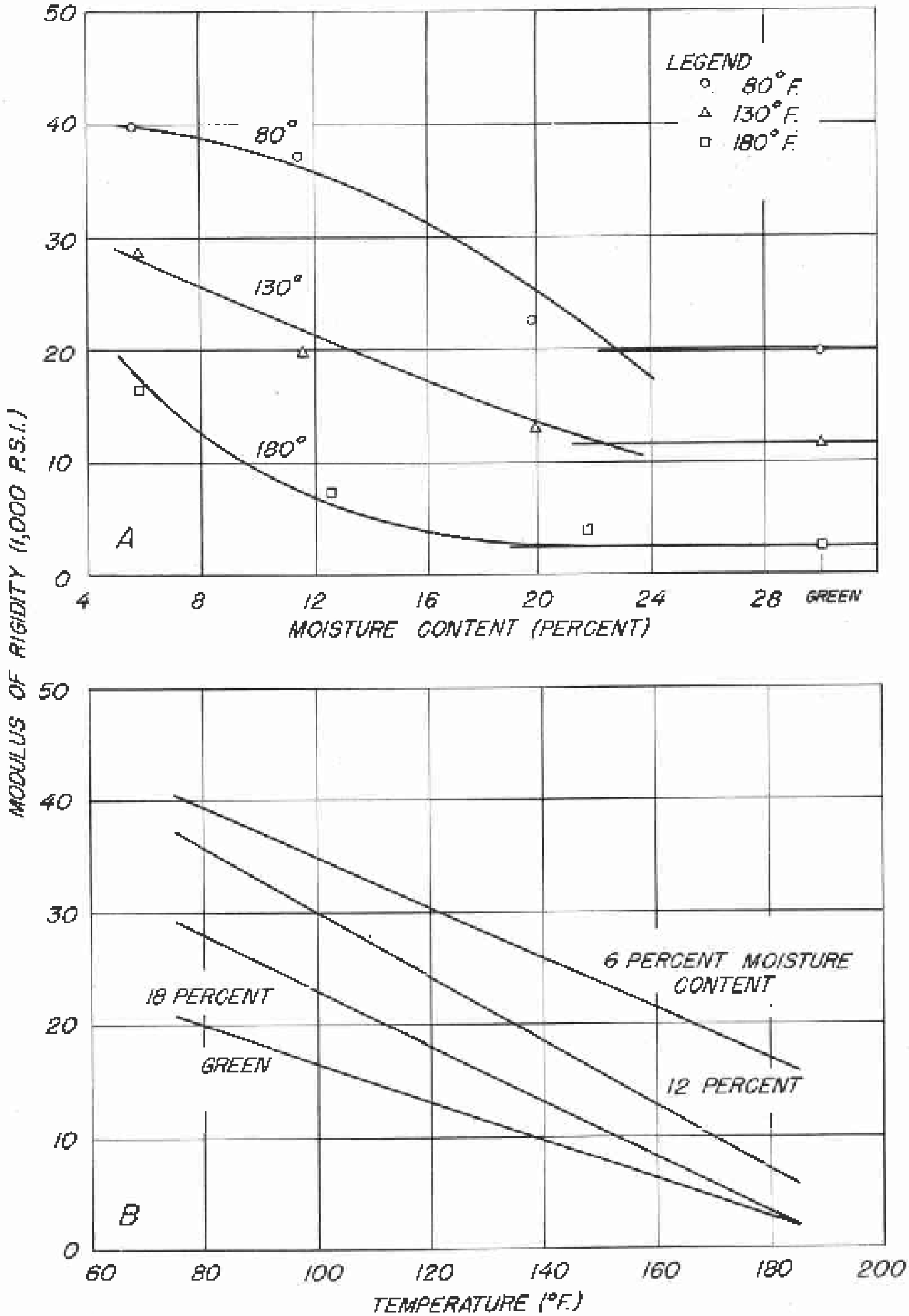
Z M 110 685

Figure 25. --Relationship of maximum strain in tension perpendicular to the grain at 90° to the growth rings to (A) moisture content and (B) temperature.



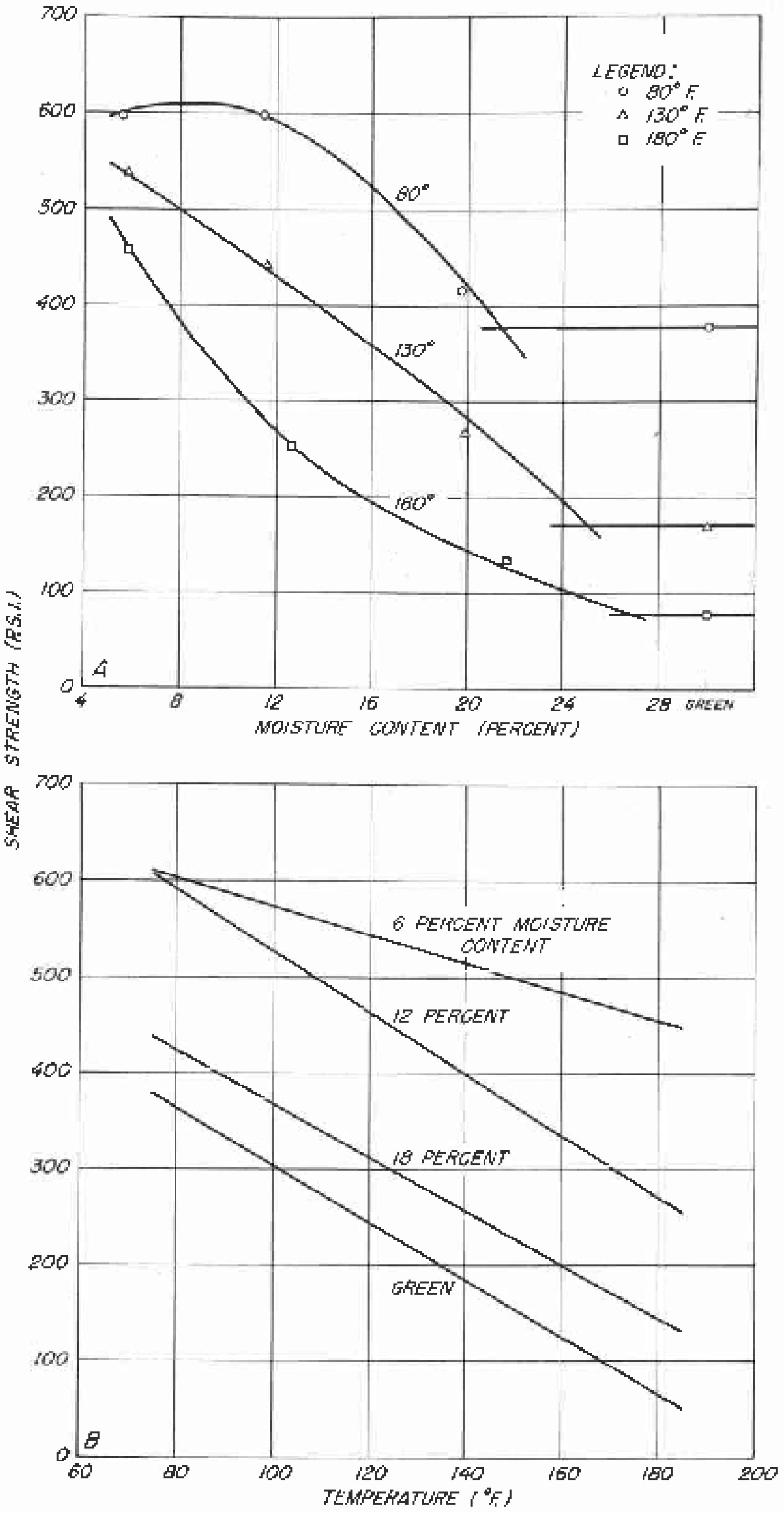
Z M 110 684

Figure 26. --Relationship of stress at 2.5 percent strain in compression perpendicular to the grain at 0° to the growth rings to (A) moisture content and (B) temperature.



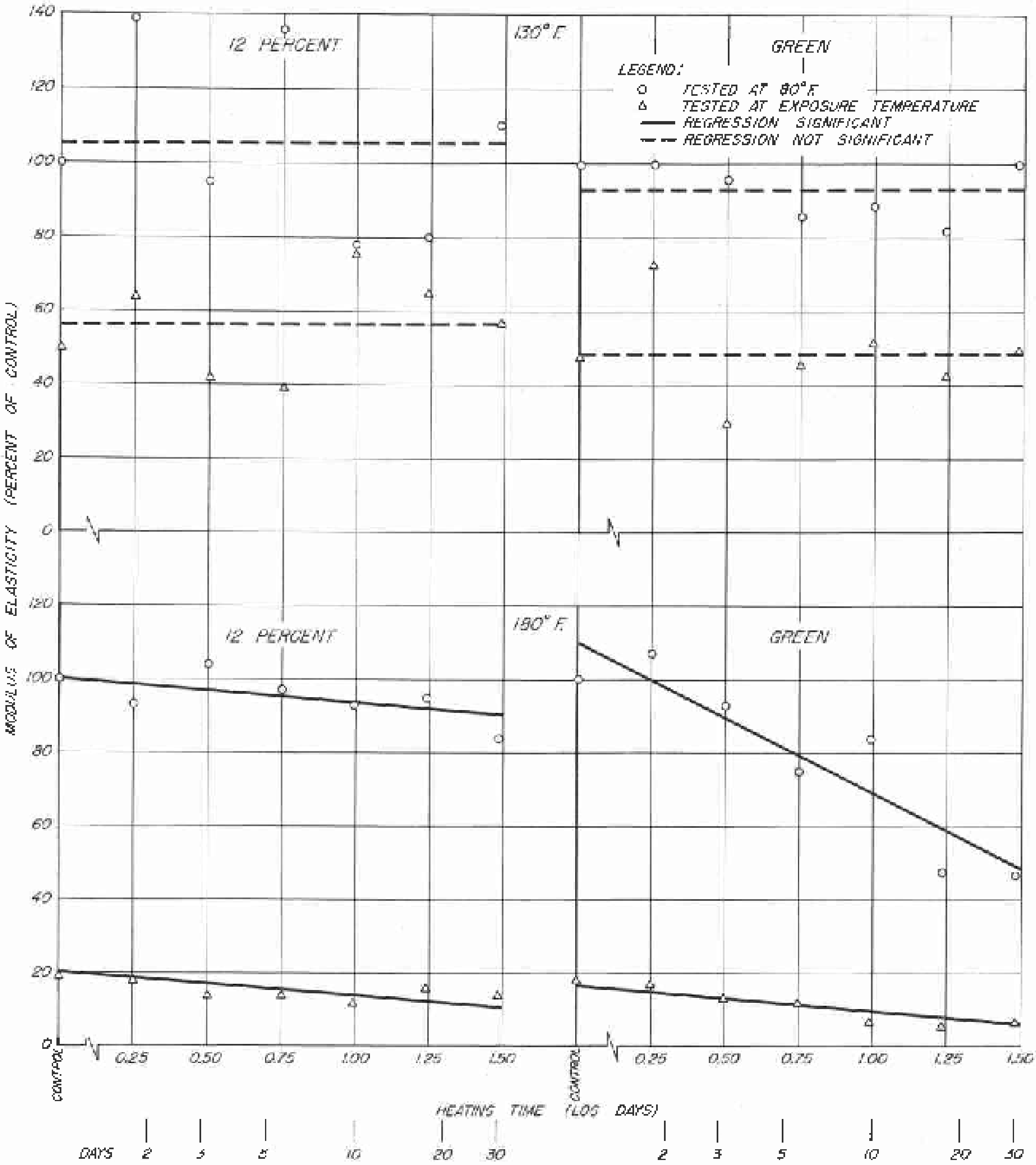
Z M 110 695

Figure 27. --Relationship of modulus of rigidity associated with strain in the TR plane to (A) moisture content and (B) temperature.



