DEFORMATION OF WOOD UNDER LOAD

by

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ABSTRACT

Creep and recovery tests in compression parallel to the grain were conducted on 2 in. by 2 in. Douglas-fir specimens 4 in. long at four different levels of moisture.

Specimens were loaded in stages up to a predetermined load. Instantaneous axial and lateral deformation as well as creep measurements were taken at each stage. Creep was observed over periods ranging from five minutes to twenty-five hours. Similarly, recovery was observed during unloading at successively lower stress levels.

There are indications that creep as well as negative creep and negative recovery were mainly due to moisture present in the cell walls.

Creep, in general, appeared to be more marked in the green specimens than in the intermediate and air-dry conditions. The only oven-dry specimen showed less creep than the air-dry specimens.

Results also show that the values of the coefficient of lateral deformation, $\mu = \frac{\Delta\epsilon_{Lateral}}{\Delta\epsilon_{Longitudinal}}$ (both radial and tangential), during the load rise were entirely different from those during the period of creep, indicating that the corresponding deformations were entirely different. The μ's for the change in load were always higher than those for the periods of creep.

All specimens tested showed a recovery of more than 50% of the longitudinal creep. This indicates that creep in wood is made up of two parts, recoverable and permanent creep.

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Part I

INTRODUCTION

Wood, which was among the earliest materials to be used for construction, has long had an established place in the major field of structural engineering. Nowadays, through the wide application of results from fundamental and applied research, novel designs of large wooden structures are possible, making wood competitive with other materials such as steel and concrete.

Glued, laminated wooden construction, for example, has already been recognized to be of primary importance in this modern world of mechanization and automation. In the near future, prestressed or reinforced wooden members will likely join other engineered wood products for a more economical and satisfactory utilization of timber.

It has become desirable, therefore, that studies be conducted on some of the basic aspects concerning the strain behaviour of wood which take into account not only the effect of the applied stress, but in addition, the effect of time.

This present investigation was carried out primarily to provide fundamental information on the creep of wood loaded in compression parallel to the grain at four levels of moisture content. It was also concerned with the effect of sustained loading at successively higher stress intensities on the modulus of elasticity, ultimate compressive strength and maximum deformation.

In common with many materials, wood, when subjected to a constant force, exhibits an increase in deformation following an initial instantaneous strain. This subsequent increase in deformation, called creep or plastic flow, is time dependent and behaves in one of two ways. The creep may take place either at a continuously decreasing rate until it approaches an ultimate or limiting value; or, it may show gradually diminishing rate at first, then a constant rate and finally an increasing rate which eventually leads to failure.

Previous investigations elsewhere have shown that wood, under all types of loading, exhibits creep even when the stress is well below the standard proportional limit (1, 3, 4, 5, 6, 7, 8)[1].

Tests at the U. S. Forest Products Laboratory as reported by Wood (8) have shown that Douglas-fir and white oak both exhibit noticeable creep when subjected to tension and compression parallel to the grain at stresses as low as 1500 psi. Wood also reported that there is an indication that creep in tension and compression is approximately proportional to stress.

Dietz (3) in his investigation of the creep behaviour of Douglas-fir found that for compressive stresses below the proportional limit, the creep is very low.

The Australian Forest Products Laboratory (1) reported

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[1] Numbers in parenthesis refer to literature cited.

observing increases in strain from 20 to 140 per cent in green mountain ash specimens subjected to compression for almost three years at stresses ranging from 10 to 35 per cent of the short time strength.

Part II

DESCRIPTION OF TEST MATERIAL

Species Used

Douglas-fir (Pseudotsuga menziesii), a species of prime importance in world markets for structural grades of lumber, was the species chosen for this particular experiment.

As reported in F. P. L. Technical Note No. 3, "Strength and Related Properties of Woods Grown in Canada", Douglas-fir shows the following average values in compression parallel to the grain:

Moisture Content[2]	41%	12%
Nominal Specific Gravity[3]	0.45	0.49
Stress at Proportional Limit	2810 psi.	4830 psi.
Maximum Crushing Stress	3610 psi.	7230 psi.
Modulus of Elasticity	1,670,000 psi.	1,950,000 psi.

Source and Selection of the Experimental Material

Material utilized in this work was obtained from a flat-sawn plank selected from a stock of Douglas-fir on hand at the Civil Engineering Laboratory, University of British Columbia.

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[2] Based on weight when oven-dry.

[3] Based on volume at test and weight when oven-dry.

In order to simplify the interpretation of the results, it was considered desirable to use test pieces free of defects including knots, as straight grained as possible, and with sufficiently flat growth rings. When selected, the plank was in an air-seasoned condition registering a moisture content of about 12% with an electric moisture meter.

Type and Preparation of Test Specimens

The specimens used in these experiments were nominally two-by-two inches in cross-section and four inches in length parallel to the grain (See Fig. 1).

The plank was surfaced on both flat grain faces to a nominal thickness of 2¼ inches, the grain direction was determined, and sticks 2¼-inch wide were ripped parallel to the grain with growth rings as nearly as possible parallel and perpendicular to the end edges of the sticks. These were cross-cut into 5-inch lengths to produce end-matched blocks for the test specimens and their controls, and into 4-inch lengths for moisture content sampling. The individual pieces were reduced to final size only after they have already attained a moisture content very near the desired final condition.

In the final processing of the test specimens and their controls, particular care was taken not only to improve further the orientation of the annual rings so as to make them essentially at right angles to a pair of faces, but

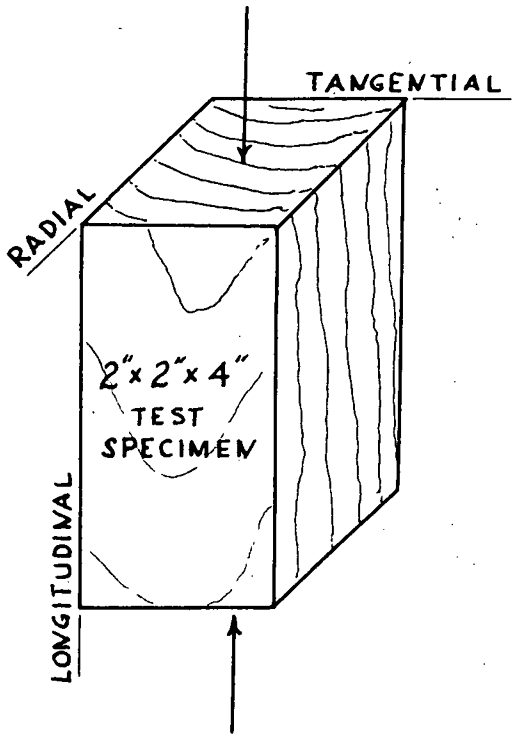


Fig. 1 - TEST SPECIMEN

also to make three sides of the blocks truly and mutually perpendicular to each other.

Each specimen was designated by a capital letter which indicated the moisture condition under which it was to be tested; air-dry condition was designated by the letter "A", intermediate moisture condition by "M", green condition by "G", and oven-dry condition by "O".

For the controls, the letter "C" was simply added. Thus, CA-1-6 indicates the control specimen in the air-dry condition.

Part III

MOISTURE CONDITIONS AT TEST

Creep and recovery tests in compression parallel to the grain were conducted at four different levels of moisture, namely:

1. Air-Dry Condition - in which the moisture content of the specimens at test was in equilibrium with the atmosphere of the testing laboratory. The specimens were generally very close to 10% moisture content.

2. Intermediate Condition - in which the moisture content was above 12% but below the fibre saturation point of the species which in this case is about 24% (2). Nominal moisture content for this condition was chosen to be 20%.

3. Green Condition - in which the moisture content was above the fibre saturation point, the moisture content ranging

from 47% to 66%.

4. Oven-Dry Condition - in which the moisture content was very close to zero.

Conditioning of the Specimens

All test specimens were stored in temperature-and-humidity controlled rooms or chambers that would bring them to the desired final moisture content under which they were to be tested.

Those assigned to tests in the air-dry condition were stored exposed to the atmospheric conditions of the testing room until they reached constant weight. These specimens came to equilibrium at moisture contents ranging from 9.3% to 10.2%.

Those to be tested in the intermediate conditions were conditioned and stored in a chamber over a saturated solution of sodium sulphate. The chamber was maintained at a temperature of 75°F. At this temperature the relative vapor pressure above the salt solution was such as to result in moisture conditions that would give a nominal equilibrium moisture content in the blocks of 20%.

Those to be tested in the green conditions were stored in a controlled-humidity-temperature room. To facilitate the conditioning of these green specimens, they were first submerged in water under a vacuum for about three days.

Those to be tested in the oven-dry condition were conditioned in a thermostatically controlled electric oven heated at 212° F and dried until no change in weight was observed for a period of twenty-four hours.

During the conditioning period, the specimens were weighed periodically, first at long intervals and finally, when they had very nearly attained their equilibrium moisture contents, more frequently. The weighing was continued until most of the specimens in each condition had maintained an almost constant weight indicating that they had attained the required equilibrium moisture content. Periodically, a moisture sample about an inch thich was taken from the centre of the moisture sample blocks and the moisture content, and its distribution throughout the cross-section, determined by the oven-dry method. (See Moisture Content and Specific Gravity Determination on page 24).

While every attempt was made to bring the air-dry, intermediate and green specimens to a uniform moisture content of 10%, 20%, and 60%, respectively, before testing, it was inevitable that some specimens exhibited a moisture content slightly higher or lower than the desired level. However, for the first two conditions, it was deemed imperative that no two specimens should have a difference in moisture of more than 10% of the nominal value, i. e., 1% and 2%, respectively, otherwise the test was discarded. For the green specimens, such limitation was not necessary since most of the strength properties of wood are influenced by moisture content only in the range below the fibre saturation point.

The specimens were kept under these conditions until removed one at a time for testing.

Part IV

EQUIPMENT USED

Testing Machine

All the testing was performed on a Balwin Tate-Emery Testing Machine with a maximum capacity of four-hundred-thousand pounds and having three ranges of load. Only two ranges, the 80,000-lb. range, graduated at 100-lb. intervals, and the 16,000-lb. range, graduated at 20-lb. intervals, were used in these experiments.

A load maintainer, which is an accessory of the testing machine, was utilized in holding the load constant over a period of time in order that creep or recovery could be developed. With the use of the load maintainer, no fluctuations in the load have been observed even when held overnight.

A stop-watch was used to measure the time intervals while observing creep or recovery.

Stress-Strain Recorder

An autographic recorder, the Microformer Stress-Strain Recorder, was used to provide a record of load versus specimen deformation measured over a gauge length of two inches. This apparatus consists essentially of two parts, the compressometer which is attached to the specimen and the microformer type recording equipment which produced autographic load-strain records of compression tests made parallel to the grain.

The recording equipment consists of a drum around which is wound a graph paper and a pen attached at the end of a push-rod which is in turn geared mechanically to the load indicating pointer of the testing machine. There are two coordinate axes in the graph; the load coordinate which is parallel to the axis of rotation of the drum and the strain coordinate which runs around the circumference of the drum. The load is marked by the pen which moves parallel to the axis of the drum while the drum rotates in proportion to specimen deformation.

The compressometer (Figs. 2 and 2a) includes a pair of gauge rings which are attached to the test specimen at a gauge length of two inches and a measuring assembly which measures the average values of displacement occurring between the gauge rings as the specimen is loaded. Each of the gauge rings is clamped to the test block by a pair of screws at points P and P_1.

The measuring assembly, which is also shown in Photograph 1, includes a heavy base supporting a vertical framework, two pairs of measuring arms and a microformer measuring unit. Each pair of measuring arms, upper arms and lower arms, pivots on a common axis A or A_1. Stable contact

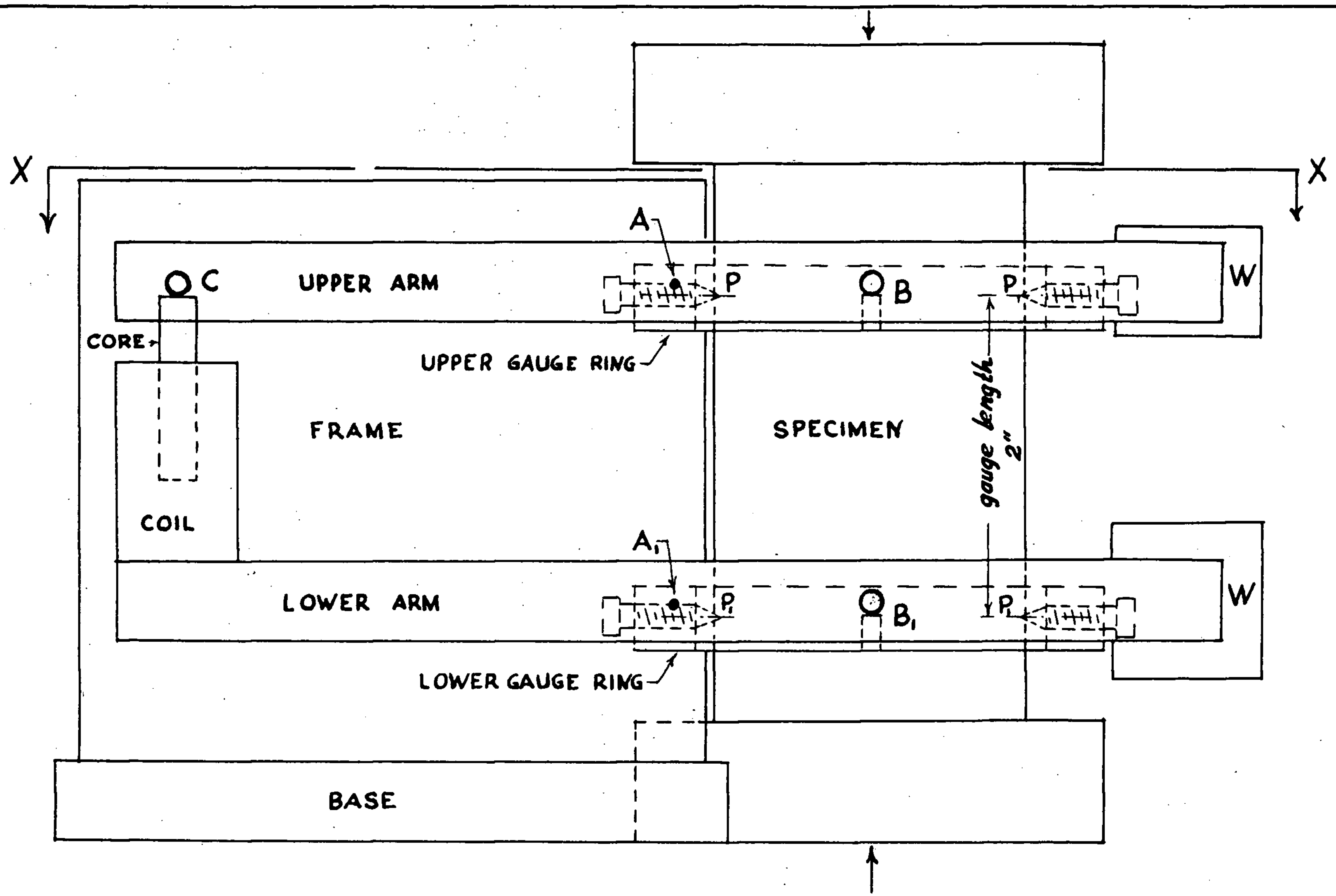
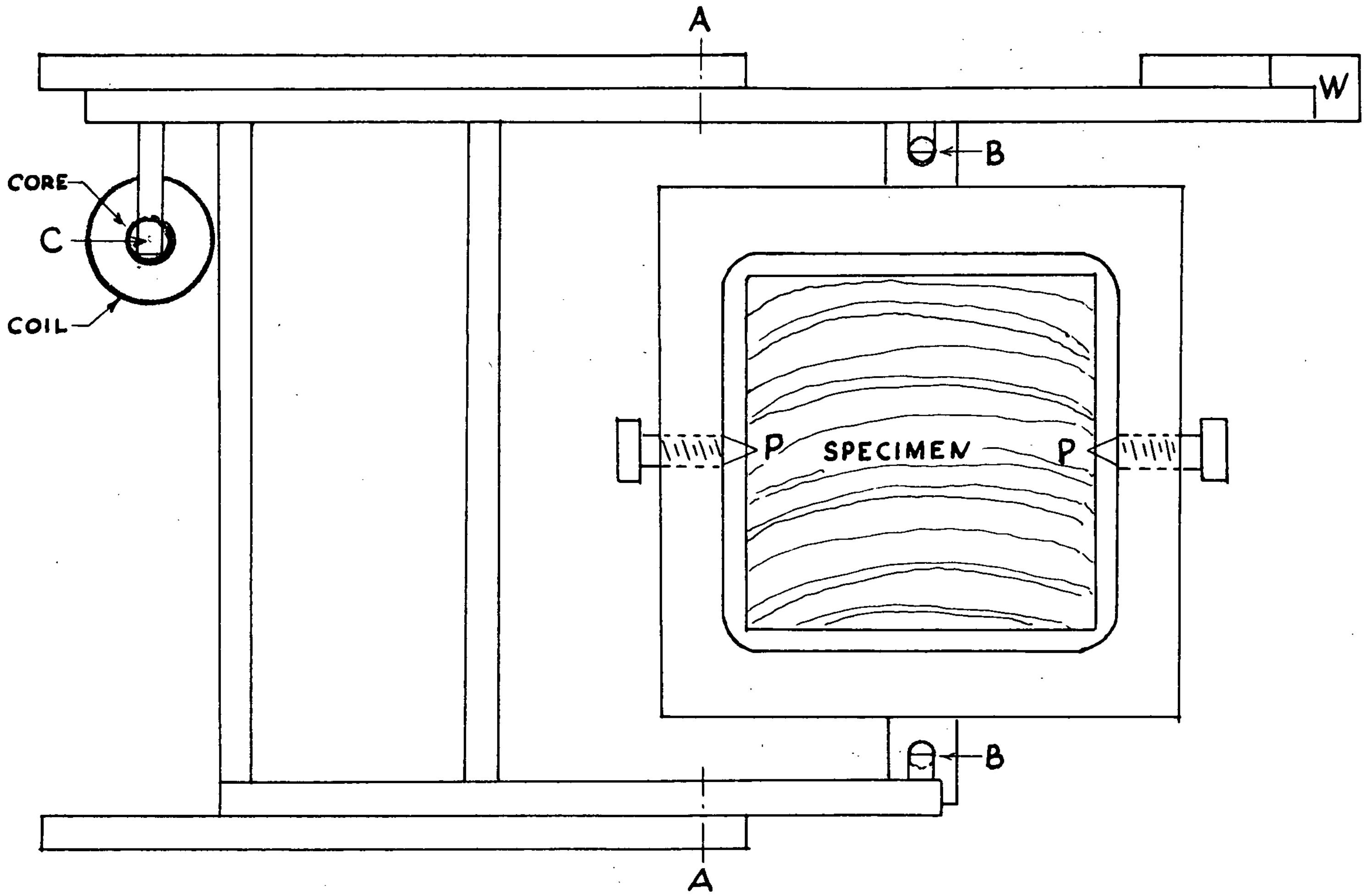
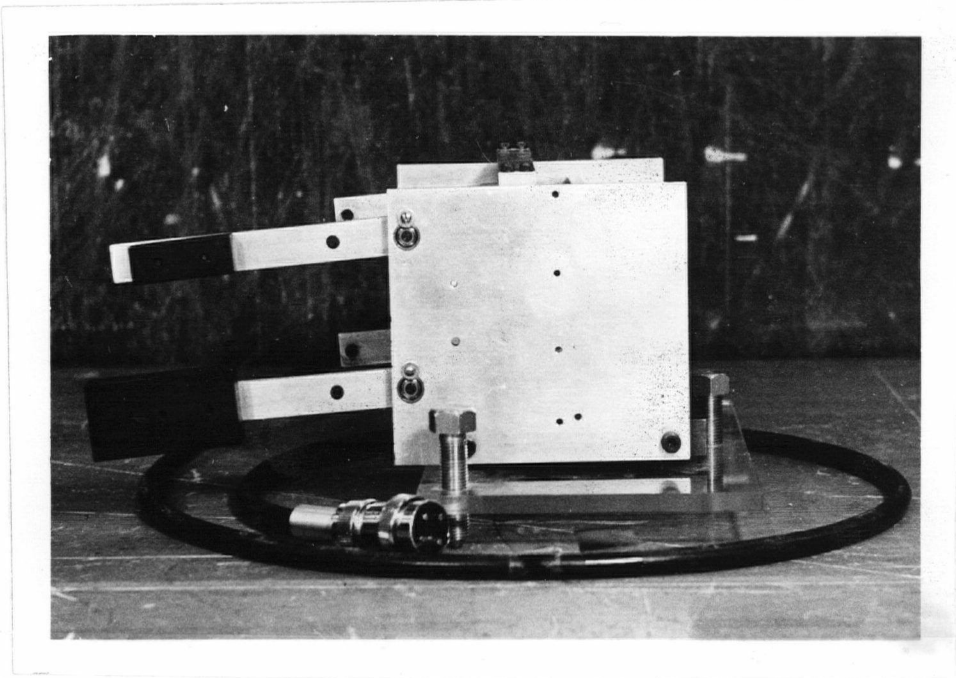


Fig. 2 - DIAGRAM OF COMPRESSOMETER



Section X-X
Fig. 2a



Photograph 1

Measuring assembly of compressometer

between the measuring arms and the gauge rings at points B or B_1 is maintained by the balance weights W.

The microformer measuring unit consisting of a coil unit and a movable core is fixed to the lower arm. The core, with a spring underneath, is forced to keep in contact with the upper arm at point C.

When the test specimen shortens under the action of the load, the distance between the gauge points P and P_1 decreases and the upper and lower arms rotate about their respective axes A and A_1 causing their rear ends to move farther from each other. This results in the movement of the core relative to the coil. This motion of the core in relation to the coil unit actuates the rotation of the drum in the recording equipment proportional to the deformation of the gauge length of the specimen.

Two of the three available strain magnification settings of the Stress-Strain Recorder were used in recording the longitudinal deformation occurring within the gauge length of two inches. These are the "Intermediate" and the "High" which correspond to strain scales of 1"~1000 micro-inches per inch and 1"~500 micro-inches per inch, respectively.

Lateral Deformation Apparatus

To measure lateral deformation, creep or strain recovery, either in the radial or tangential directions, a special apparatus was devised. This apparatus was designed and patterned after the one developed and used by Dr. A. Hrennikoff of the Department of Civil Engineering of the University of British Columbia for measuring the lateral strain and creep of a concrete cylindrical specimen.

As shown in Fig. 3, it consists of two channel-shaped steel collars A joined by two bent iso-elastic[4] strips which are fastened to the collars by means of small screws. The square ring formed by the collars and bent strips is clamped on the test specimens by two large thumb screws B passing through the mid-points of the collars. The iso-elastic springs form the sensitive elements which bend as the specimen undergoes distortion in the lateral dimension when it is subjected to a longitudinal compressive force. The bending strains in the iso-elastic springs are sensed by two Budd SR-4, Type CS-141-B electrical resistance strain gauges glued on the inner and the outer faces of both springs. All inside gauges C and separately all ouside gauges D are connected in series and attached to the active and compensating terminals of a Baldwin SR-4 Type L Strain Indicator whose readings are nearly proportional to the lateral strains in the specimen. With this arrangement, the inside gauges were also made active, but stressed differently from the outside ones. The indicator would then show the difference of the two strains which are of the opposite

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[4] Iso-elastic is an alloy of iron, nickel and chromium possessing particularly fine elastic properties.

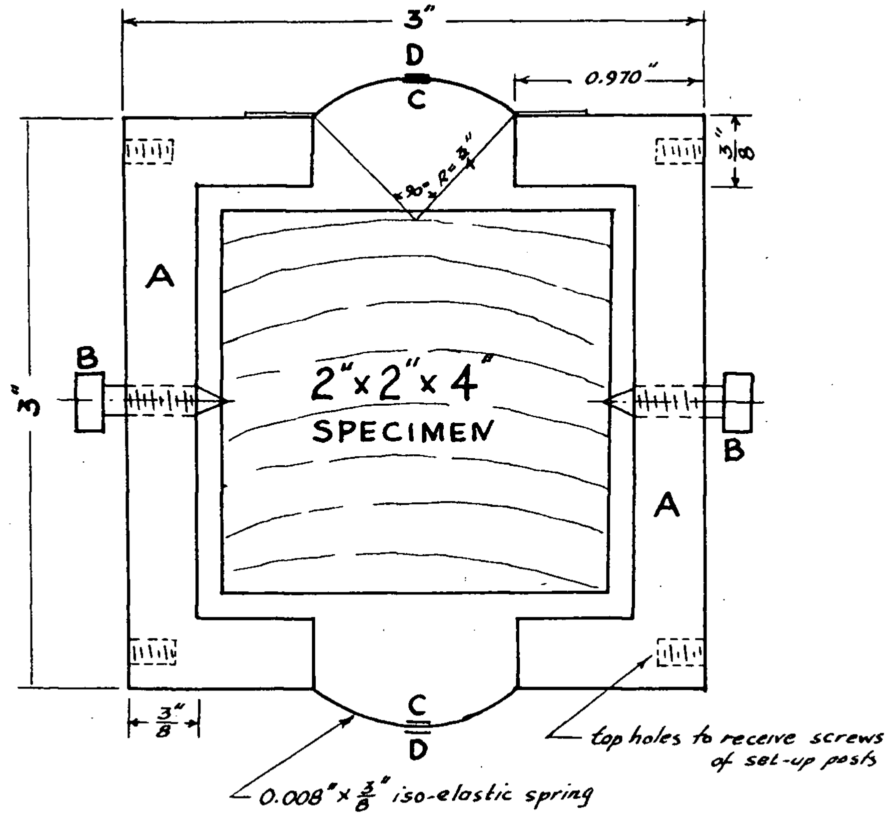


Fig. 3 - LATERAL DEFORMATION APPARATUS ATTACHED TO THE RADIAL SIDES TO MEASURE TANGENTIAL DEFORMATION

signs, thus increasing the sensitivity of the apparatus.

In order to be able to make simultaneous observations on the lateral strain, creep or recovery on both radial and tangential faces of the specimen, two apparatuses of this kind were made and used. It was also necessary to use a Baldwin switching and balancing unit to be able to read several gauges while using only one strain indicator.

The design of the lateral deformation apparatus consists mainly of determining the cross-sectional dimensions and geometry of the iso-elastic springs. Based on a useful range of strain of 3,000 micro-inches per inch, the spring was designed so that its stress will not exceed its elastic limit of 50 kips per square inch. In addition, a minimum force of about a third of a pound, was provided for as the initial force necessary to hold the apparatus in the specimen by friction alone.

When calibrated, the two apparatuses showed a sensitivity of 3.18 and 3.36 which means that a strain reading of 1 micro-inch per inch in the indicator corresponds to a strain of 3.18 or 3.36 micro-inches per inch on the test specimen.

Calibration of the apparatus was done by means of a 2-inch diameter cold rolled steel cylinder the lateral strains of which are known from strain gauges mounted directly on the cylinder.

Part V

EXPERIMENTAL PROCEDURE

Measuring and Weighing of Test Specimens

Immediately before testing, each specimen was weighed to an accuracy of 0.01 gram and its cross-sectional dimension and length measured to the nearest 0.01 inch. After weighing and measuring, it was carefully wrapped and sealed completely with Saran Wrap, a polyvinyl plastic film, in order to prevent any increase or decrease in the moisture content of the specimen while the testing was in progress.

Immediately after each creep-recovery test, the specimen was weighed again to determine whether or not there was any change in moisture during the test. When a variation in weight of more than 1% was found, the test was cancelled. The change in weight before and after testing of the test specimens reported in this work was found to have a maximum value of only 0.3% which is an indication of the effectiveness of wrapping the specimens with Saran Wrap.

Preparing the Specimen for Testing

The proper attachment to the test specimen of the four rings (two lateral deformation rings and the two compressometer rings) was accomplished with the aid of four set-up posts, which, together with the rings, formed a rigid frame (See Photograph 2). One lateral deformation ring is clamped on the tangential sides of the test block to measure strain in the radial direction and the other on the radial faces to measure tangential distortion. Centre to centre distance of these two rings is five-eights of an inch and they are placed equidistant from the upper and lower compressometer rings. The posts are removed when the rings have been securely attached in their respective positions.

Photograph 2 shows the four rings and the set-up posts forming a rigid frame before attachment to the specimen. Photograph 3 shows the rings attached to the specimen.

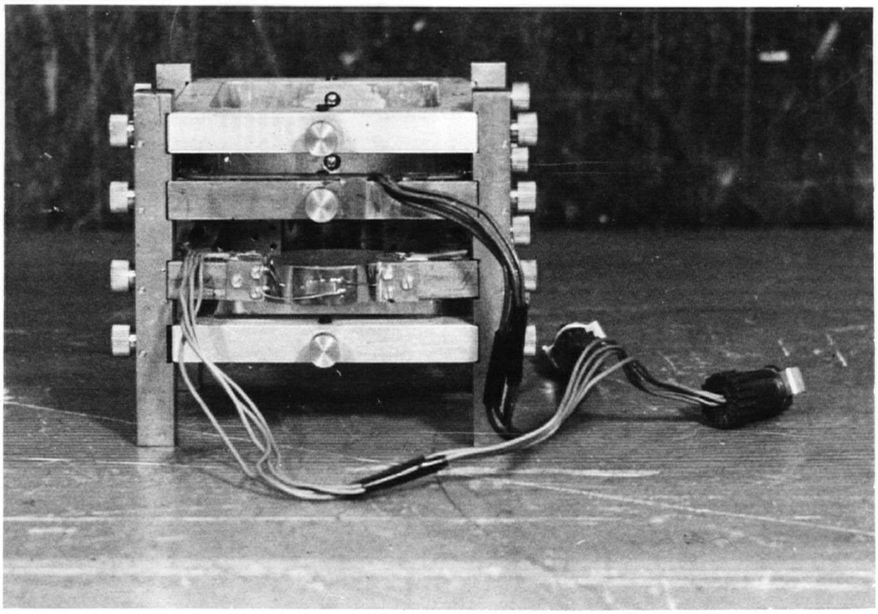
Compression Tests of Control Specimens

Initially, one end-matched control specimen was taken at random from each condition and tested in compression parallel to the grain according to standard procedures, except that the special compressometer was used to measure a deformation over a 2-inch gauge length. The specimen was subjected to progressive loading until failure, the rate of loading being maintained at a constant speed of approximately 0.012 inch per minute as per ASTM specifications. This gives the rate of loading from the following formula:

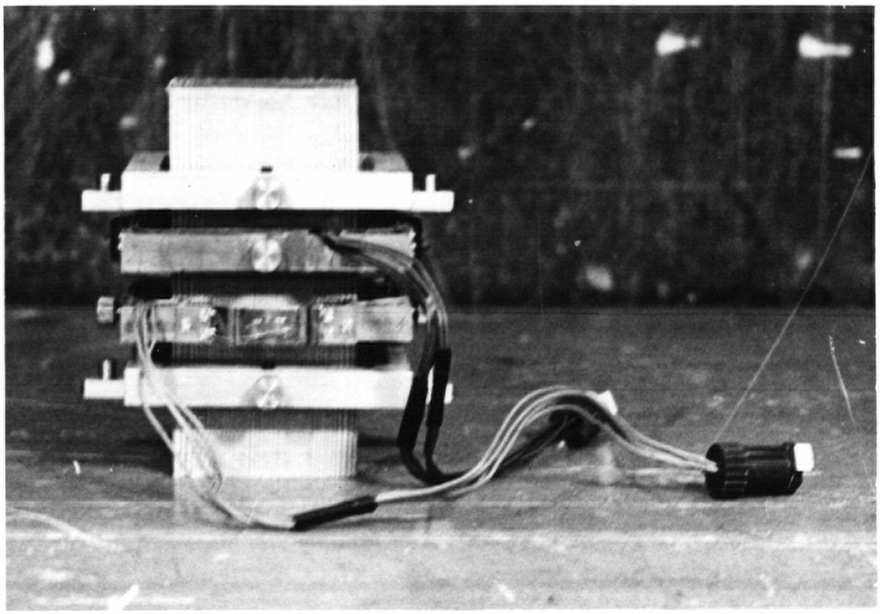
$$n = Z \times \ell$$

where n = speed of the movable head of the machine in inches per minute.
Z = rate of fibre strain per inch of fibre length
ℓ = length of compression specimen

The value commonly used for Z is 0.003, therefore, n = 0.012 inch per minute.



Photograph 2
Lateral deformation and compressometer rings rigidly connected with four set-up posts before attachment to a specimen.



Photograph 3
Lateral deformation and compressometer rings shown in their proper positions on the specimen.

While the recorder made possible the continuous and automatic recording of the load-axial strain graph, at least two persons were needed for the test, one reading the load and the other reading and recording the lateral strains from the strain indicator. The lateral strains were then plotted against load. From these sets of load-deformation curves, the two Poisson's ratios, μ_{LR} and μ_{LT} , were calculated. The Poisson's ratio μ_{LR} or μ_{LT} represents the numerical value of the ratio of the strain along the radial or tangential direction to that along the longitudinal direction due to a compressive stress parallel to the grain.