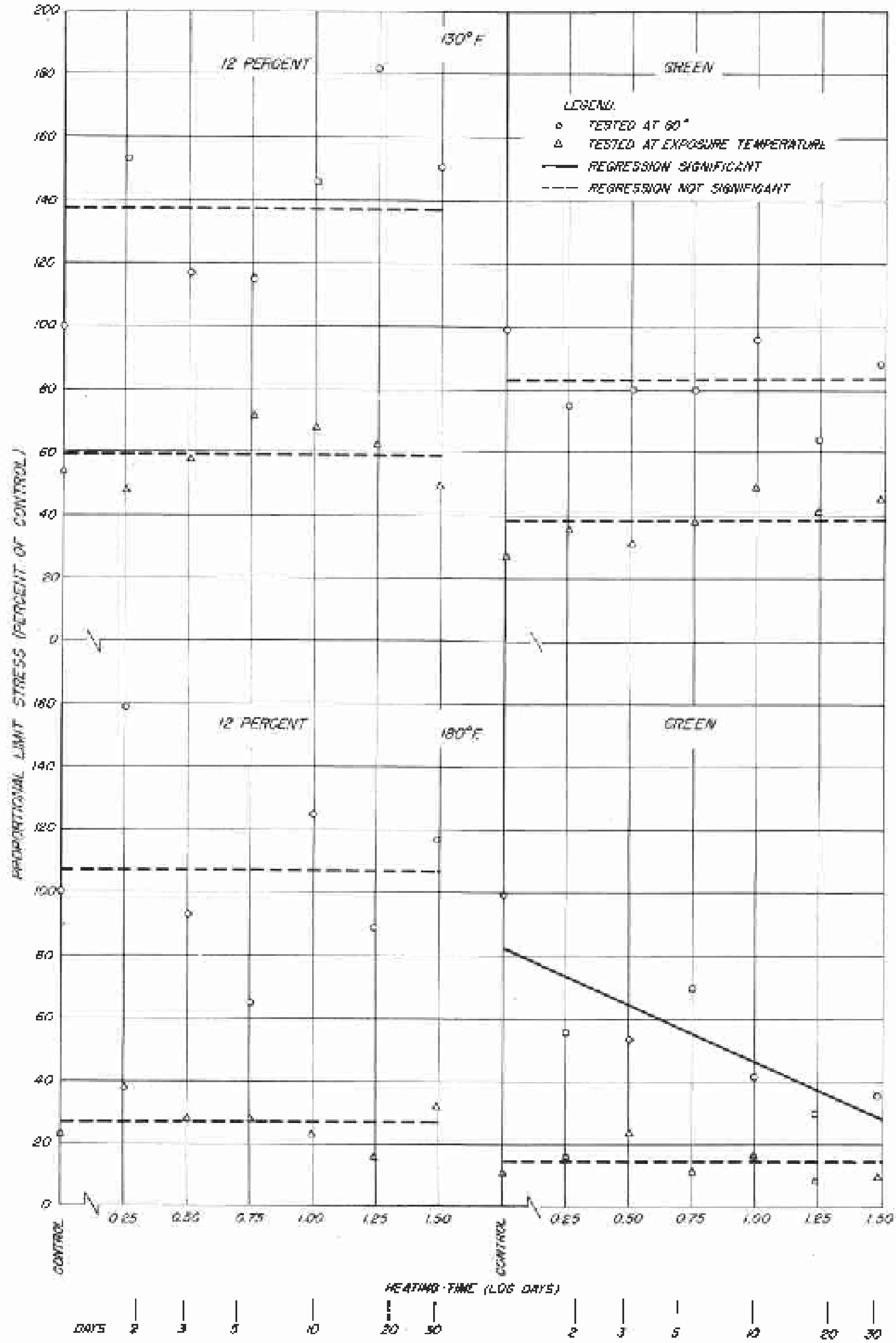
Z M 110 686

Figure 28.--Relationship of shear strength associated with strain in the TR plane to (A) moisture content and (B) temperature.



Z M 110 687

Figure 29. --Effect of duration of heating on modulus of elasticity in tension perpendicular to the grain.



Z M 110 688

Figure 30. --Effect of duration of heating on proportional limit stress in tension perpendicular to the grain.

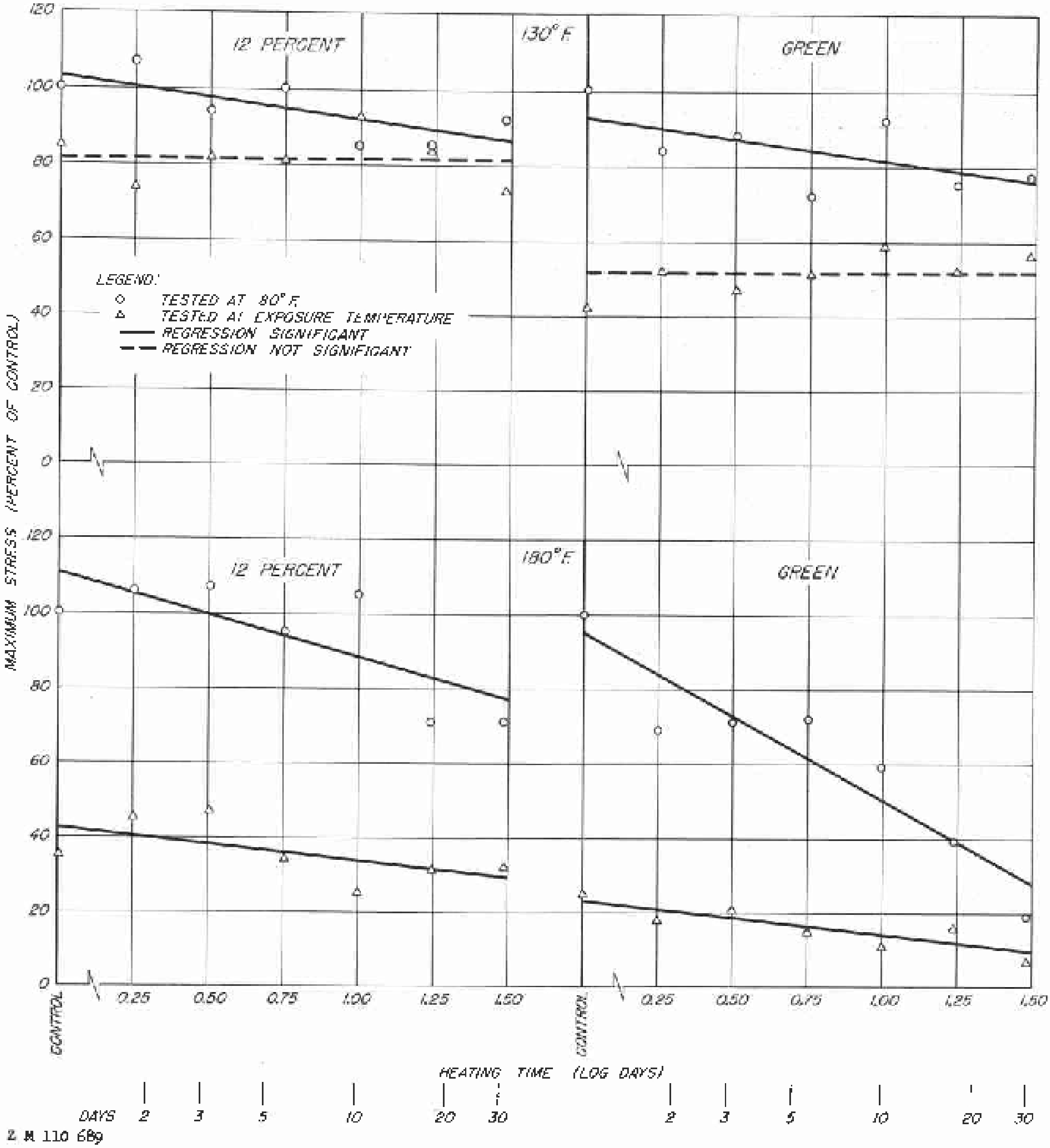
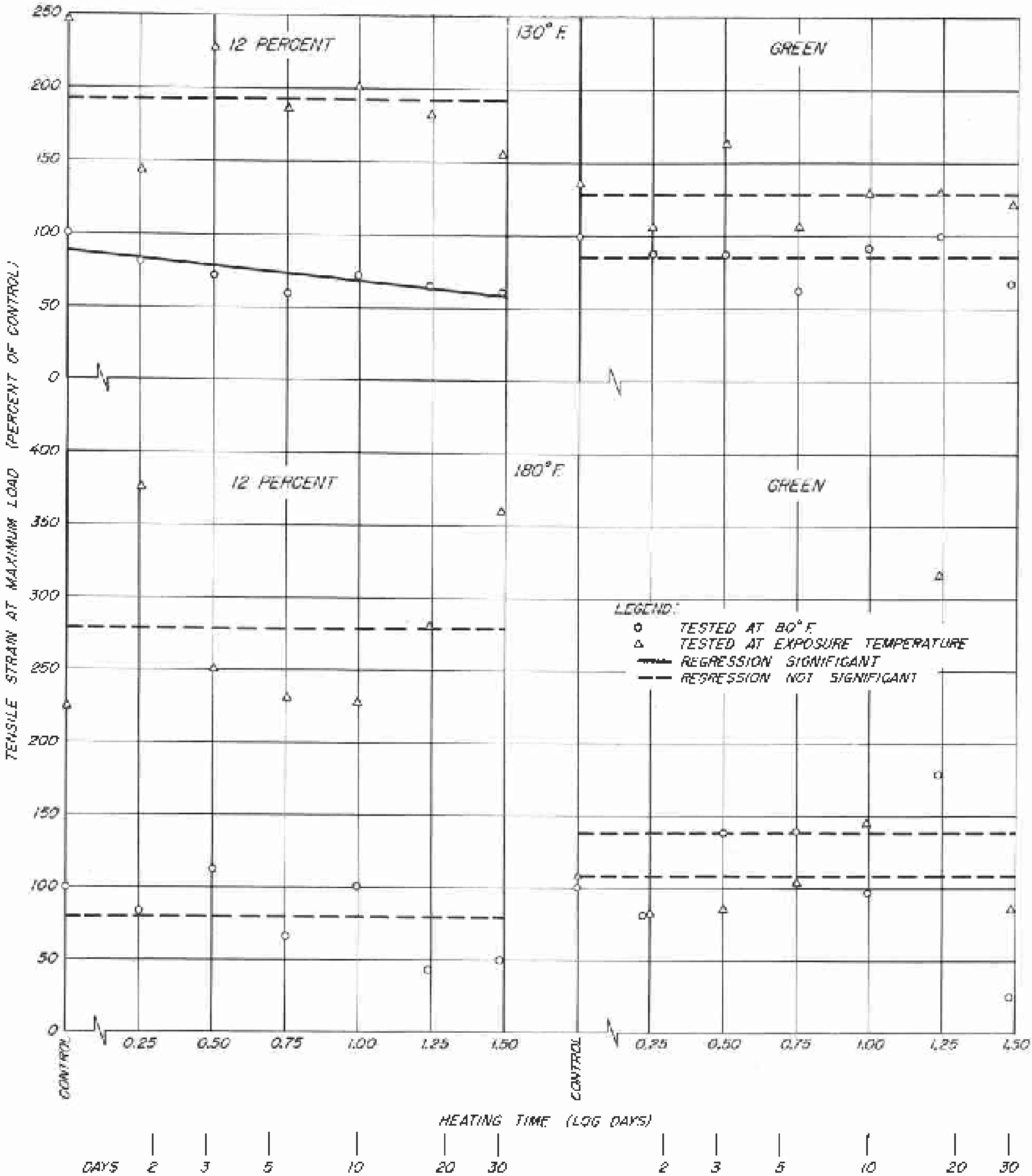
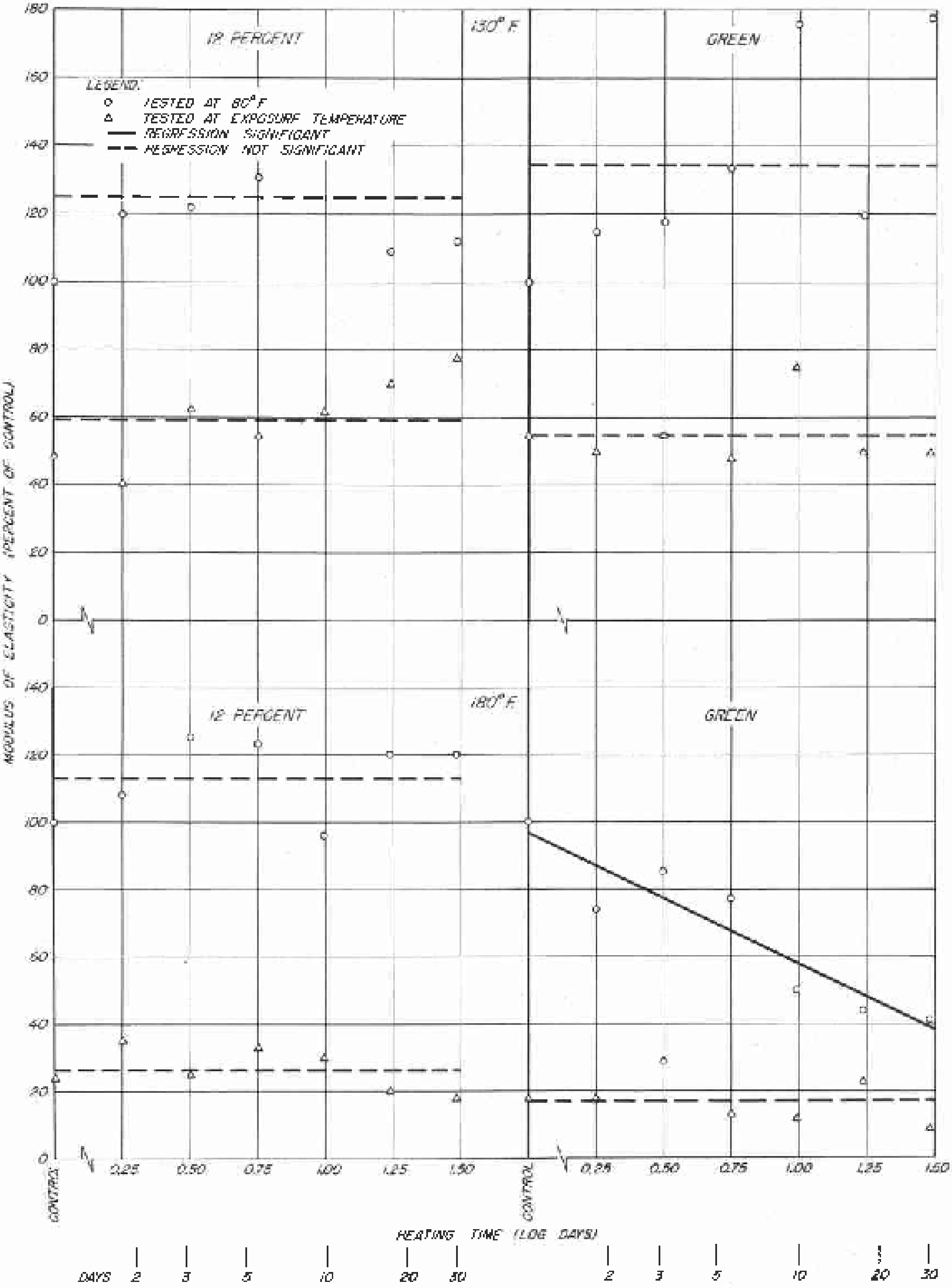


Figure 31.--Effect of duration of heating on maximum stress in tension perpendicular to the grain.



Z M 110 690

Figure 32. --Effect of duration of heating on strain at maximum load in tension perpendicular to the grain.



Z M 110 691

Figure 33.--Effect of duration of heating on modulus of elasticity in compression perpendicular to the grain.