The results of these tests established the ultimate crushing strength of each of the three conditions of testing and permitted a selection of the various fixed stress-levels to which the other specimens were to be loaded in a stepwise manner.

Step-by-Step Creep and Recovery Tests

In this type of test the specimen was subjected to compression parallel to the grain in successive steps at the desired various stress levels. A very rapid rate of loading was used so that no creep would come into play during the application of the load. The time of loading from one stress-level to the next higher one was about five seconds.

At every designated level of stress, the load was sustained for a desired period of time to record the creep strain along the three perpendicular axes, after which the load was raised to the next step and at successively higher stress levels according to the loading schedule given in Tables 1, 2 and 3. Several load levels, chosen arbitrarily, were used, ranging from 13 to 91 per cent of the control's maximum load for the air-dry specimens, from 24 to 96 per cent for the intermediate conditions and from 23 to 81 per cent for the green specimens.

As in the testing of the control specimens, the load axial-strain relation was recorded automatically, and lateral strains, both in the radial and tangential directions, were read from the strain indicator and recorded throughout the duration of the test. In addition, time intervals were noted on the load-axial strain graph while simultaneous readings were made for any change of deformation in the lateral directions.

Creep was observed and recorded under a sustained loading for a minimum period of five minutes in some stress levels and a maximum of twenty-five hours at other levels of load. Measurements of creep were made every minute for the first five or ten minutes, every two or three minutes for the next ten or twenty minutes, and then as the creep rate became smaller, at convenient random time increments.

After stressing to a selected maximum stress-level had been completed, the specimen was unloaded in a similar step-by-step manner (See Tables 1, 2 and 3 for unloading schedule).

Table 1 - SCHEDULE OF STEP-BY-STEP LOADING-UNLOADING TESTS (AIR-DRY CONDITION)

Load Level	LOADING									UNLOADING					
kips	4	8	12	16	18	20	22	24	28	20	16	12	8	4	0
Per cent of max. load of controls	13	26	39	52	59	65	72	78	91	65	52	39	26	13	0
Specimen	Time duration of sustained load at each load level in minutes														
A-1-5		5	5	5		20		225			5	5	5	20	330
A-1-7		5	15	15		20		15			5	5	5	15	180
A-1-4	5	5	5	5	1510		1500				5	5	5	15	3095
A-1-3(a)		5	30	25									25	30	135
(b)		5	15	25		35						5	15	35	195
(c)		5	15	15		15		15	5	5	5	5	5	10	135

Table 2 - SCHEDULE OF STEP-BY-STEP LOADING-UNLOADING TESTS (INTERMEDIATE CONDITION)

Load Level	LOADING						UNLOADING		
kips	4	8	10	12	15	16	8	4	0
Per cent of max. load of controls	24	48	60	72	89	96	48	24	0
Specimen	Time duration of sustained load at each load level in minutes								
M-1-2	5	60		60			5	5	215
M-1-9	5	5		5	75		5	10	145
M-1-3	5	20		30		10	5	15	155
M-1-10	5	5		5	1040		10	20	1250
M-1-4(a)	5	5	30					10	75
(b)	5	5	5	60			5	10	150
M-1-7(a)	5	5		30			5	10	70
(b)	5	5		5	30		5	10	115

Table 3 - SCHEDULE OF STEP-BY-STEP LOADING-UNLOADING TESTS (GREEN CONDITION)

Load Level	LOADING					UNLOADING		
kips	4	8	10	12	14	8	4	0
Per cent of max. load of controls	23	46	58	69	81	46	23	0
Specimen	Time duration of sustained load at each load level in minutes							
G-1-9	5	10		10		5	10	75
G-1-5	5	5	962				20	1025
G-1-3	5	20	20	10		5	5	90
G-1-6	5	15	30	10		5	15	135
G-1-7(a)	5	25	25				10	95
(b)	5	25	25	25	15	5	10	150

(a) 1st. cycle of repetitive loading.
(b) 2nd. cycle of repetitive loading.
(c) 3rd. cycle of repetitive loading.

Longitudinal and lateral strain recovery - the creep on the unloading part of the cycle - were observed and recorded following the same technique used in creep observation.

Finally, the same specimen was tested in a continuous operation without stops to failure at a machine speed of 0.012 inch per minute. Each test was continued until the load fell well below the maximum. This final test was done only after there was no further discernible recovery taking place in the specimen in its unloaded state after a considerable length of time which was in all cases equal or more than the testing time.

Repetitive Loading

In this test, the specimen was loaded as in the previous step-by-step creep and recovery tests. Then after being unloaded, the specimen was loaded again in a similar step-wise fashion. For each succeeding loading cycle the selected maximum stress-level was made higher than that of the previous one. Specimens tested in this type of repetitive loading were not reloaded until strain recovery, both axial and lateral, was virtually complete. A recovery period of at least two hours at the unloaded state was allowed between loading cycles. As before, each specimen was finally loaded to failure.

Part VI

MOISTURE CONTENT AND SPECIFIC GRAVITY DETERMINATION

The moisture content and specific gravity of each test specimen were determined from a small sample taken adjacent to the point of failure.

Moisture Content

The moisture content was determined by the oven-dry method in the following manner:

(1) After each final test, and after weighing the specimen, a moisture sample about an inch in thickness was taken and cut into sections as shown in Fig. 4. Moisture determinations were made for the core and each of the shells separately in order to determine the moisture distribution at the cross-section of the block.

(2) Immediately after sawing, all loose splinters were removed and each section was weighed to the nearest 0.01 gram by means of a Mettler type balance graduated to the nearest 0.10 gram but which could be read by interpolation to the nearest 0.01 gram.

(3) The material was then put into a thermostatically controlled electric oven heated at 212° F and dried until there was no variation in weight for a period of twenty-four hours.

(4) Upon attaining this condition of constant weight, i. e., when all the moisture had been evaporated, the material was again carefully weighed.

(5) The loss in weight expressed in per cent of the oven-dry weight indicates the moisture content of the specimen from which the sample was cut.

The variation in moisture content between the core and shells was limited to 0.1 %.

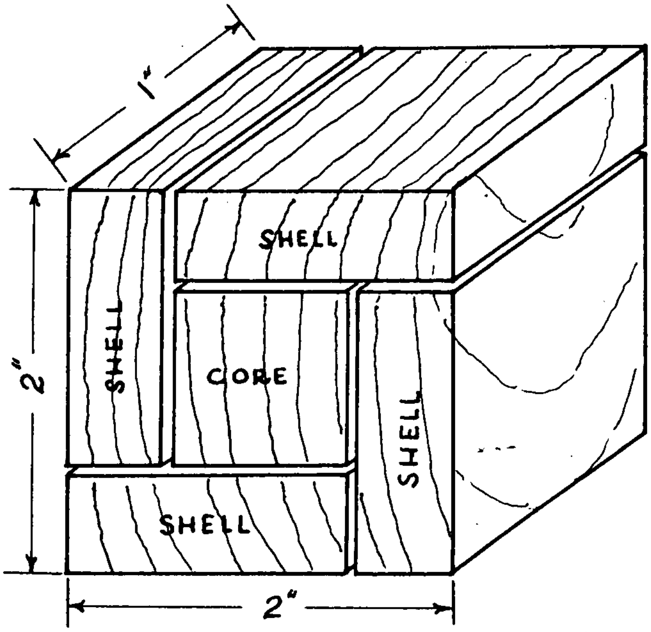


Fig. 4 - METHOD OF CUTTING MOISTURE SAMPLE FOR DETERMINATION OF SHELL AND CORE MOISTURE DISTRIBUTION

Specific Gravity

The specific gravity for each specimen was calculated to the nearest 0.001 on the oven-dry weight, volume at test basis.

Part VII
RESULTS AND DISCUSSIONS

Creep and Recovery

Creep and recovery data, both axial and lateral, obtained from tests in compression parallel to the grain at the four moisture content conditions investigated are presented in Tables 4 and 5.

In general, creep, in the longitudinal and lateral directions, was found to be more marked in the green specimens than in either the intermediate or air-dry condition. The only oven-dry specimen showed lesser creep than the air-dry ones.

Apparently, creep in wood is due mainly to the moisture present in the cell walls. Upon application of the load, water in the walls is compressed so as to carry part of the load. While the load is held constant, the moisture is forced into the cell cavities and the pressure is relieved. The load, previously carried by the compressed water is transferred to the fibrous material, thus causing further deformation. The reason that the oven-dry specimen still showed some creep is probably due to the fact that all the moisture was not expelled.

During the rise in load, the specimen undergoes an increase in the lateral directions. When the load is sustained for a period of time, lateral creep occurs usually in the sense of bulging. In some cases, however, the lateral creep occurred in the opposite direction. This unusual phenomenon, in which the lateral dimension tends to contract instead of expanding further under a sustained longitudinal compressive stress, and which we will now call negative creep, has been observed to be more marked and predominant in the green specimens than in the specimens of intermediate moisture content. For the latter, only one, usually the upper level, in three stress levels at which creep was observed showed negative creep while in the green condition almost all of the stress levels showed negative creep.

Similar phenomena were also observed in the unloading part of the test. When the stress is reduced or released, a decrease in the lateral directions occurs, and a further contraction usually develops during the period of sustained load. At the low levels of stress in the intermediate and green conditions, however, an expansion in the lateral dimensions was noted during recovery following unloading. Again we will term this as negative recovery. As with negative creep, there was a preponderance of negative recovery observed in the green specimens.

However, not all the stress levels under which negative creep was recorded exhibited a similar negative recovery. For example, in Specimen M-1-2, there was a consistent negative creep both in the radial and tangential directions but no negative recovery either radially or tangentially was recorded. This was also found to be true with Specimen G-1-3 (Fig. 15), but in the tangential direction only. On the other hand, the creep and recovery in the two lateral directions of Specimen G-1-6 (Fig. 16) were found to be both negative. Such is the case, too, with Specimens M-1-4 and G-1-3 in their radial directions.

Since neither negative creep nor recovery was observed in the air-dry specimens tested and because such behaviour was found to have occurred more in the green than in the intermediate condition, it becomes obvious that the moisture content of the specimens had something to do with the negative creeping and recovery. It seems that during the rapid application of the load, pressure in the water within the cell structure builds up causing lateral expansion in addition to the normal distortion of the wood substance. When the load is sustained, some moisture finds its way into adjoining cavities. The water pressure in the cell walls is thus reduced, resulting in the lateral contraction of the fibres. Hence, negative creep is developed. Negative recovery can be explained in the same way. After reduction or removal of the load, suction is developed and the moisture is attracted back to the cell walls, thus causing lateral expansion during the period of sustained load.

Creep-Time Relationships

For each individual test specimen, axial creep values, expressed as percentages of the total elastic strain, from zero load to the stress level of the creep, were plotted against time at every creep level and smooth curve lines were fitted visually. The stress levels are expressed as percentages of the specimen's actual maximum crushing stress. By way of explanation, the specimen's actual maximum crushing stress, as used here, is the ultimate strength obtained from the static compression parallel to the grain test performed after the specimen had been subjected to the step-by-step creep and recovery tests as described earlier. Due to the natural variability of wood, and due to the effect of the first type of testing, the actual stress levels, expressed as the percentages of the ultimate compressive strength of each specimen, differed somewhat from the assumed stress levels which were based on the compressive strength of the control specimens.

Typical creep curves showing the relationship of creep-percentage-of-elastic-strain and time, under various stresses, are shown in Figs. 5 and 6 for the air-dry specimens, in Figs. 7 and 8 for the intermediate condition, and in Figs. 9 and 10 for the green specimens. Each set of curves is the result of a test with an individual specimen.

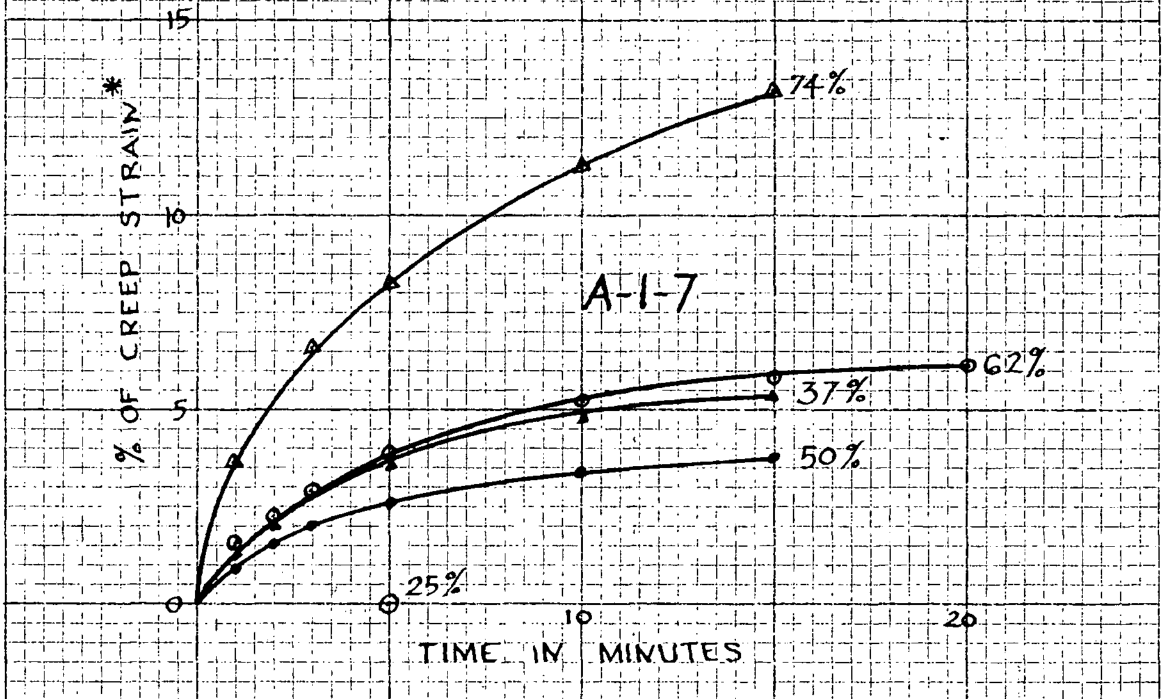


FIG. 5 - AXIAL CREEP - TIME RELATIONSHIP AT DIFFERENT STRESS LEVELS AIR-DRY SPECIMEN IN COMPRESSION PARALLEL TO GRAIN STEP-BY-STEP LOADING.
STRESS LEVELS ARE SHOWN AS PERCENTAGES OF ITS ACTUAL CRUSHING STRENGTH.

*CREEP STRAIN AS PERCENTAGE OF TOTAL ELASTIC STRAIN UP TO EACH PARTICULAR STRESS LEVEL.

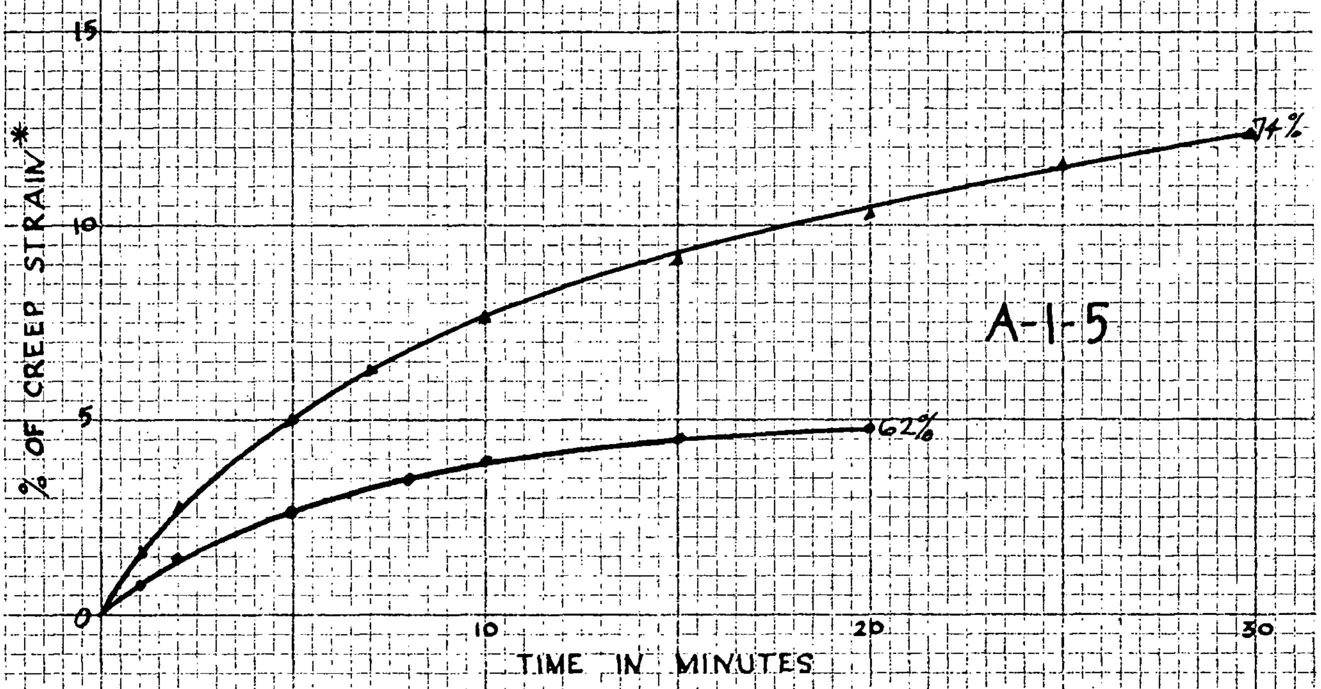


FIG. 6 - AXIAL CREEP-TIME RELATIONSHIP AT DIFFERENT STRESS LEVELS AIR-DRY SPECIMEN IN COMPRESSION PARALLEL TO GRAIN STEP-BY-STEP LOADING. STRESS LEVELS ARE SHOWN AS PERCENTAGES OF ITS ACTUAL CRUSHING STRENGTH.