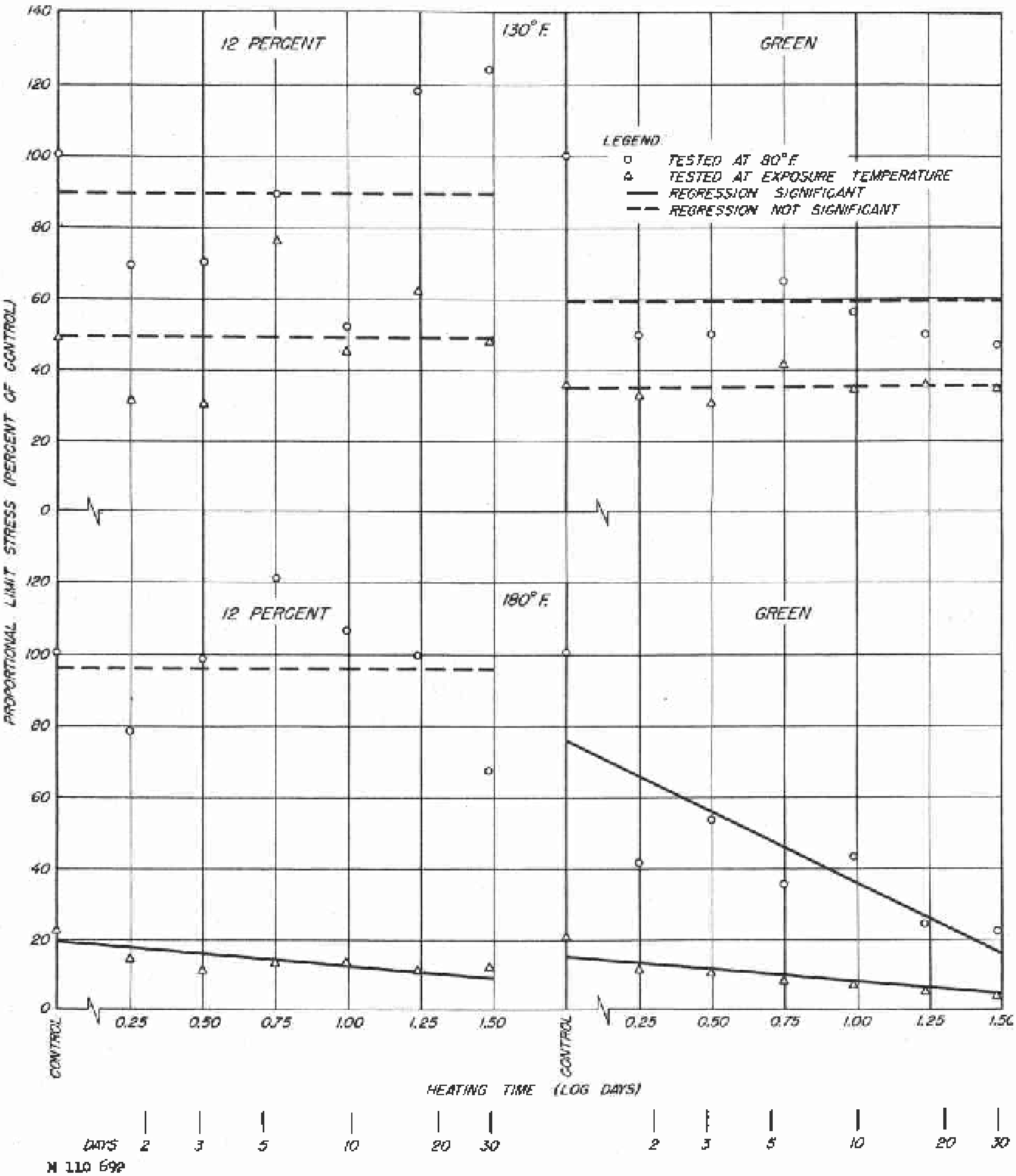
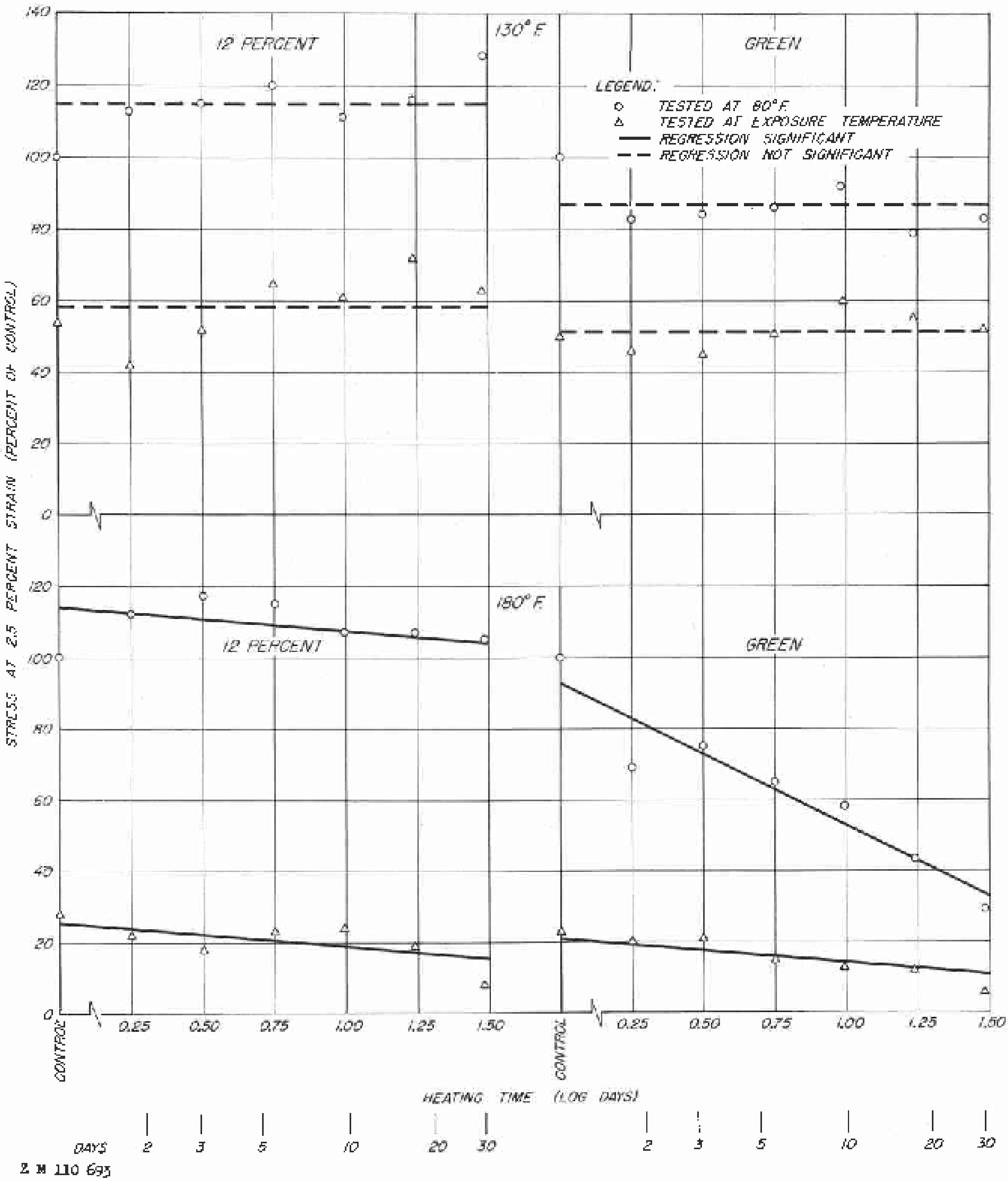


Figure 34. --Effect of duration of heating on proportional limit stress in compression perpendicular to the grain.



Z M 110 693

Figure 35.--Effect of duration of heating on stress at 2.5 percent strain in compression perpendicular to the grain.

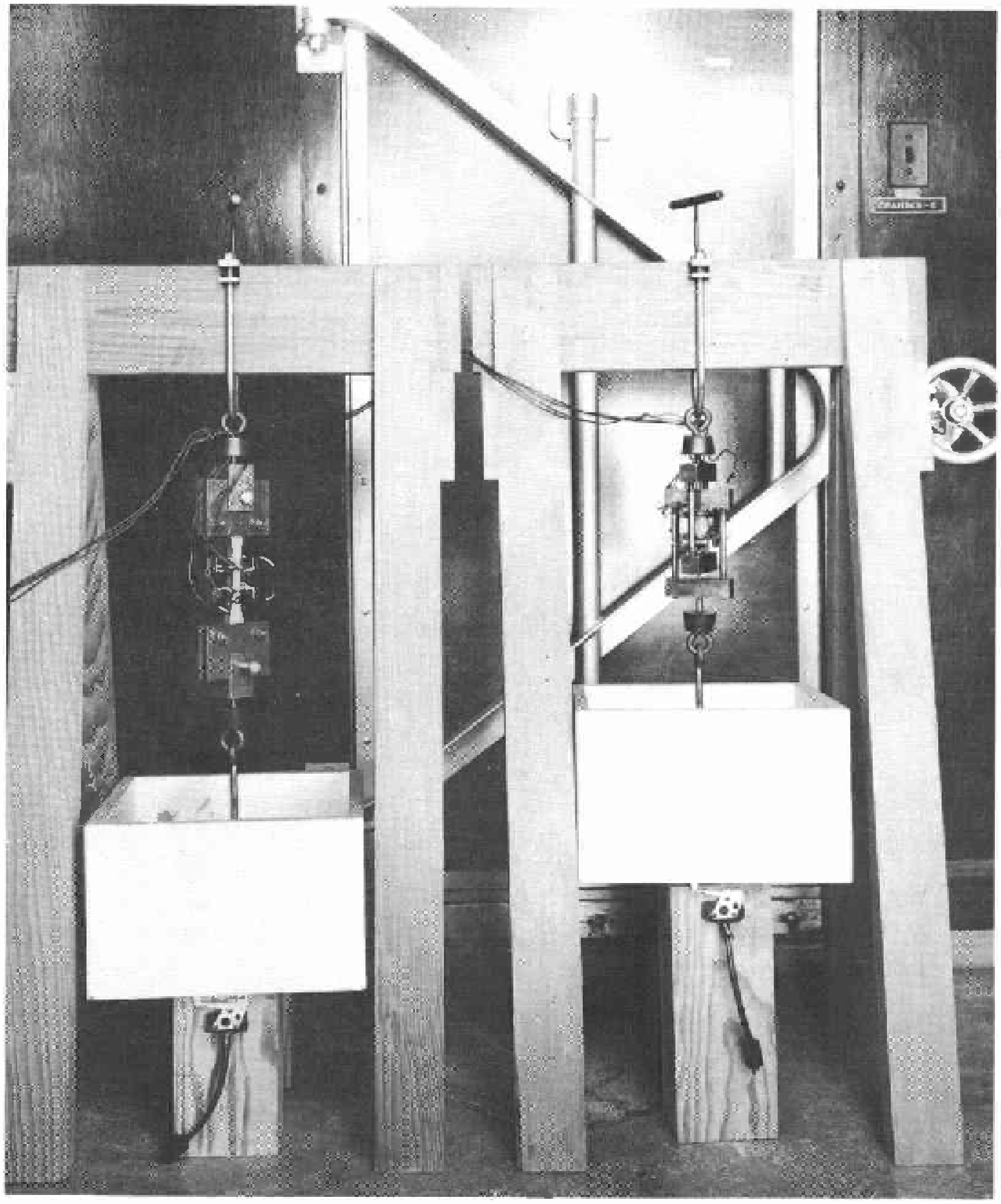


Figure 36. --Apparatus for creep and recovery tests in tension and compression perpendicular to the grain.