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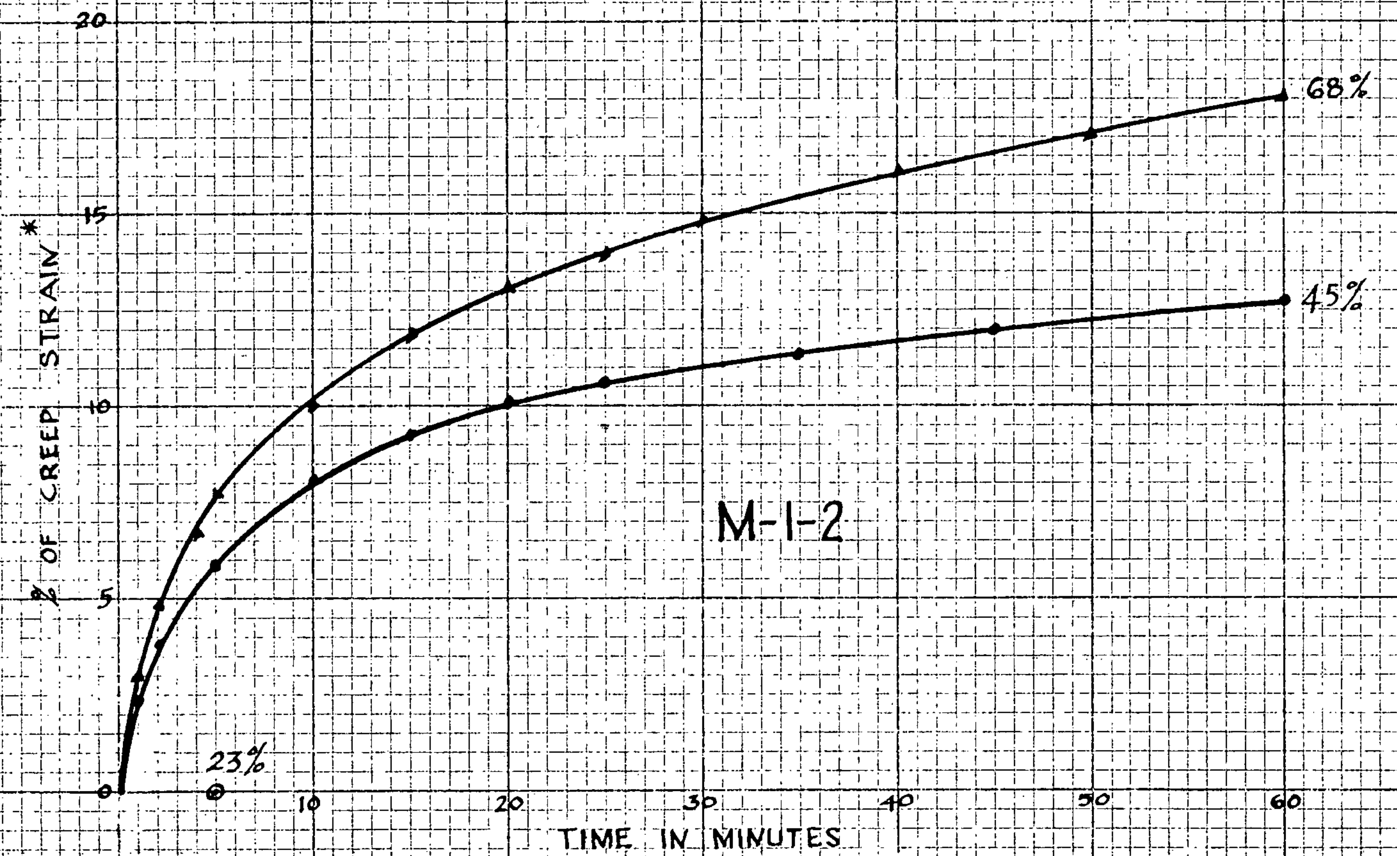

FIG. 7 - AXIAL CREEP-TIME RELATIONSHIP AT DIFFERENT STRESS LEVELS. INTERMEDIATE AIR-DRY - GREEN SPECIMEN IN COMPRESSION PARALLEL TO GRAIN. STEP-BY-STEP LOADING. STRESS LEVELS ARE SHOWN AS PERCENTAGES OF ACTUAL CRUSHING STRENGTH.

*CREEP STRAIN AS PERCENTAGE OF TOTAL ELASTIC STRAIN UP TO EACH PARTICULAR STRESS LEVEL.

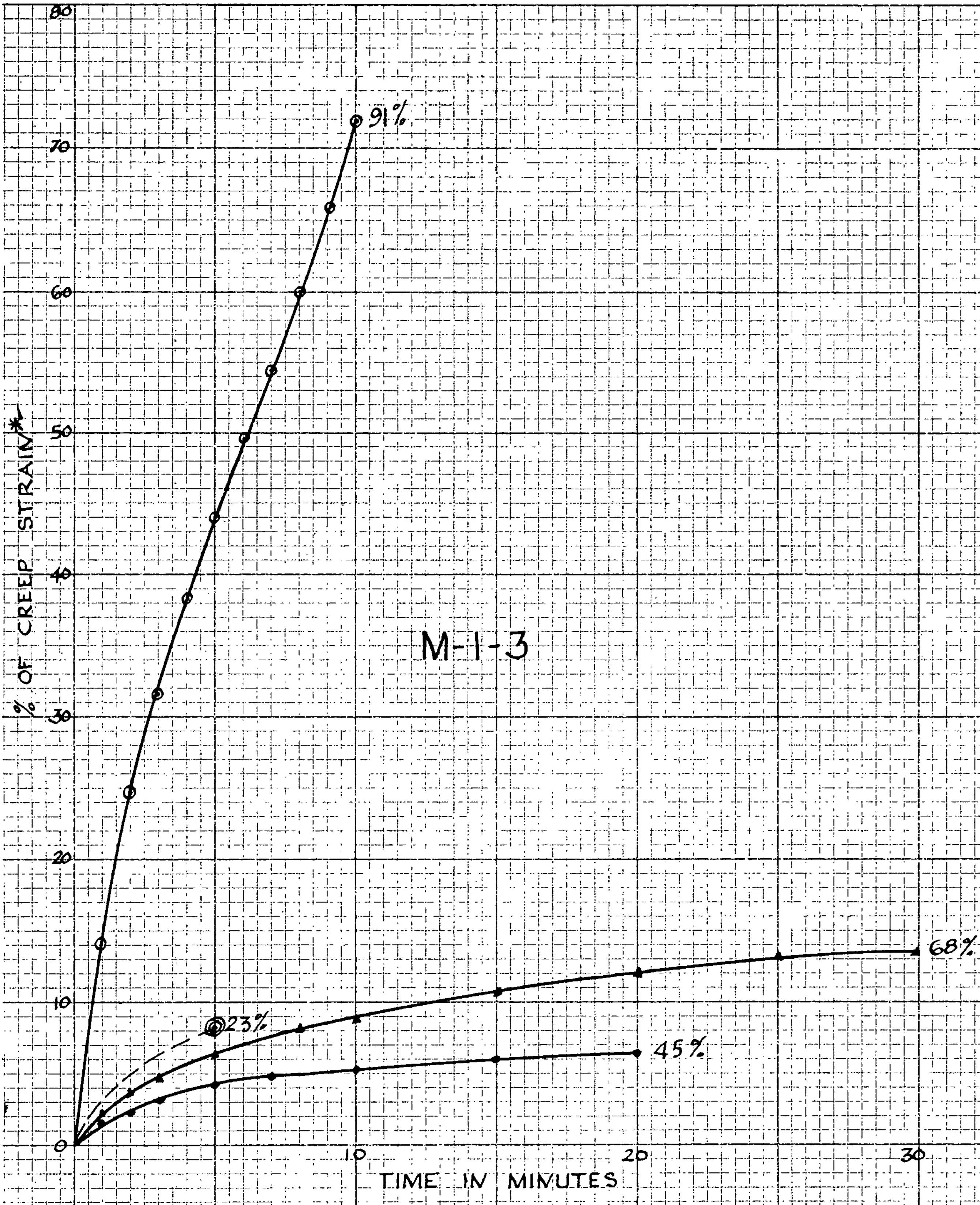

FIG. 8 - AXIAL CREEP-TIME RELATIONSHIP AT DIFFERENT STRESS LEVELS INTERMEDIATE AIR-DRY - GREEN SPECIMEN IN COMPRESSION PARALLEL TO GRAIN STEP-BY-STEP LOADING. STRESS LEVELS ARE SHOWN AS PERCENTAGES OF ITS ACTUAL CRUSHING STRENGTH.

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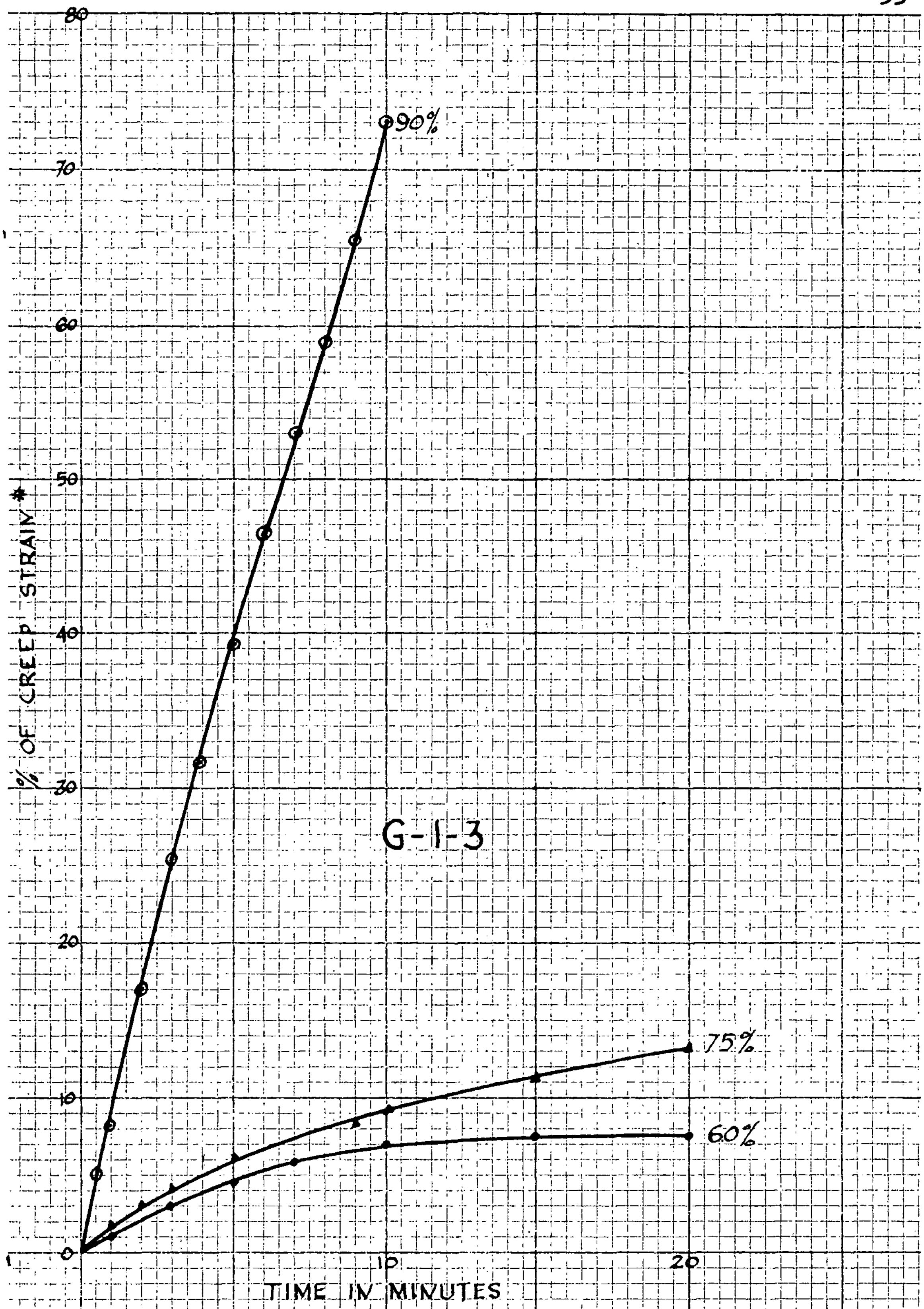

FIG. 9 - AXIAL CREEP-TIME RELATIONSHIP AT DIFFERENT STRESS LEVELS GREEN SPECIMEN IN COMPRESSION PARALLEL TO GRAIN STEP-BY-STEP LOADING. STRESS LEVELS ARE SHOWN AS PERCENTAGES OF ITS ACTUAL CRUSHING STRENGTH.

*CREEP STRAIN AS PERCENTAGE OF TOTAL ELASTIC STRAIN UP TO EACH PARTICULAR STRESS LEVEL.

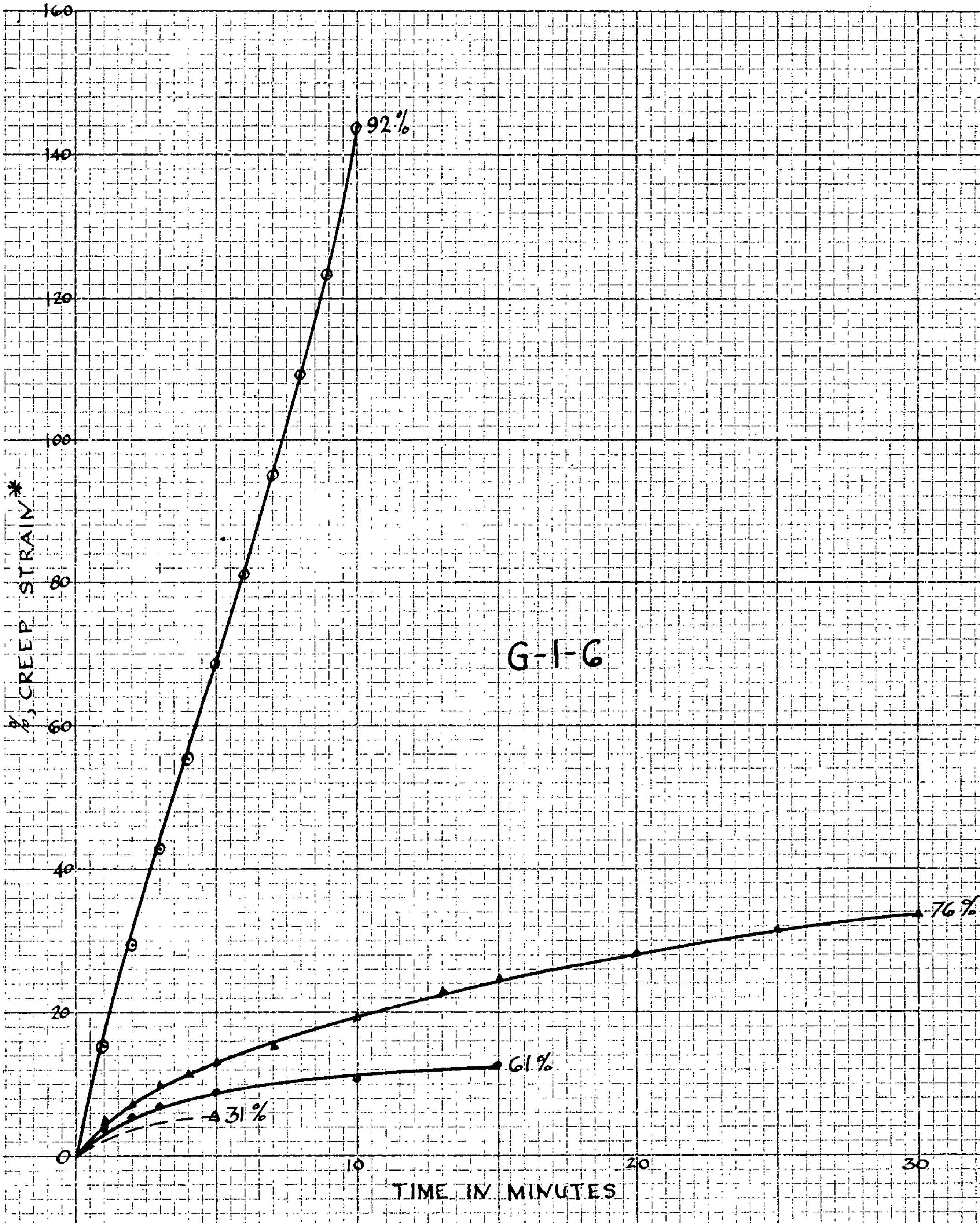

FIG 10 - AXIAL CREEP-TIME RELATIONSHIP AT DIFFERENT STRESS LEVELS GREEN SPECIMEN IN COMPRESSION PARALLEL TO GRAIN STEP-BY-STEP LOADING. STRESS LEVELS ARE SHOWN AS PERCENTAGES OF ITS ACTUAL CRUSHING STRENGTH.

*CREEP STRAIN AS PERCENTAGE OF TOTAL ELASTIC STRAIN UP TO EACH PARTICULAR STRESS LEVEL.

At about 90% stress level it appears that there is a rapid increase in creep, first at a decreasing rate, then at a constant rate and finally again at an increasing rate. Although none of the specimens was allowed to fail under a constant load, other investigators (8) have pointed out that the increase in the rate of creep is a sign of imminent failure.

Continuous deformation at a diminishing rate, until an almost constant value is ultimately reached, is characteristic of the creep curves for stress levels up to about 70%. These curves are relatively flatter than those of the 70 - 77% stress levels. Within the stress levels and time range used in this investigation, these curves indicate that creep proceeds rapidly for the first few minutes after which the rate gradually diminishes with increasing time.

Coefficient of Lateral Deformation

A specimen subjected to a compressive force undergoes deformation not only in the direction of the applied load but also in the lateral direction. Within the elastic limit of the material, the ratio of these deformations, lateral to longitudinal, is commonly known as the Poisson's ratio. In wood, this elastic property is obtained from standard tests made at a uniform rate of loading.

Similar ratios are given in Tables 6 and 7. They are herein referred to as the coefficients of lateral deformation, $\mu = \frac{\Delta\epsilon_{Lateral}}{\Delta\epsilon_{Longitudinal}}$. These are of two kinds, namely, the ratio of strain increments for the change in load and the ratio of strains during the period of creep or recovery.

In order to distinguish them from the usual Poisson's ratios, μ_{LR} and μ_{LT} , we designate the coefficients of radial and tangential deformation by μ_R and μ_T , respectively.

Typical μ diagrams are presented in Figs. 11 and 12 for the air-dry specimens, in Figs. 13 and 14 for the intermediate condition and in Figs. 15 and 16 for the green condition. Fig. 17 is that of the oven-dry specimen.

The values of the coefficient of lateral deformation, both radial and tangential, during the period of creep are entirely different from those during the load rise, indicating that the corresponding deformations are entirely different. In all the specimens tested, the μ's for the period of creep showed consistently lower values than those for the change in load.

At almost all stress levels, the coefficient of tangential deformation exhibited a higher value than its radial counterpart. This is probably due to the medullary rays running radially in the wood which restricts its deformation in the radial direction.

During the loading part of the cycle, some of the sum $\mu_R + \mu_T$ have been observed to be greater than one, indicating that the material in a way opens up. On the other hand, the negative sum $\mu_R + \mu_T$ indicates a reduction in volume of the material.

Whenever feasible, the μ's during the period of creep were calculated separately for different parts of time intervals. These values appear to become smaller with increase in time for the intermediate condition while the reverse is true for the air-dry condition.

Step-wise Loading and Modulus of Elasticity

Illustrated in Graphs 1, 2, 3, 4, and 5 are typical graphs traced automatically by the stress-strain recorder during the step-wise creep-recovery tests in compression parallel to the grain. At each level of load, short vertical lines were drawn on the horizontal portions of the graphs. These represent time increments in minutes during which creep or recovery, axial or lateral, was recorded. Whenever there was measurable creep or recovery, marking was done every minute for the first five or ten minutes, every two or three minutes for the next ten or twenty minutes, and so on, the time intervals gradually increasing thereafter.

Due to the rapid rate at which the load was raised, the load axial deformation relationship was, for all practical purposes, linear on each load increment. Such a linear behaviour was observed to exist in some specimens even up to stress regions beyond the standard proportional limit of the material, where it would normally plot as a curved line under the ordinary rate of testing. Graphs 2 and 4, with load levels up to 95 and 92 per cent of the specimen's actual strength, respectively, will serve to illustrate the foregoing statement.

Obviously, the curved portion of a stress-strain graph as ordinarily obtained by the conventional testing method, is mainly due to creep that is taking place within the duration of the loading time.

In general, however, the slopes of the straight lines between two consecutive loads for each graph are not of equal magnitude. As one goes from one interval to the next higher interval, the slopes have a tendency to become smaller, though not consistently so. Consequently, because the modulus of elasticity is directly proportional to the slope, a similarly decreasing Young's modulus is evident from the figures in Table 6.

In the air-dry specimens, the decrease in the modulus of elasticity was of the order of 2 to 6 per cent with the exception of Specimen A-1-3 where a 12% reduction was noted from the first- to the second-step interval. Generally, the percentage decrease was greater in the intermediate condition and slightly higher for the green specimens, the former having a maximum reduction of 21% and the latter a maximum of 26%.

The said linearity in the graphs is also evident during unloading, although to a lesser degree, especially during the last unloading step where a pronounced curvilinear graph has been observed in all the intermediate and green specimens.

This curvilinear characteristic could be attributed to the moisture in the wood. Upon release of the load, suction is developed causing tension in the water at first and finally the water that had been forced out of the cell walls during the period of creep, is reverted. This accounts to the curvature of the unloading curve.

It will also be observed from the same graphs that in the formation of the hysteresis loop, the strain for a given load increment is generally greater upon releasing the stress than upon applying it. Or, putting it in another way, the modulus of elasticity is smaller on release of a load than on its application. This seems to indicate that upon decrease or removal of the compressive stress, there is, in addition to the elastic strain, an immediate recovery of a portion of the creep. This was found to be true in all the specimens tested in the intermediate and green conditions while the air-dry specimens did not show such a consistent trend.

Effect of Creep-Recovery Tests on the Subsequent Stress-Deformation Relation

Graphs 6, 7, 8 and 9 are examples of typical graphs showing the load-axial and load-lateral strain relationships obtained from a compression parallel to the grain test done at a uniform testing rate of about 0.012 inch per minute. As in the other graphs, the load-axial curve was automatically recorded while the two other graphs (radial and tangential) were plotted from experimental data obtained through the strain indicator.

With the exception of Graph 6, which is that of a control specimen, these graphs are all from specimens that have been previously subjected to the creep and recovery tests. It will be noticed from the last two graphs, which are those of the intermediate and green conditions, respectively, that the load-axial curves show a deviation from straightness almost from the origin, although the curvature is not very pronounced. This characteristic is present in all the curves of the intermediate and green specimens.

Graph 7, on the other hand, is typical for the air-dry specimens, with the exception of Specimen A-1-5, which also exhibited a non-proportional stress-strain relationship similar to that of either Graph 8 or 9. All the curves, however, showed a definite peak that indicated maximum load from which the maximum stress and strain values as given in Table 8 were obtained.

Also included in Table 8 are the moisture content and specific gravity of each specimen, and the modulus of elasticity and Poisson's ratios of the controls. From this table a comparison of the properties of the individual specimens with those of their corresponding controls can be made. All the air-dry specimens tested have shown higher ultimate compressive strength than their controls, the increase being of the order of 4 to 8 per cent. Likewise, for the intermediate condition, all but two showed greater strength than their controls, the percentage of increase varying from 5 to 16. For the green specimens, the opposite result was obtained that is, the control showed higher crushing stress. A reduction of about 20 per cent was noted in all but one of the green specimens.

All the specimens tested at the three moisture conditions (air-dry, intermediate and green) exhibited strains at maximum load consistently greater than those of their respective controls.

Permanent Set

Axial and lateral (radial and tangential) permanent set and strain recovery expressed as percentage of the axial creep are tabulated in Table 9.

Each of the residual strain values was taken at the time when no more measurable recovery was taking place. From the table it will readily be observed that, in all cases, more than half of the axial creep that had taken place had been ultimately recovered. Hence, creep of wood could then be classified into two kinds, namely, recoverable creep which other workers have considered as an elastic after-effect or delayed elasticity, and permanent creep or plastic deformation. Recoverable creep in the lateral direction was not determined because of the accidental disturbance of the lateral deformation apparatus at the end of the test.

Conclusions

The more important conclusions in this investigation are as follows:

1. Creep, both longitudinal and lateral, in the green specimens was, in general, more marked than in either the intermediate or air-dry condition. The oven-dry specimen showed creep response less than that of the air-dry specimens. Creep, therefore, could be attributed mainly to the presence of moisture in the cell walls.

2. Negative creep and negative recovery in the lateral directions observed in the intermediate and green conditions were due to moisture present in the cell walls.

3. Values of the coefficient of lateral deformation, $\mu = \frac{\Delta \epsilon_{Lateral}}{\Delta \epsilon_{Longitudinal}}$ (both radial and tangential), during the load rise are entirely different from those during the period of creep, indicating that the corresponding deformations are entirely different. The μ in the tangential direction is usually greater than the μ in the radial direction. This is probably due to the medullary rays running radially in the wood which somehow restrict its deformation in that direction.

4. Decreasing moduli of elasticity have been observed during loading at successively higher stress levels.

5. Stress-strain curves from final tests of the intermediate and green specimens were found to be curvilinear from the beginning of loading, although the curvature was not very pronounced.

6. More than half of the longitudinal creep that had developed was ultimately recovered in all the specimens tested.

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Table 8- VALUES FROM FINAL STATIC TESTS IN COMPRESSION PARALLEL TO GRAIN FOLLOWING CREEP-RECOVERY TESTS

Specimen	Moisture Content (%)	Specific Gravity	Max. Stress (psi.)	Max. Strain (micro-in./in.)	Modulus of Elasticity (1000psi)	Poisson's Ratio μ_{LR}	Poisson's Ratio μ_{LT}
O-1-1	oven-dry	0.472	11,400	12,200			
CA-1-6*	9.6	0.497	7300	6000	1890	0.372	0.402
A-1-5	9.6	0.504	7860	7300			
A-1-7	10.2	0.541	7760	11,050			
A-1-4	9.3	0.492	7750	6700			
A-1-3	9.6	0.492	7600	6200			
CM-1-1*	19.9	0.491	4190	4400	1610	0.210	0.596
M-1-2	20.8	0.491	4400	4800			
M-1-9	20.3	0.518	3720	4720			
M-1-3	21.8	0.490	4400	5500			
M-1-10	20.0	0.541	4850	7900			
M-1-4	20.0	0.500	4180	4650			
CG-1-10*	63.0	0.547	4100	3850	2000	0.342	0.651
G-1-9	46.9	0.545	3290	4300			
G-1-5	60.5	0.498	3280	6240			
G-1-3	65.5	0.504	3320	4250			
G-1-6	62.1	0.499	3250	6600			
G-1-7	57.4	0.547	3900	4850			

* Control specimens were not subjected to creep-recovery tests.

Table 9- PERMANENT SET AND STRAIN RECOVERY OF DOUGLAS-FIR TESTED FOR CREEP

Specimen	Permanent Set			Strain Recovery
	Radial	Tangential	Longitudinal	Percentage of Axial Creep
	(micro-inches per inch)			
O-1-1	0	17	270	51.8
A-1-5	48	77	300	70.4
A-1-7	48	91	370	53.1
A-1-4	*	*	270	56.5
A-1-3(a)	*	*	0	100.0
(b)	*	10	40	87.3
(c)	*	232	700	55.5
M-1-2	-27	*	80	83.5
M-1-9	0	-16	750	77.7
M-1-3	-27	-127	490	79.9
M-1-10	138	29	1440	64.6
M-1-4(a)	-32	43	100	60.6
(b)	-32	40	160	81.9
M-1-7(a)	*	-6	50	78.2
(b)	34	-19	80	90.6
G-1-9	-30	*	220	82.1
G-1-5	60	-35	800	76.7
G-1-3	-22	-20	175	89.4
G-1-6	-67	-29	460	87.0
G-1-7(a)	*	*	30	89.3
(b)	*	60	180	88.8

* No values recorded due to accidental disturbance of the lateral deformation apparatus.
(a) Values of 1st. cycle.
(b) Values of 2nd. cycle.
(c) Values of 3rd. cycle.