Z M 108 879

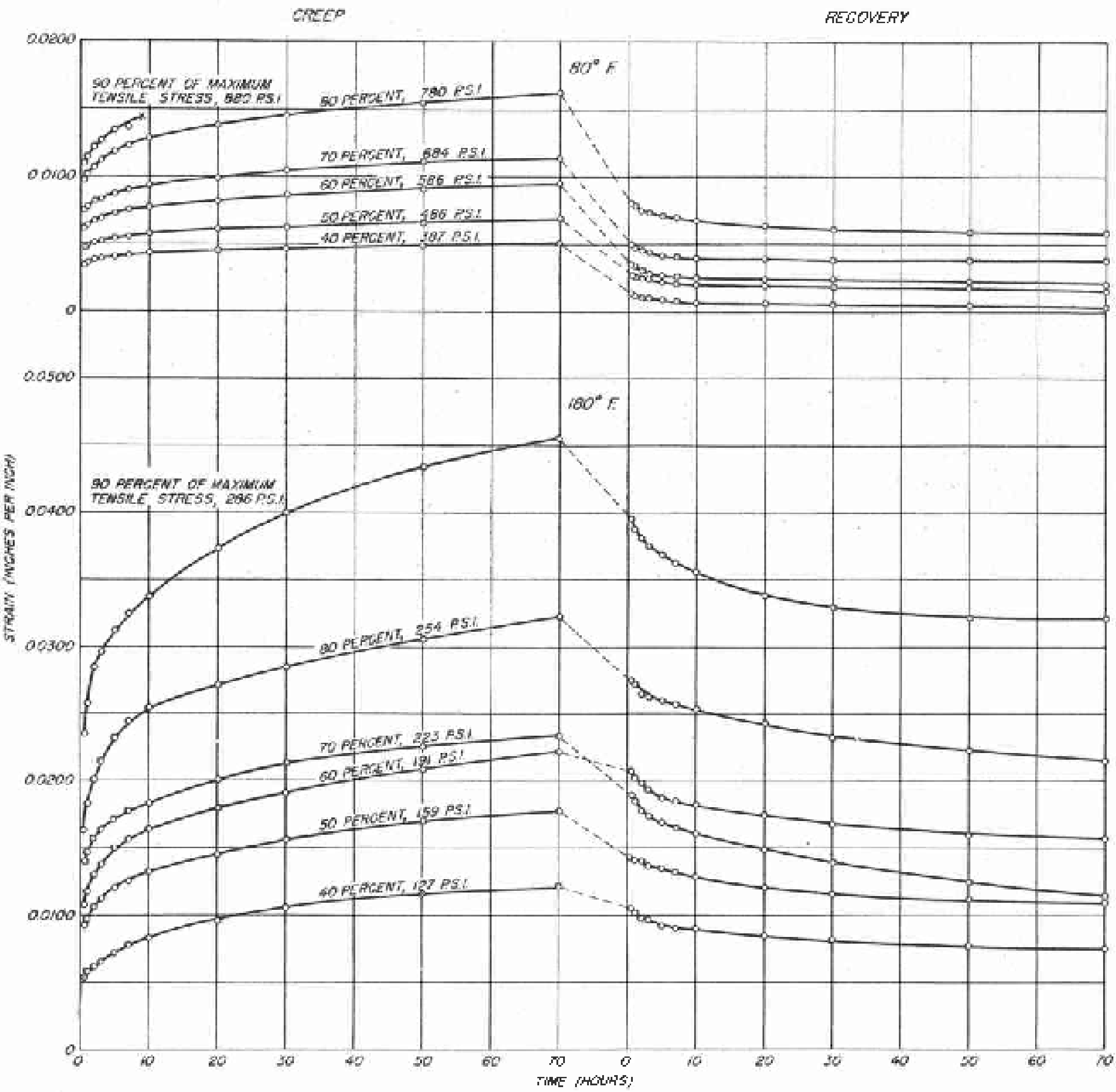


Figure 37. --Creep and recovery from creep in tension perpendicular to the grain at 12 percent moisture content.

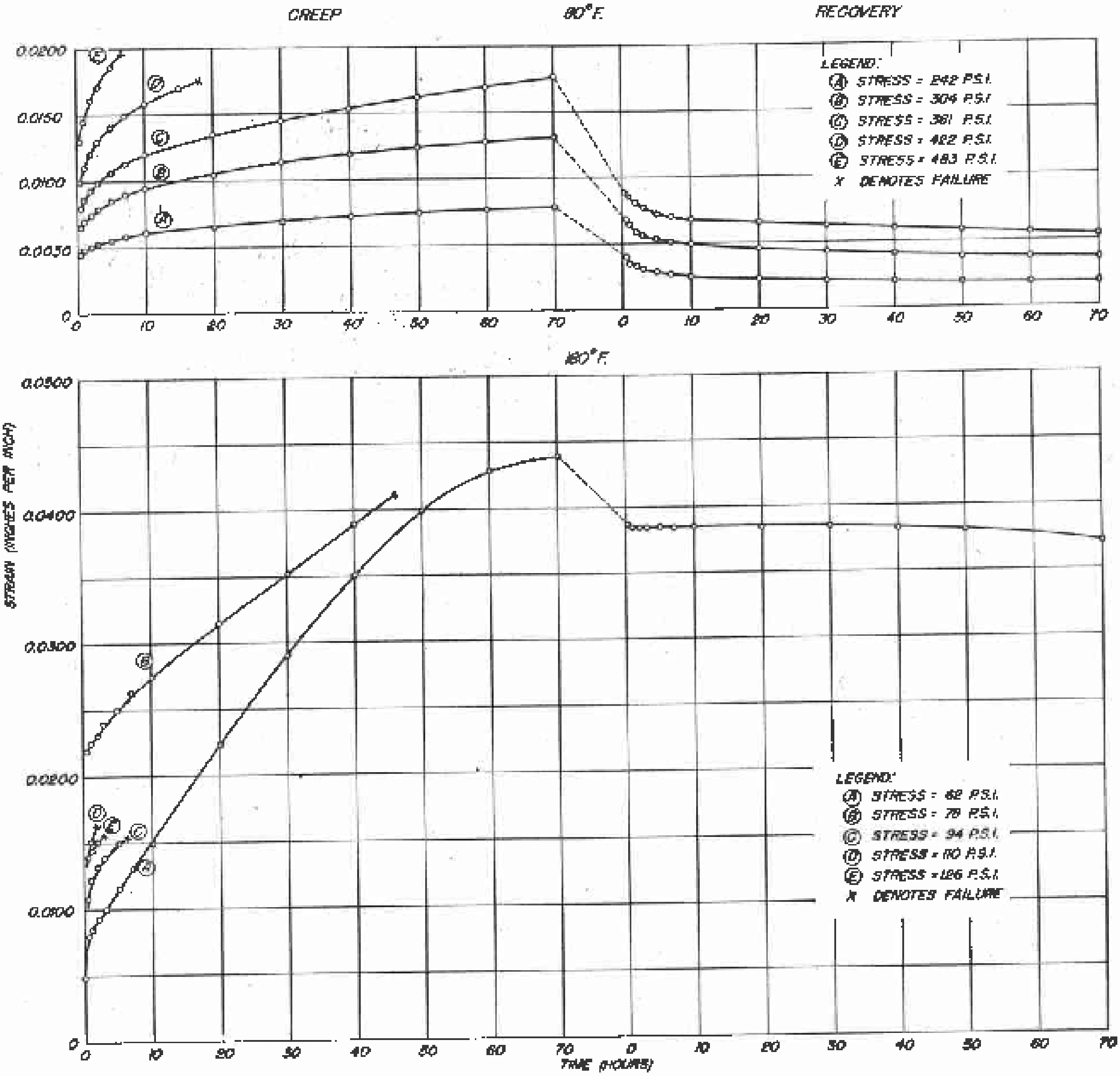


Figure 38. --Creep and recovery from creep in tension perpendicular to the grain in the green condition.

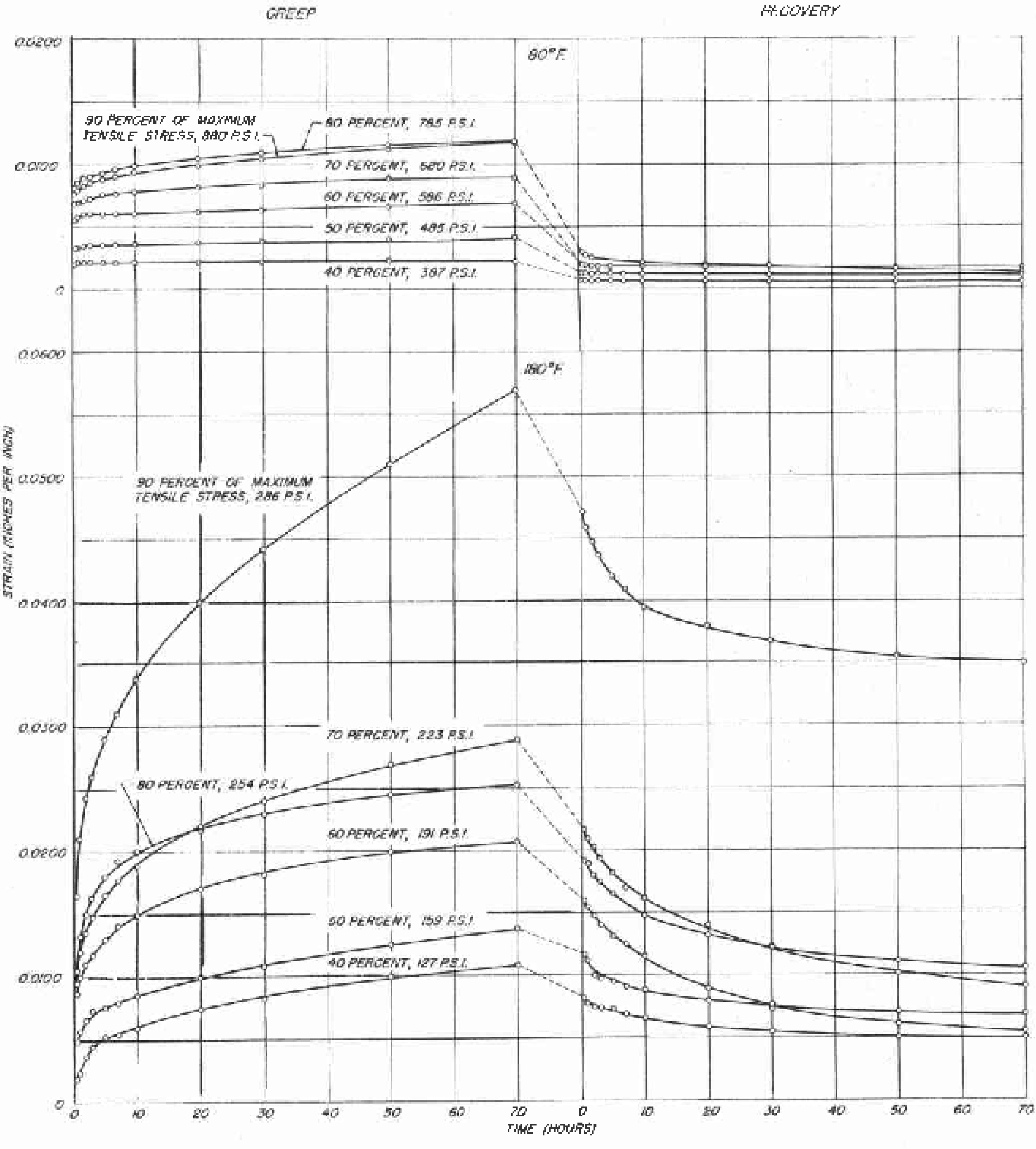


Figure 39. --Creep and recovery from creep in compression perpendicular to the grain at 12 percent moisture content.

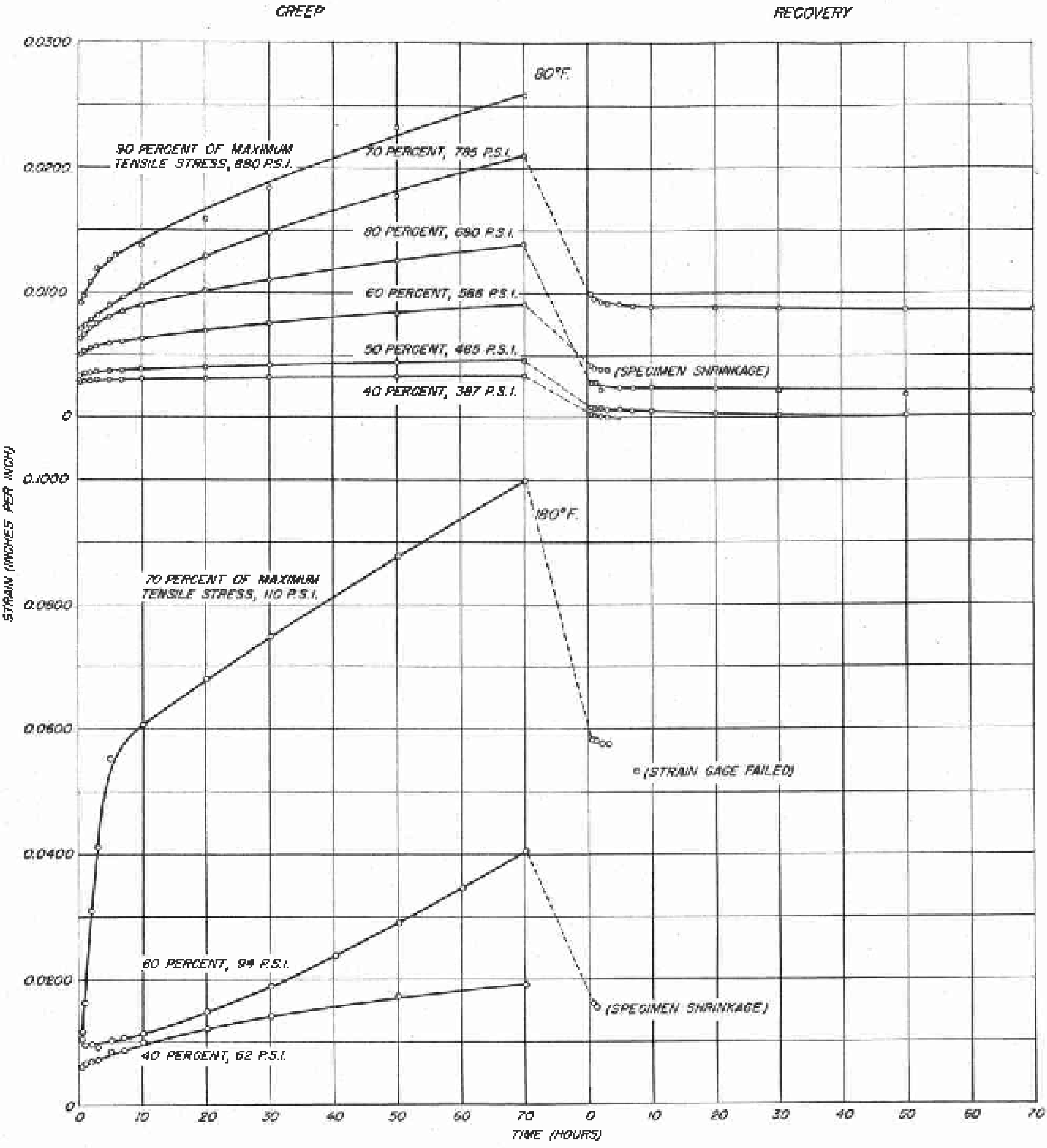
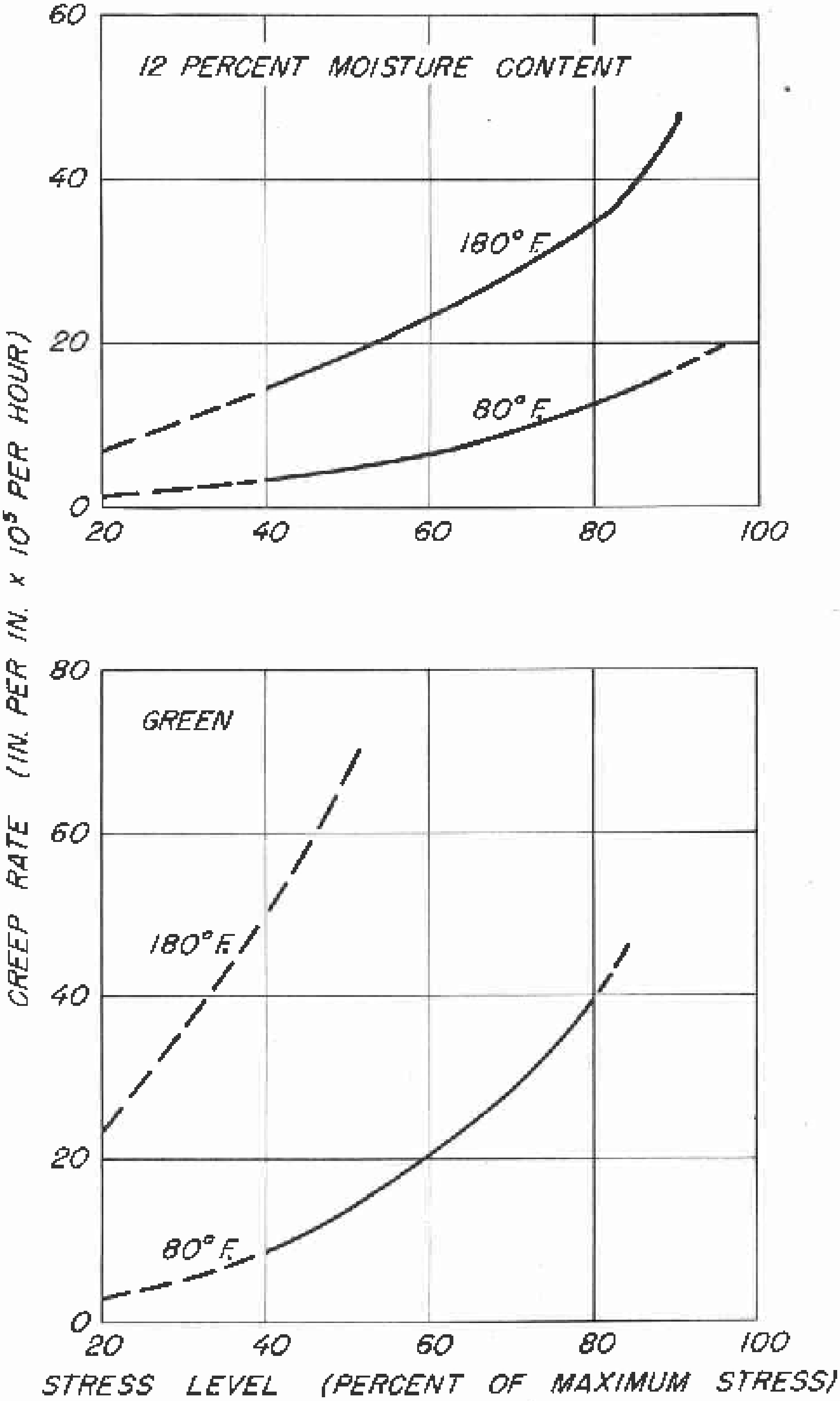
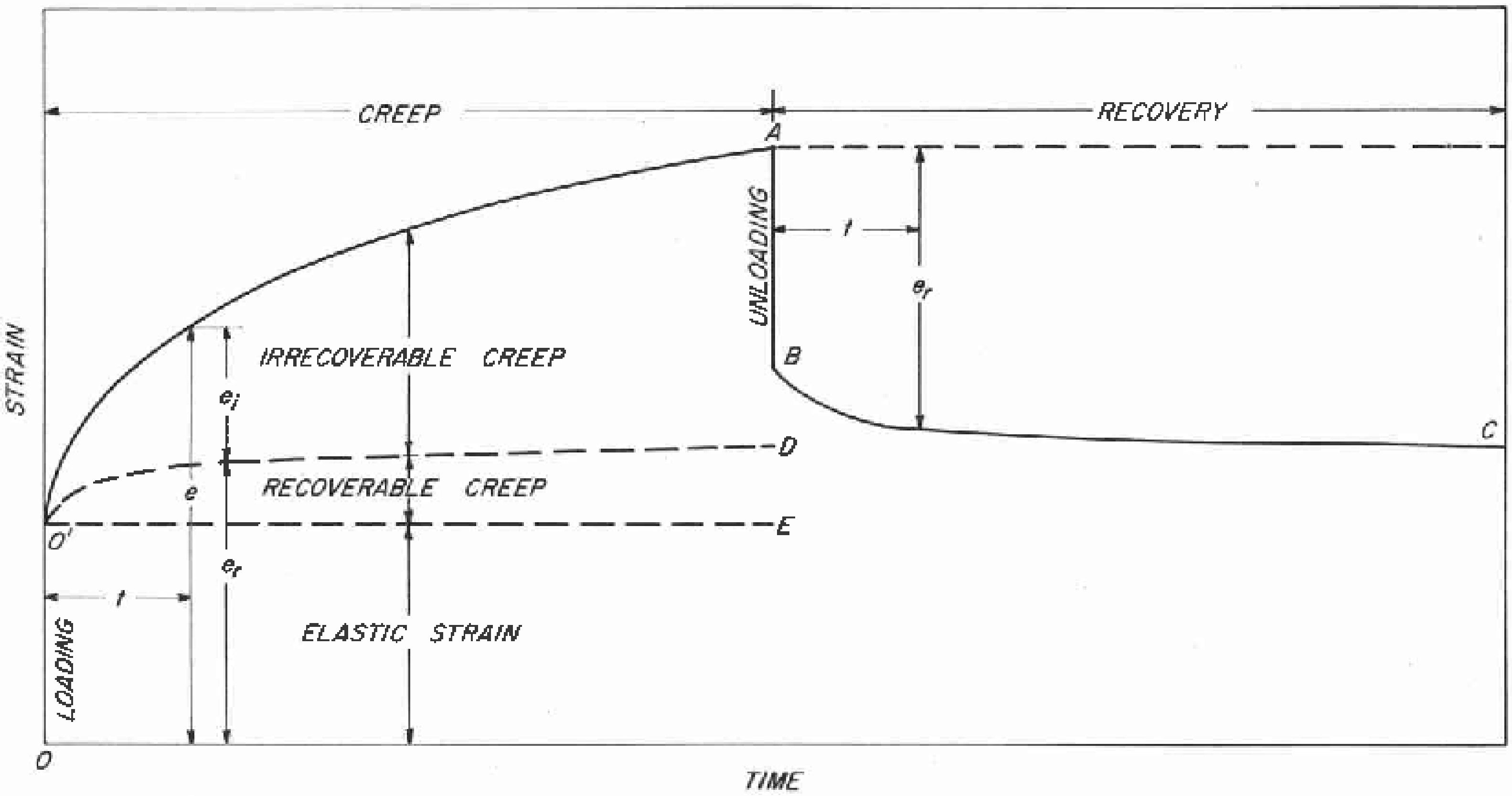


Figure 40. --Creep and recovery from creep in compression perpendicular to the grain in the green condition.