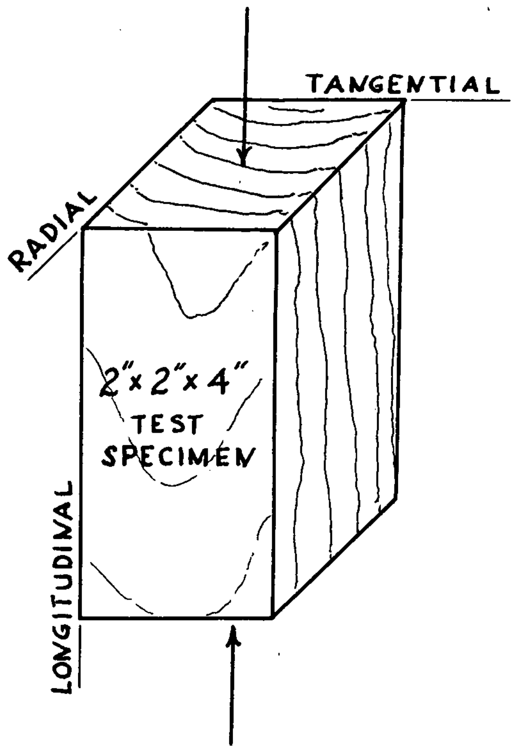


Fig. 1 - TEST SPECIMEN

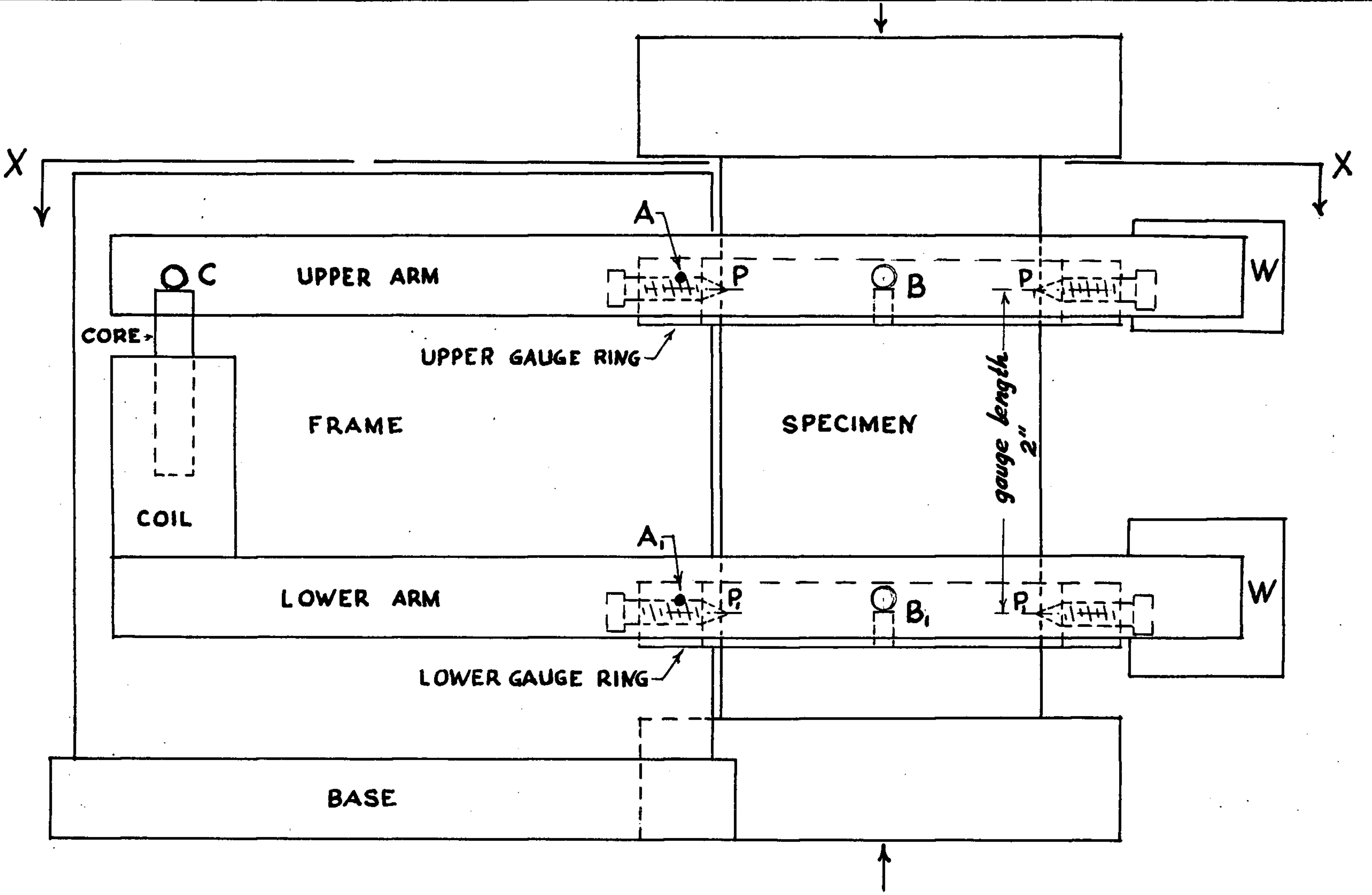
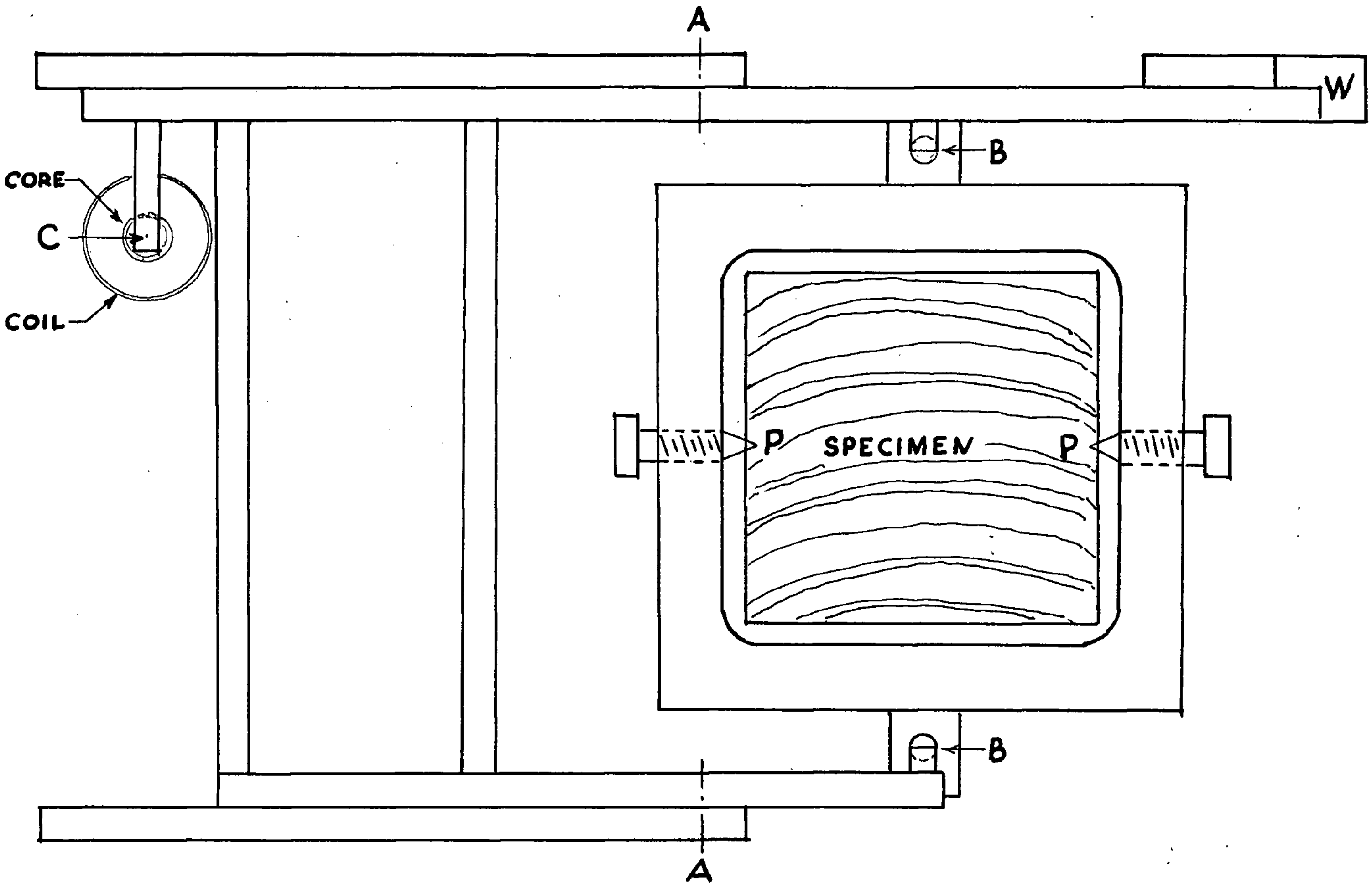


Fig. 2 - DIAGRAM OF COMPRESSOMETER



Section X-X
Fig. 2a

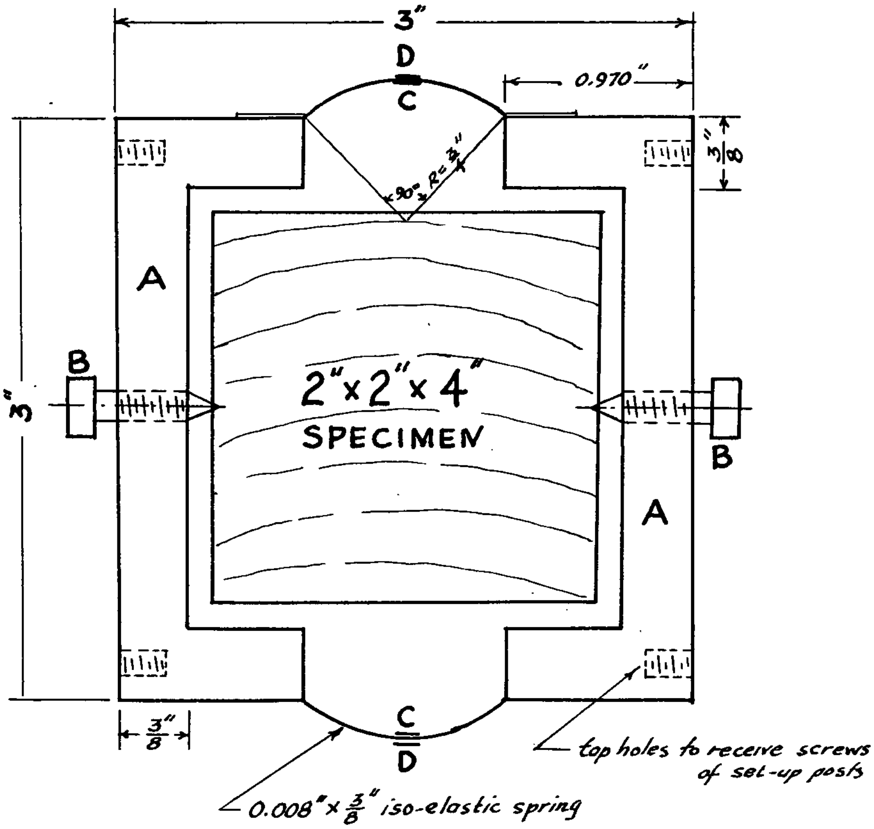


Fig. 3 - LATERAL DEFORMATION APPARATUS ATTACHED TO THE RADIAL SIDES TO MEASURE TANGENTIAL DEFORMATION

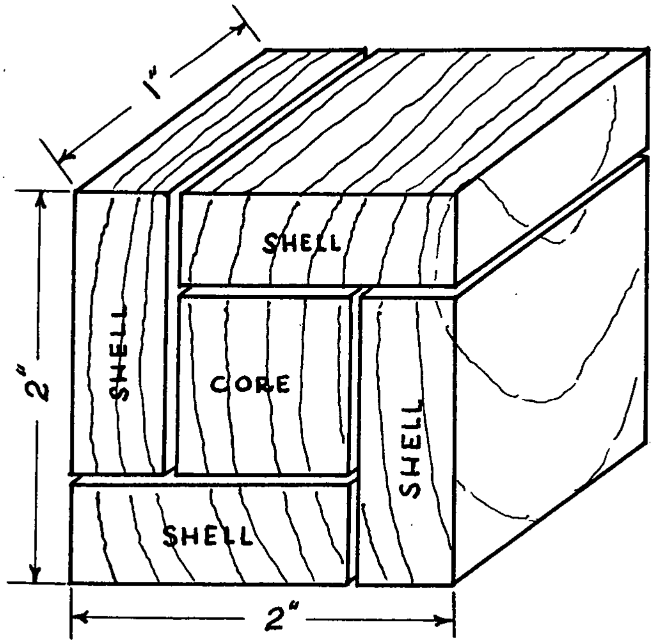


Fig. 4 - METHOD OF CUTTING MOISTURE SAMPLE FOR DETERMINATION OF SHELL AND CORE MOISTURE DISTRIBUTION

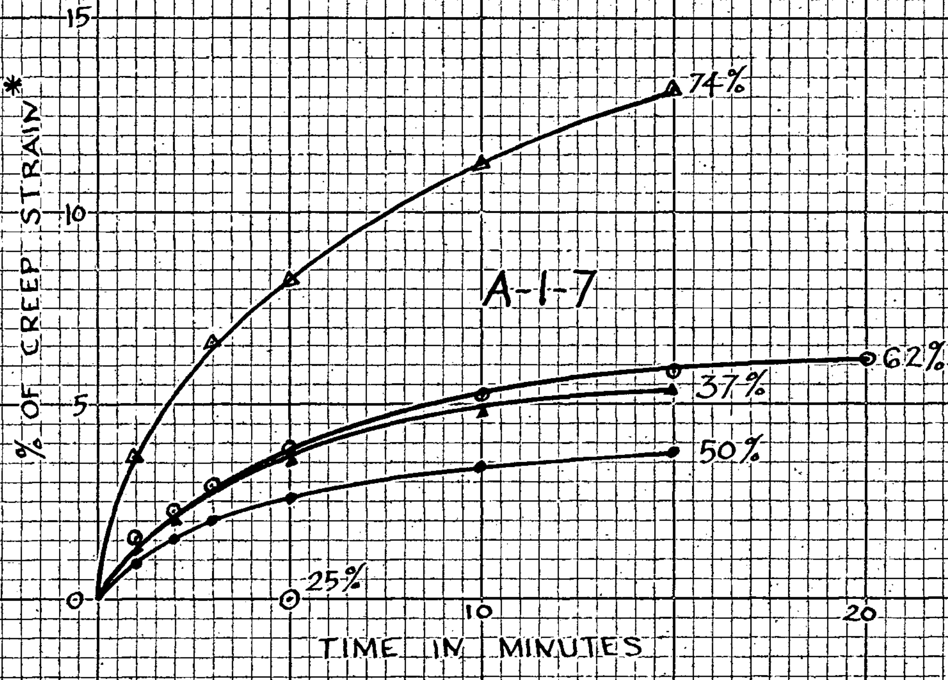


FIG. 5 - AXIAL CREEP - TIME RELATIONSHIP AT DIFFERENT STRESS LEVELS AIR-DRY SPECIMEN IN COMPRESSION PARALLEL TO GRAIN STEP-BY-STEP LOADING. STRESS LEVELS ARE SHOWN AS PERCENTAGES OF ITS ACTUAL CRUSHING STRENGTH.

*CREEP STRAIN AS PERCENTAGE OF TOTAL ELASTIC STRAIN UP TO EACH PARTICULAR STRESS LEVEL.

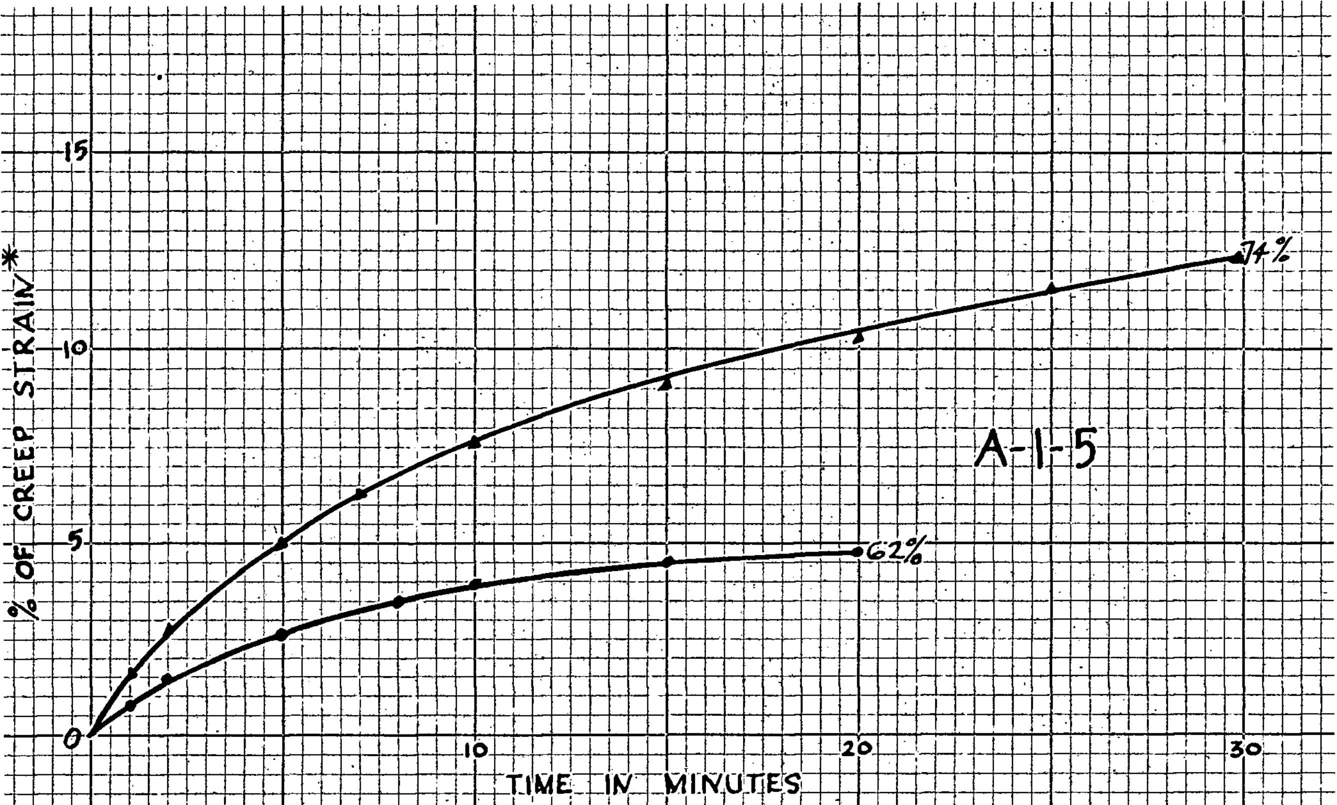


FIG. 6 - AXIAL CREEP-TIME RELATIONSHIP AT DIFFERENT STRESS LEVELS AIR-DRY SPECIMEN IN COMPRESSION PARALLEL TO GRAIN STEP-BY-STEP LOADING. STRESS LEVELS ARE SHOWN AS PERCENTAGES OF ITS ACTUAL CRUSHING STRENGTH.

* CREEP STRAIN AS PERCENTAGE OF TOTAL ELASTIC STRAIN UP TO EACH PARTICULAR STRESS LEVEL.