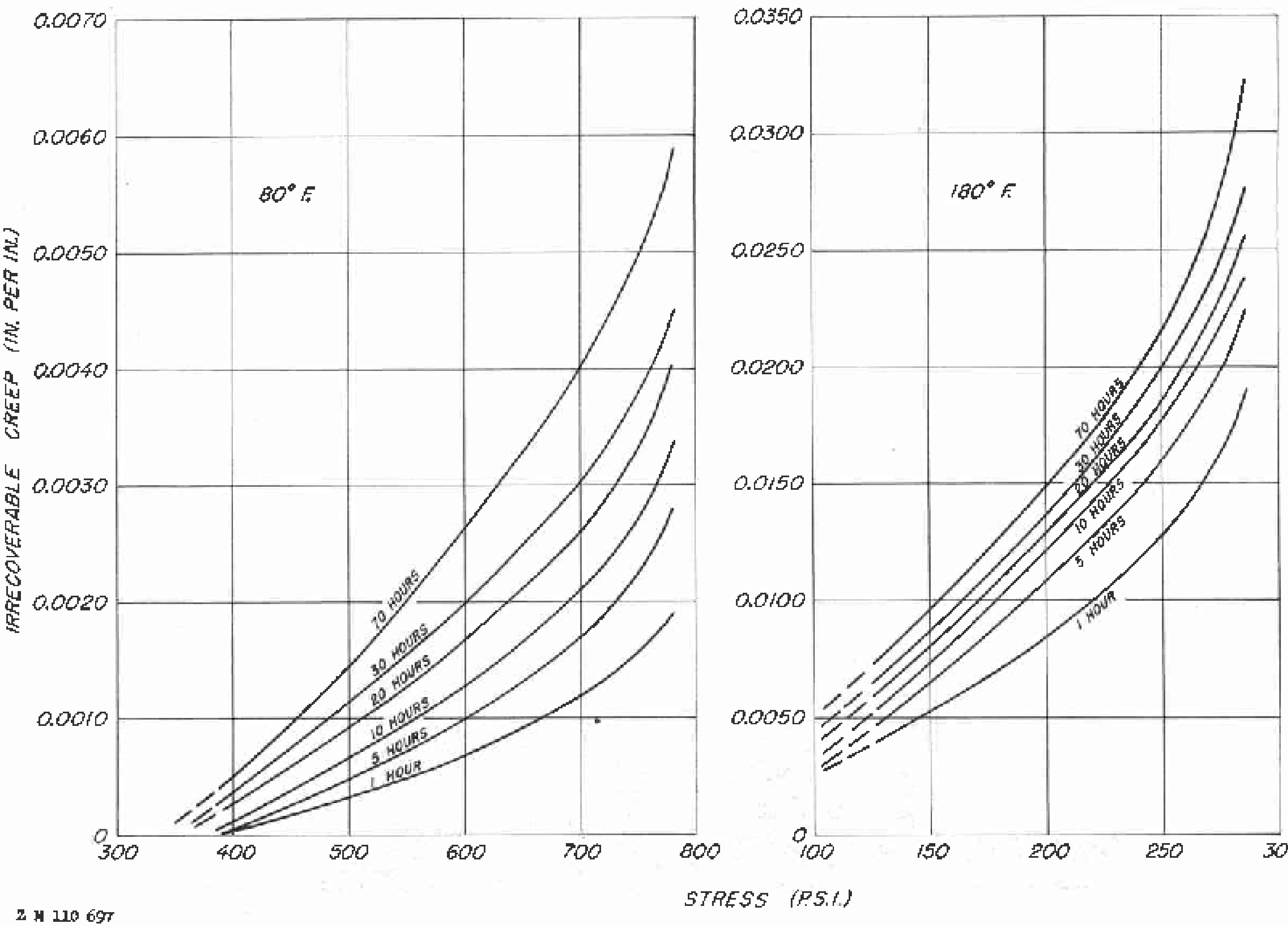
Z M 110 695

Figure 41. --Relationship of creep rate in tension perpendicular to the grain to stress level.



2 M 110 696

Figure 42. --Method of estimating rate of development of irrecoverable creep by superposition of recovery curve on creep curve.



Z M 110 697

Figure 43. --Relationship between irrecoverable creep and stress in tension perpendicular to the grain at 12 percent moisture content.

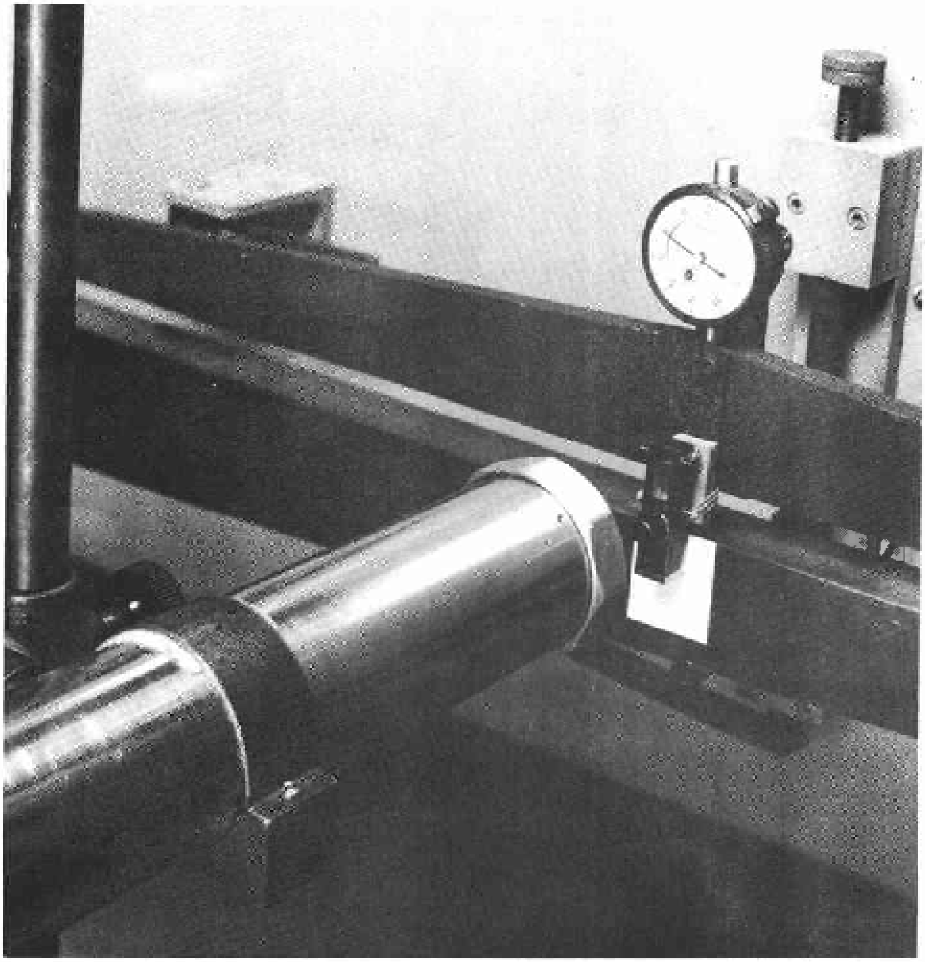


Figure 44. --Dial bar with dial and Tuckerman extensometer for measuring load on relaxation specimen in a fatigue machine.
Z M 108 880

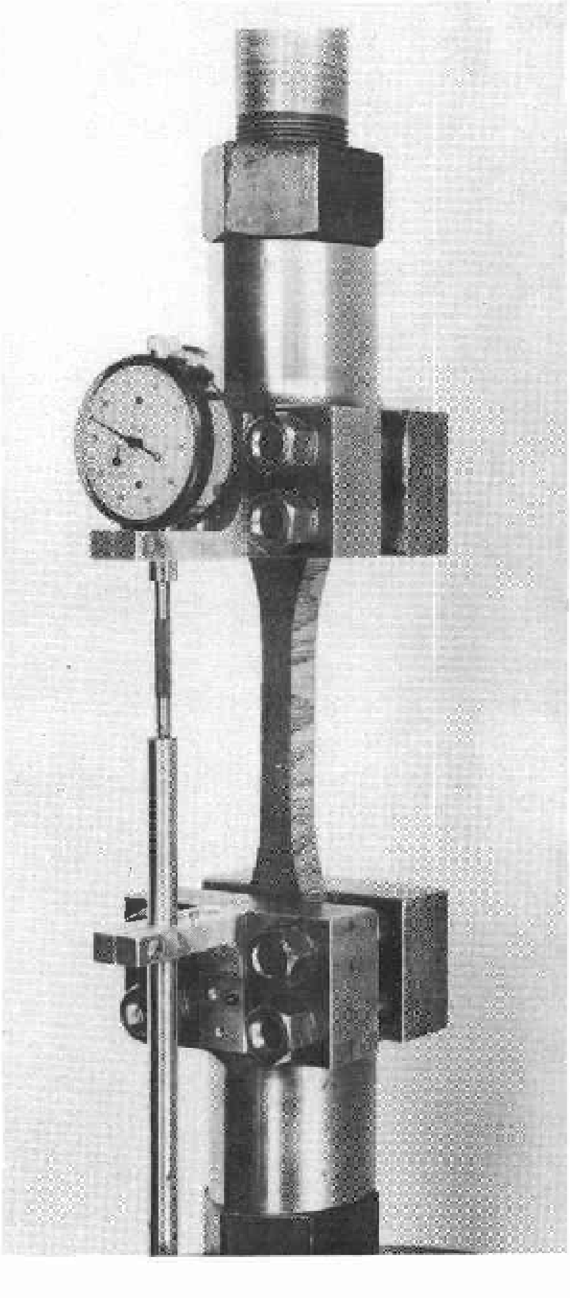


Figure 45. --Arrangement of specimen in grips of fatigue machine for stress relaxation test in tension perpendicular to the grain.
Z M 108 878

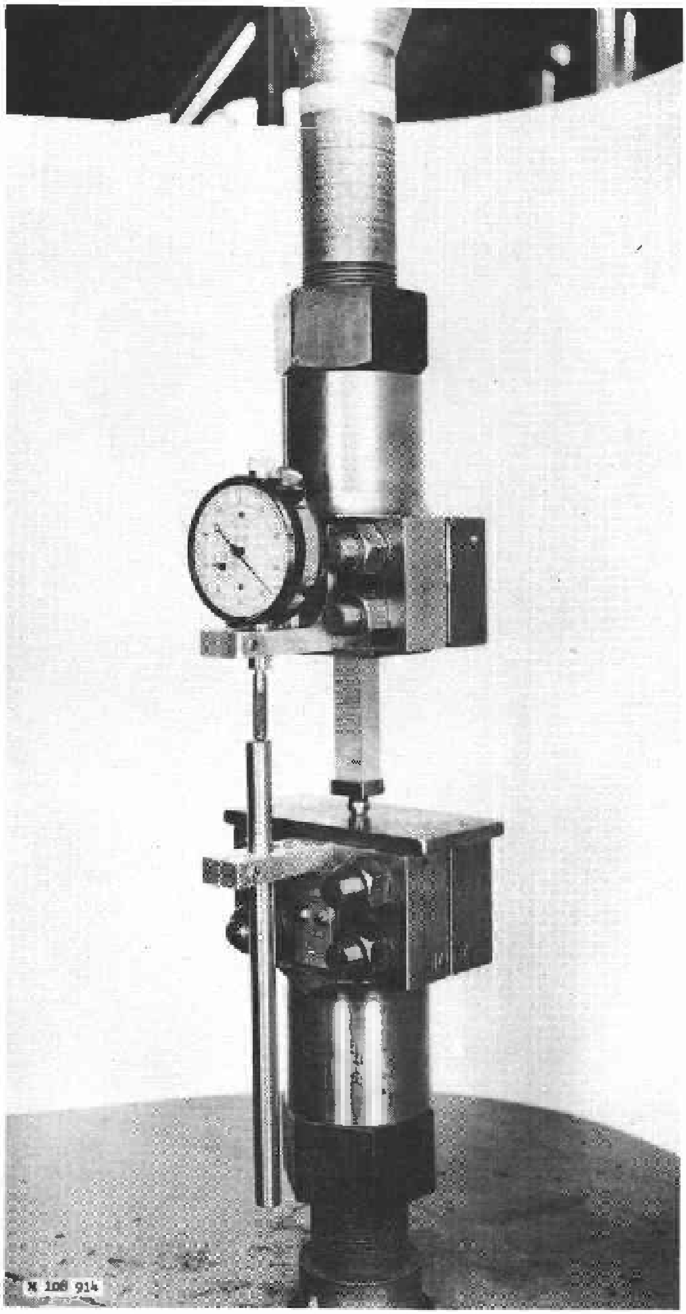


Figure 46.--Arrangement of specimen in grips of fatigue machine for stress relaxation test in compression perpendicular to the grain.

Z M 108 914

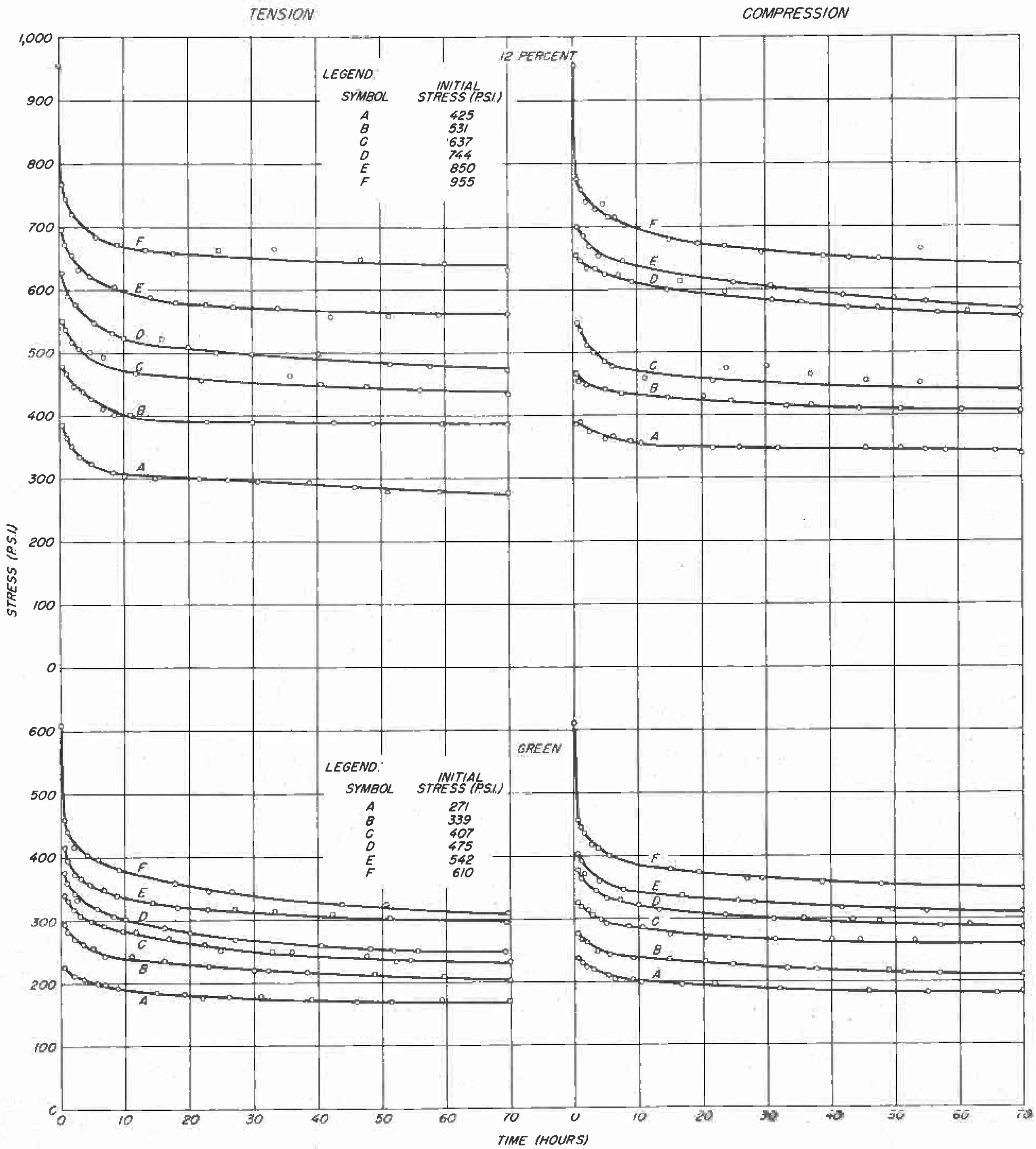


Figure 47. --Stress relaxation in tension and compression perpendicular to the grain at 75° F.

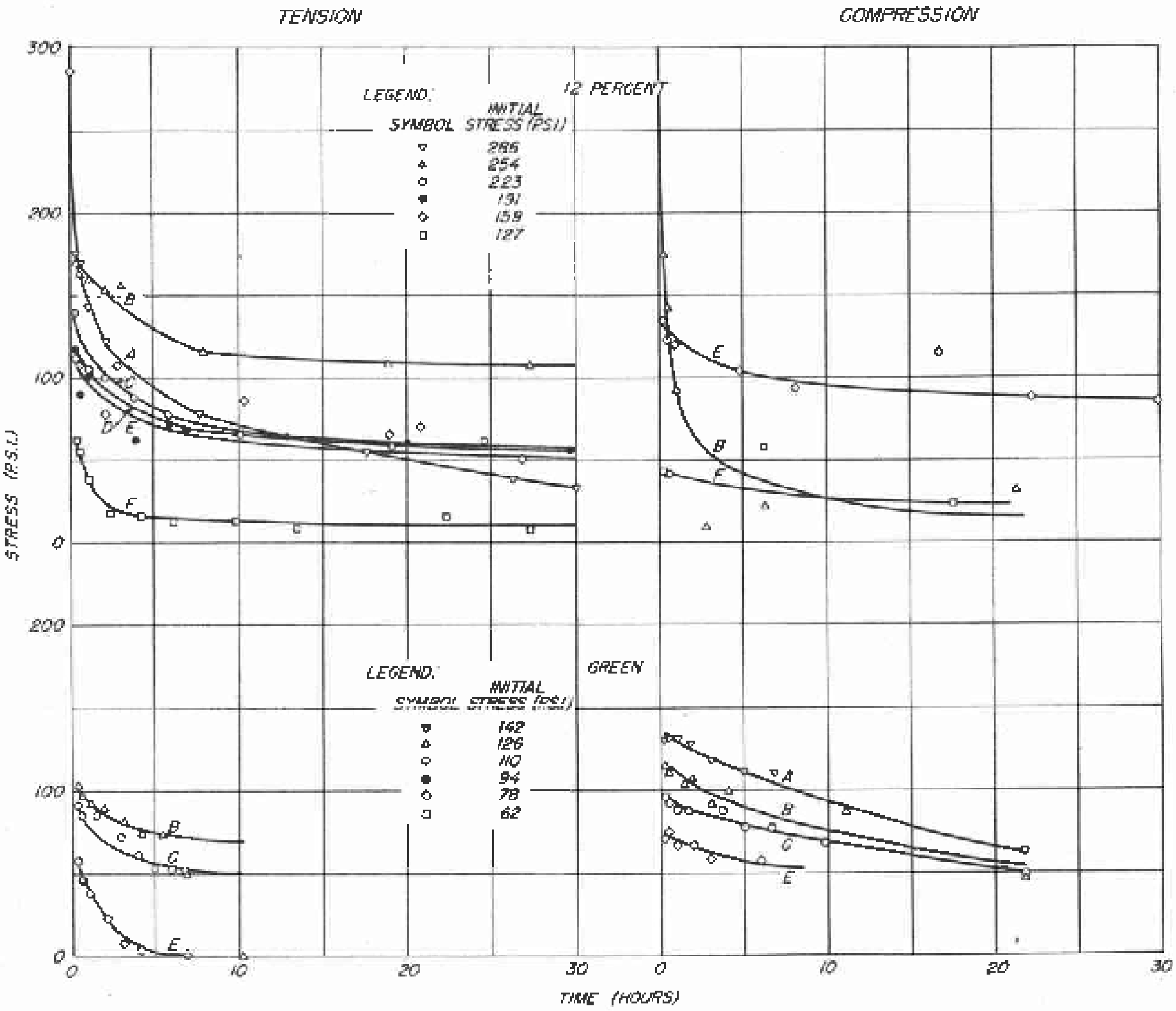


Figure 48. --Stress relaxation in tension and compression perpendicular to the grain at 180° F.