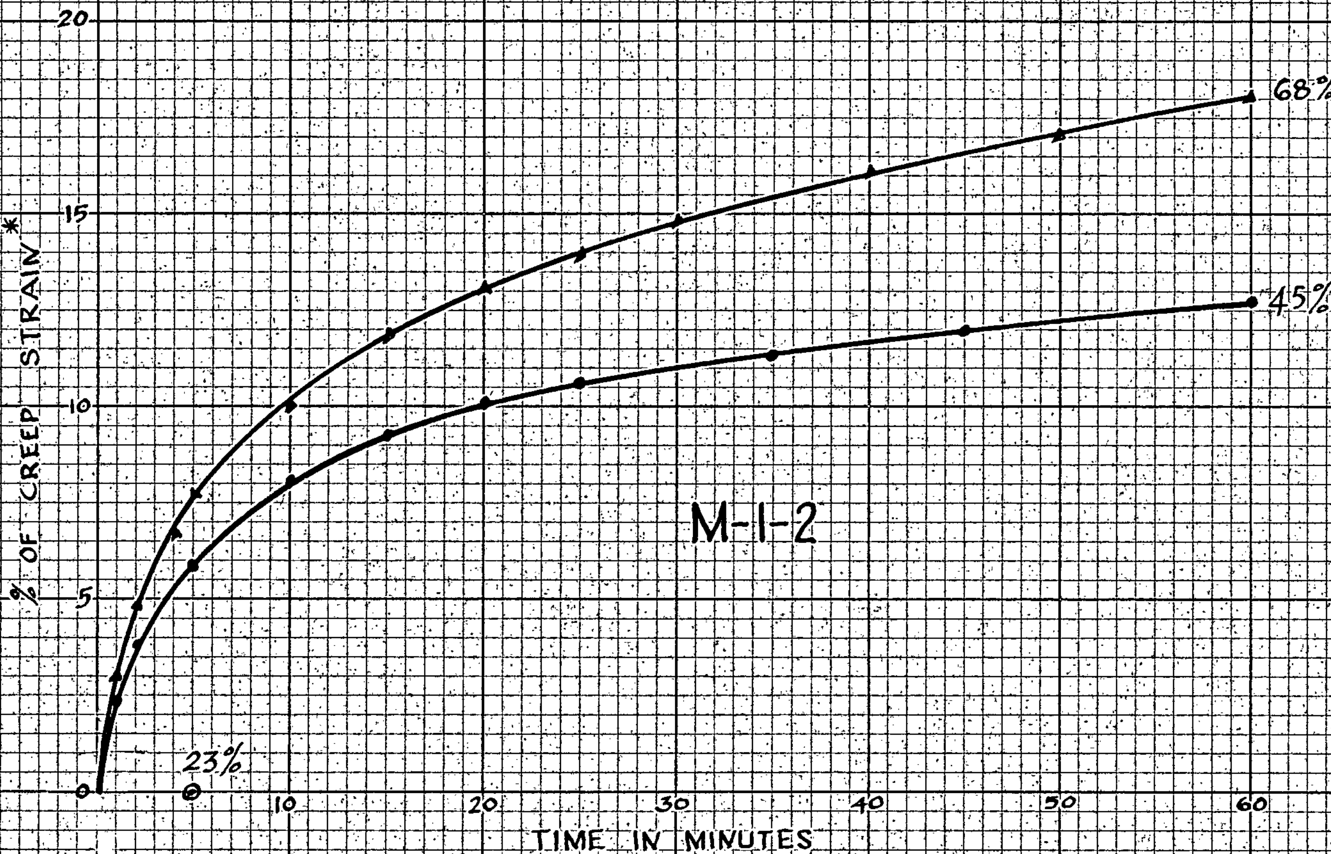


FIG. 7 - AXIAL CREEP-TIME RELATIONSHIP AT DIFFERENT STRESS LEVELS INTERMEDIATE AIR-DRY - GREEN SPECIMEN IN COMPRESSION PARALLEL TO GRAIN STEP-BY-STEP LOADING. STRESS LEVELS ARE SHOWN AS PERCENTAGES OF ACTUAL CRUSHING STRENGTH.

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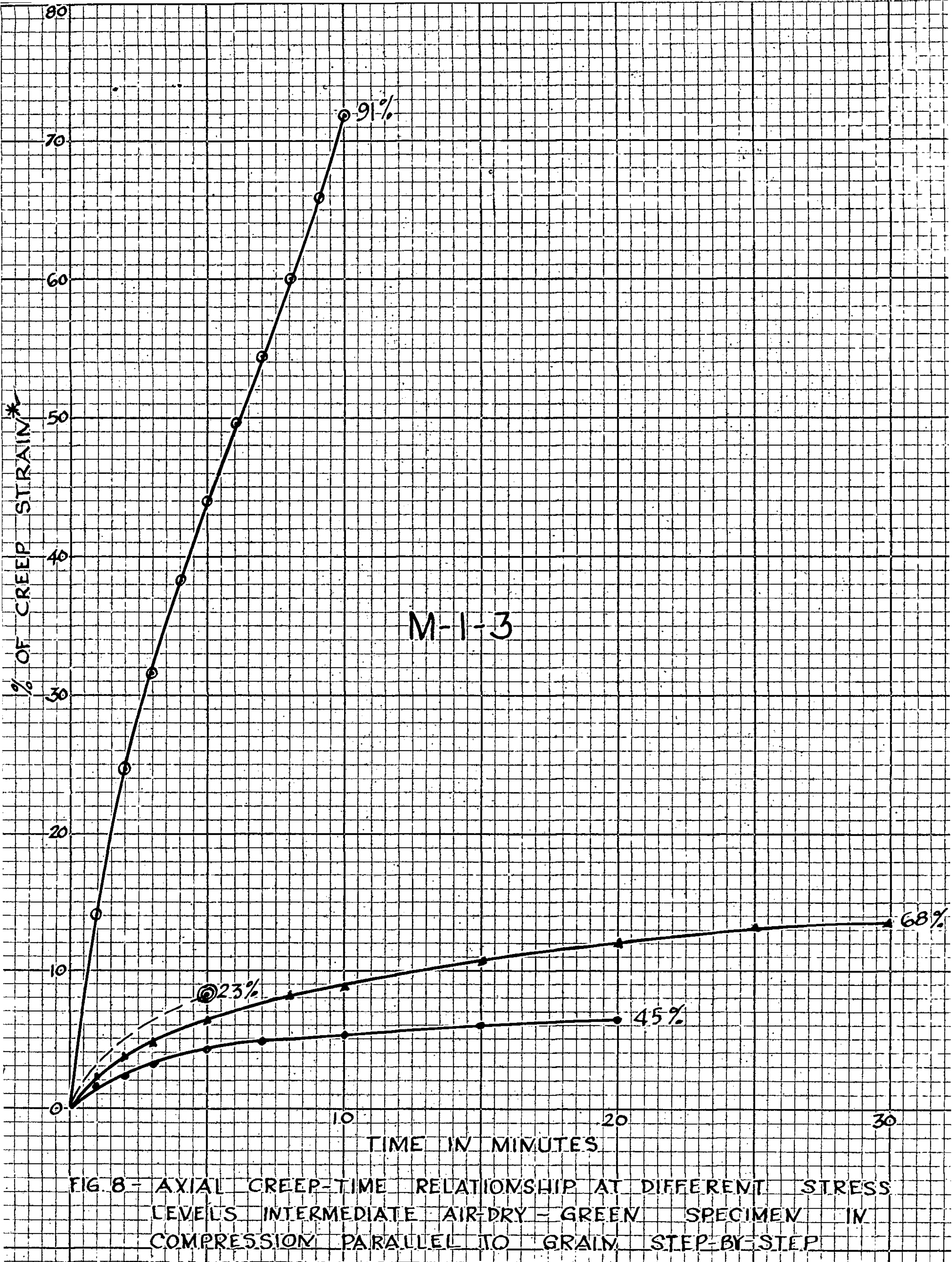

FIG. 8 - AXIAL CREEP-TIME RELATIONSHIP AT DIFFERENT STRESS LEVELS INTERMEDIATE AIR-DRY - GREEN SPECIMEN IN COMPRESSION PARALLEL TO GRAIN STEP-BY-STEP LOADING. STRESS LEVELS ARE SHOWN AS PERCENTAGES OF ITS ACTUAL CRUSHING STRENGTH.

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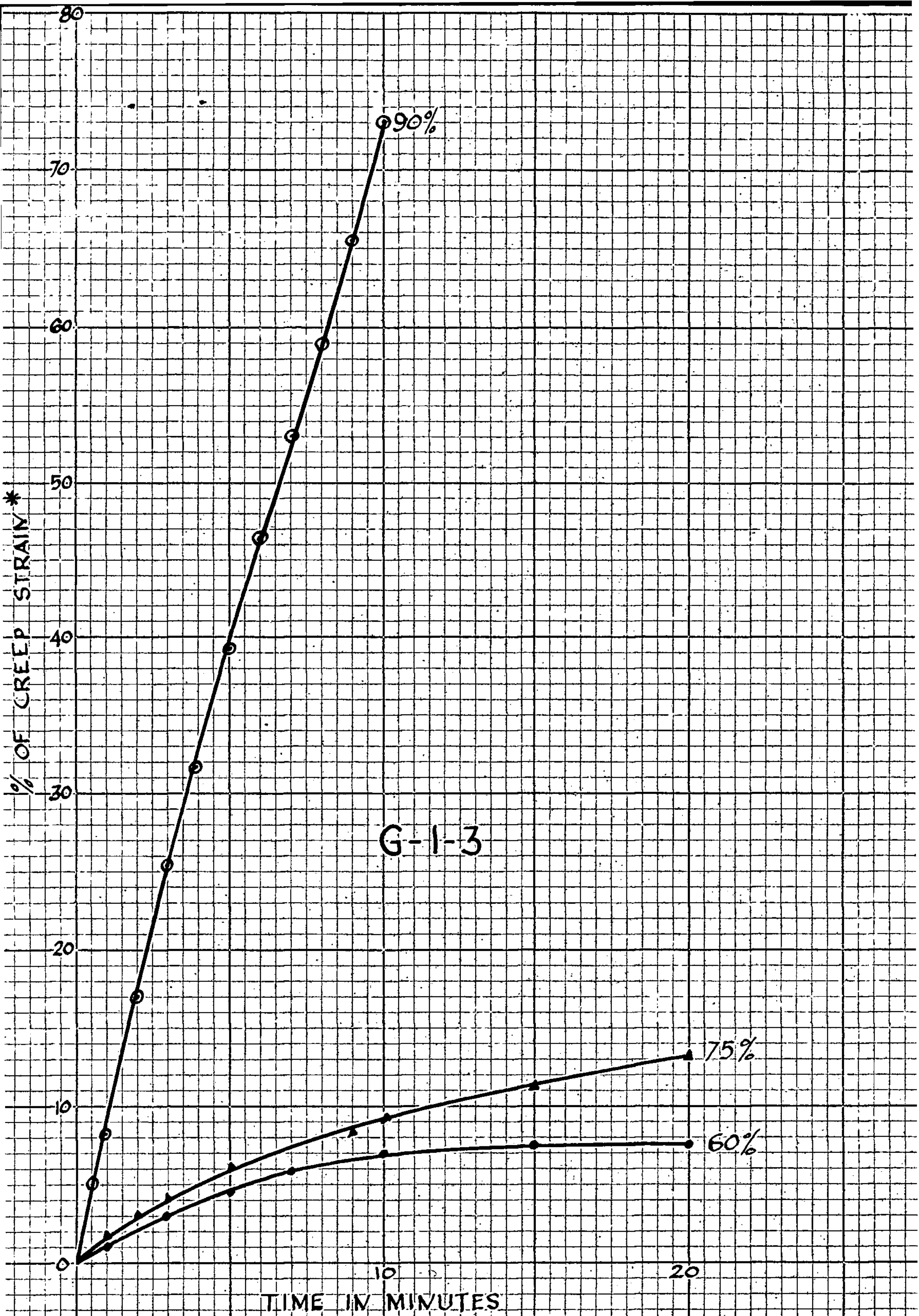

FIG. 9 - AXIAL CREEP-TIME RELATIONSHIP AT DIFFERENT STRESS LEVELS GREEN SPECIMEN IN COMPRESSION PARALLEL TO GRAIN STEP-BY-STEP LOADING. STRESS LEVELS ARE SHOWN AS PERCENTAGES OF ITS ACTUAL CRUSHING STRENGTH.

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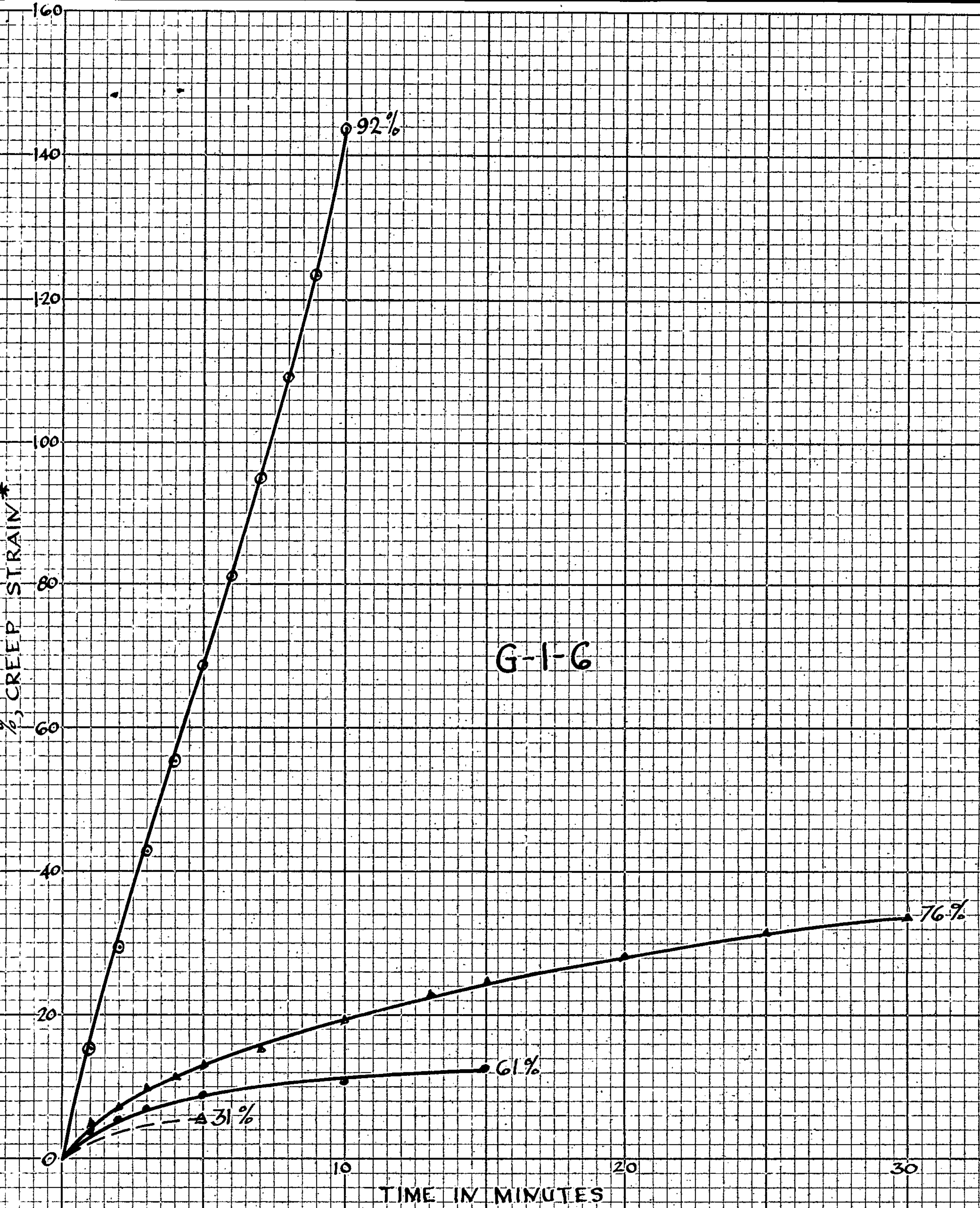

FIG. 10 - AXIAL CREEP-TIME RELATIONSHIP AT DIFFERENT STRESS LEVELS GREEN SPECIMEN IN COMPRESSION PARALLEL TO GRAIN STEP-BY-STEP LOADING. STRESS LEVELS ARE SHOWN AS PERCENTAGES OF ITS ACTUAL CRUSHING STRENGTH.

*CREEP STRAIN AS PERCENTAGE OF TOTAL ELASTIC STRAIN UP TO EACH PARTICULAR STRESS LEVEL

Table 1 - SCHEDULE OF STEP-BY-STEP LOADING-UNLOADING TESTS (AIR-DRY CONDITION)

Load Level	LOADING									UNLOADING					
kips	4	8	12	16	18	20	22	24	28	20	16	12	8	4	0
Per cent of max. load of controls	13	26	39	52	59	65	72	78	91	65	52	39	26	13	0
Specimen	Time duration of sustained load at each load level in minutes														
A-1-5		5	5	5		20		225			5	5	5	20	330
A-1-7		5	15	15		20		15			5	5	5	15	180
A-1-4	5	5	5	5	1510		1500				5	5	5	15	3095
A-1-3(a)		5	30	25									25	30	135
(b)		5	15	25		35						5	15	35	195
(c)		5	15	15		15		15	5	5	5	5	5	10	135

Table 2 - SCHEDULE OF STEP-BY-STEP LOADING-UNLOADING TESTS (INTERMEDIATE CONDITION)

Load Level	LOADING						UNLOADING		
kips	4	8	10	12	15	16	8	4	0
Per cent of max. load of controls	24	48	60	72	89	96	48	24	0
Specimen	Time duration of sustained load at each load level in minutes								
M-1-2	5	60		60			5	5	215
M-1-9	5	5		5	75		5	10	145
M-1-3	5	20		30		10	5	15	155
M-1-10	5	5		5	1040		10	20	1250
M-1-4(a)	5	5	30					10	75
(b)	5	5	5	60			5	10	150
M-1-7(a)	5	5		30			5	10	70
(b)	5	5		5	30		5	10	115

Table 3 - SCHEDULE OF STEP-BY-STEP LOADING-UNLOADING TESTS (GREEN CONDITION)

Load Level	LOADING					UNLOADING		
kips	4	8	10	12	14	8	4	0
Per cent of max. load of controls	23	46	58	69	81	46	23	0
Specimen	Time duration of sustained load at each load level in minutes							
G-1-9	5	10		10		5	10	75
G-1-5	5	5	962				20	1025
G-1-3	5	20	20	10		5	5	90
G-1-6	5	15	30	10		5	15	135
G-1-7(a)	5	25	25				10	95
(b)	5	25	25	25	15	5	10	150

(a) 1st. cycle of repetitive loading.
(b) 2nd. cycle of repetitive loading.
(c) 3rd. cycle of repetitive loading.

Table 4- CREEP DATA FOR DOUGLAS-FIR LOADED IN STEP-BY-STEP MANNER AT SUCCESSIVELY HIGHER STRESS LEVELS

Specimen	1st. Step: Stress Level (psi.)	1st. Step: Duration of Sustained Stress (minutes)	1st. Step: CREEP Longi-tudinal (micro-inches per inch)	1st. Step: CREEP Radial	1st. Step: CREEP Tangen-tial	2nd. Step: Stress Level (psi.)	2nd. Step: Duration of Sustained Stress (minutes)	2nd. Step: CREEP Longi-tudinal (micro-inches per inch)	2nd. Step: CREEP Radial	2nd. Step: CREEP Tangen-tial	3rd. Step: Stress Level (psi.)	3rd. Step: Duration of Sustained Stress (minutes)	3rd. Step: CREEP Longi-tudinal (micro-inches per inch)	3rd. Step: CREEP Radial	3rd. Step: CREEP Tangen-tial
O-1-1	2020 (18%)*	5	10	0	0	3030 (27%)	5	10	0	0	4040	10	30	0	0
A-1-5	1940 (25%)	5	20	0	0	2910 (37%)	5	20	3	3	3880 (49%)	5	45	6	7
A-1-7	1920 (25%)	5	0	0	0	2880 (37%)	15	90	0	7	3840 (50%)	15	85	6	20
A-1-4	970 (12%)	5	0	0	0	1940 (25%)	5	15	0	0	2910 (38%)	5	30	3	3
A-1-3(a)	1940 (26%)	5	30	-	0	2910 (38%)	30	60	0	0	3880 (51%)	25	80	0	0
(b)		5	20	-	0		15	50	6	7		25	70	6	7
(c)		5	30	0	3		15	45	6	10		15	40	9	10
M-1-2	1000 (23%)	5	5	0	0	2000 (45%)	60	150	-17#	-54	3000 (68%)	60	330	-24	-45
M-1-9	950 (25%)	5	20	-3	-3	1900 (51%)	5	50	10	13	2850 (76%)	5	150	37	38
M-1-3	1000 (23%)	5	50	0	3	2000 (45%)	20	80	3	7	3000 (68%)	30	270	-6	-7
M-1-10	950 (19%)	5	40	3	6	1900 (39%)	5	65	7	10	2860 (58%)	5	80	10	13
M-1-4(a)	1000 (24%)	5	25	0	3	2000 (48%)	5	65	-13	24	2500 (60%)	30	170	-57	74
(b)		5	40	0	13		5	50	-3	20		5	35	-10	7
M-1-7(a)	950 (20%)	5	20	0	0	1900 (40%)	5	25	3	-3	2860 (61%)	30	185	40	18
(b)		5	20	0	0		5	50	3	6		5	55	6	10
G-1-9	950 (28%)	5	0	0	-	1900 (57%)	10	40	-6	-	2860 (86%)	10	1190	-150	-
G-1-5	1000 (31%)	5	20	-3	-3	2000 (61%)	5	75	-13	-10	2500 (76%)	962	3330	-124	-251
G-1-3	1000 (30%)	5	0	0	0	2000 (60%)	20	90	-19	-24	2500 (75%)	20	200	-29	-34
G-1-6	1000 (31%)	5	30	0	-10	2000 (61%)	15	150	-30	-35	2500 (76%)	30	530	-64	-38
G-1-7(a)	950 (24%)	5	20	-6	-	1900 (48%)	25	140	-41	0	2380 (60%)	25	120	-38	3
(b)		5	30	-6	-		25	135	-25	0		25	75	-13	-13

Specimen	4th. Step: Stress Level (psi.)	4th. Step: Duration of Sustained Stress (minutes)	4th. Step: CREEP Longi-tudinal (micro-inches per inch)	4th. Step: CREEP Radial	4th. Step: CREEP Tangen-tial	5th. Step: Stress Level (psi.)	5th. Step: Duration of Sustained Stress (minutes)	5th. Step: CREEP Longi-tudinal (micro-inches per inch)	5th. Step: CREEP Radial	5th. Step: CREEP Tangen-tial	6th. Step: Stress Level (psi.)	6th. Step: Duration of Sustained Stress (minutes)	6th. Step: CREEP Longi-tudinal (micro-inches per inch)	6th. Step: CREEP Radial	6th. Step: CREEP Tangen-tial
O-1-1	5050 (44%)	35	90	00	6	6060 (53%)	65	180	3	6	7070 (62%)	40	240	3	6
A-1-5	4850 (62%)	20	120	19	20	5820 (74%)	225	810	137	155					
A-1-7	4800 (62%)	20	175	32	60	5770 (74%)	15	445	95	161					
A-1-4	3890 (50%)	5	25	3	7	4360 (56%)	1510	250	51	77	5340 (69%)	1500	300	89	91
A-1-3(a)															
(b)	4860 (64%)	35	140	25	34										
(c)		15	50	9	13	5830 (77%)	15	270	63	67	6800 (88%)	5	1140	267	336
M-1-2															
M-1-9	3560 (95%)	75	2320	67	-38										
M-1-3	4000 (91%)	10	2035	83	353										
M-1-10	3570 (73%)	1015	3870	309	232										
M-1-4(a)															
(b)	300 (72%)	60	760	-64	276										
M-1-7(a)															
(b)	3570 (76%)	30	730	71	124										
G-1-9															
G-1-5															
G-1-3	3000 (90%)	10	1350	-70	-218										
G-1-6	3000 (92%)	10	2820	-94	-220										
G-1-7(a)															
(b)	2860 (72%)	25	275	-45	-47	3330	15	1100	-41	-44					

*Stress level expressed as percentage of specimen's actual crushing strength.
#Negative sign indicates negative creep which is opposite to bulging.

(a) Values for 1st. cycle of loading.
(b) Values for 2nd. cycle of loading.
(c) Values for 3rd. cycle of loading.

Table 5- RECOVERY DATA FOR DOUGLAS-FIR UNLOADED IN STEP-BY-STEP MANNER AT SUCCESSIVELY LOWER STRESS LEVELS

Specimen	1st. Step Stress Level (psi.)	1st. Step Duration of Sustained Stress (minutes)	1st. Step RECOVERY Longitudinal (micro-inches per inch)	1st. Step RECOVERY Radial (micro-inches per inch)	1st. Step RECOVERY Tangential (micro-inches per inch)	2nd. Step Stress Level (psi.)	2nd. Step Duration of Sustained Stress (minutes)	2nd. Step RECOVERY Longitudinal (micro-inches per inch)	2nd. Step RECOVERY Radial (micro-inches per inch)	2nd. Step RECOVERY Tangential (micro-inches per inch)	3rd. Step Stress Level (psi.)	3rd. Step Duration of Sustained Stress (minutes)	3rd. Step RECOVERY Longitudinal (micro-inches per inch)	3rd. Step RECOVERY Radial (micro-inches per inch)	3rd. Step RECOVERY Tangential (micro-inches per inch)
O-1-1	5050 (44%)*	5	20	0	0	4040 (35%)	5	0	0	0	3030 (27%)	5	0	0	0
A-1-5	3880 (49%)	5	40	0	0	2910 (37%)	5	50	0	7	1940 (25%)	5	50	0	7
A-1-7	3840 (50%)	5	50	13	10	2880 (3&%)	5	40	13	10	1920 (25%)	5	50	13	17
A-1-4	3890 (50%)	5	30	0	10	2910 (38%)	5	15	0	3	1940 (25%)	5	25	0	7
A-1-3(a)	1940 (26%)	25	0	0	0	970 (13%)	30	0	0	0	0 (0%)	135	100	3	13
(b)	2910 (38%)	5	20	3	10	1940 (26%)	15	10	6	6	970 (13%)	35	25	10	10
(c)	4860 (64%)	5	25	6	10	3880 (51%)	5	30	3	7	2910 (38%)	5	50	3	17
M-1-2	2000 (45%)	5	20	0	6	1000 (23%)	5	30	3	3	0 (0%)	215	170	27	32
M-1-9	1900 (51%)	5	170	20	44	950 (25%)	10	400	17	80	0 (0%)	145	700	0	-16#
M-1-3	2000 (45%)	5	195	0	6	1000 (23%)	15	400	10	10	0 (0%)	155	1050	27	32
M-1-10	1900 (39%)	10	185	-3	57	950 (19%)	20	530	34	105	0 (0%)	1250	1520	60	64
M-1-4(a)	1000 (24%)	10	50	0	3	0 (0%)	75	20	0	3					
(b)	2000 (48%)	5	25	0	7	1000 (24%)	10	140	-6	44	0 (0%)	150	390	-12	84
M-1-7(a)	1900 (40%)	5	15	0	0	950 (20%)	10	25	13	3	0 (0%)	70	25	17	6
(b)	1900 (40%)	5	120	3	6	950 (20%)	10	180	10	25	0 (0%)	115	165	37	54
G-1-9	1900 (57%)	5	55	16	-	950 (28%)	10	260	13	-	0 (0%)	75	295	-29	-
G-1-5	1000 (31%)	20	350	-47	10	0 (0%)	1025	900	-232	-22					
G-1-3	2000 (60%)	5	55	0	12	1000 (30%)	5	200	-9	10	0 (0%)	85	600	-29	3
G-1-6	2000 (61%)	5	95	-7	0	1000 (31%)	15	450	-40	-10	0 (0%)	115	540	-67	-29
G-1-7(a)	950 (24%)	10	50	-12	10	0 (0%)	95	10	-3	3					
(b)	1900 (48%)	5	100	-22	17	950 (24%)	10	350	-32	17	0 (0%)	150	430	-38	34

Specimen	4th. Step Stress Level (psi.)	4th. Step Duration of Sustained Stress (minutes)	4th. Step RECOVERY Longitudinal (micro-inches per inch)	4th. Step RECOVERY Radial (micro-inches per inch)	4th. Step RECOVERY Tangential (micro-inches per inch)	5th. Step Stress Level (psi,)	5th. Step Duration of Sustained Stress (minutes)	5th. Step RECOVERY Longitudinal (micro-inches per inch)	5th. Step RECOVERY Radial (micro-inches per inch)	5th. Step RECOVERY Tangential (micro-inches per inch)	6th. Step Stress Level (psi.)	6th. Step Duration of Sustained Stress (minutes)	6th. Step RECOVERY Longitudinal (micro-inches per inch)	6th. Step RECOVERY Radial (micro-inches per inch)	6th. Step RECOVERY Tangential (micro-inches per inch)
O-1-1	2020 (18%)	5	10	0	0	1010 (9%)	10	20	0	0	0 (0%)	230	10	0	0
A-1-5	970 (12%)	20	100	10	30	0 (0%)	330	205	41	44					
A-1-7	960 (12%)	15	75	19	30	0 (0%)	150	175	25	17					
A-1-4	970 (12%)	15	60	0	10	0 (0%)	3095	180	10	60					
A-1-3(a)															
(b)	0 (0%)	195	45	6	7										
(c)	1940 (26%)	5	80	0	23	970 (13%)	10	165	0	54	0 (0%)	135	245	6	81

*Stress level expressed as percentage of specimen's actual crushing strength.

#Negative sign indicates negative recovery(bulging)
(a) Values for 1st. cycle of unloading.
(b) Values for 2nd. cycle of unloading.
(c) Values for 3rd. cycle of unloading.

Table 6 - MODULUS OF ELASTICITY AND COEFFICIENTS OF LATERAL DEFORMATION DURING LOADING IN STEP-BY-STEP MANNER AT SUCCESSIVELY HIGHER STRESS LEVELS

Specimen	1st. Step: Modulus of Elasticity (1000 psi)	1st. Step: Coefficient of Lateral Deformation, During Loading μ_R	During Loading μ_T	During Creep μ_R	During Creep μ_T	2nd. Step: Modulus of Elasticity (1000 psi)	2nd. Step: Coefficient of Lateral Deformation, During Loading μ_R	During Loading μ_T	During Creep μ_R	During Creep μ_T	3rd. Step: Modulus of Elasticity (1000 psi)	3rd. Step: Coefficient of Lateral Deformation, During Loading μ_R	During Loading μ_T	During Creep μ_R	During Creep μ_T
O-1-1	1800	0.232	0.406	0.000	0.000	1800	0.211	0.486	0.000	0.000	1740	0.186	0.490	0.000	0.000
A-1-5	2110	.175	.305	0	0	1980	.196	.339	.150	.150	1940	.236	.362	.133	.156
A-1-7	1690	.349	.448	0	0	1780	.359	.481	0	.078	1720	.352	.486	.071	.236
A-1-4	2060	.528	.336	0	0	2060	.344	.343	0	0	2020	.346	.369	.100	.100
A-1-3(a)	2200	-	.995	-	0	1940	.183	.456	0	0	1870	.248	.485	0	0
(b)	2020	-	.819	-	0	1940	.178	.450	.120	.140	1940	.236	.450	.086	.100
(c)	1900	.208	.600	0	.100	1870	.208	.423	.133	.222	1870	.238	.433	.225	.250
M-1-2	1750	.530	.625	0	0	1670	.479	.525	-.113	-.360	1540	.415	.470	-.073	-.136
M-1-9	1790	.444	.912	-.150	-.150	1500	.330	.661	.200	.260	1460	.331	.626	.246	.254
M-1-3	1600	.391	.444	0	.060	1480	.256	.388	.038	.082	1490	.253	.387	-.022	-.022
M-1-10	1900	.539	.808	.075	.150	1830	.531	.635	.108	.154	1800	.526	.623	.125	.162
M-14(a)	1790	.573	.475	0	.120	1610	.306	.460	-.200	.369	1560	.298	.460	-.336	.435
(b)	1660	.450	.465	0	.325	1600	.292	.439	-.060	.400	1600	.250	.431	-.286	-.200
M-1-7(a)	1980	.775	.665	0	0	1670	.475	.491	.120	-.120	1670	.466	.482	.216	.097
(b)	1980	.742	.621	0	0	1640	.466	.480	.060	.120	1610	.434	.463	.109	.182
G-1-9	1420	.461	-	0	-	1400	.342	-	-.150	-	1240	.252	-	-.126	-
G-1-5	1560	.275	.710	-.150	-.150	1330	.234	.482	-.173	-.133	1390	.158	.450	-.037	-.076
G-1-3	1850	.338	.618	0	0	1670	.282	.598	-.211	-.267	1470	.309	.494	-.145	-.170
G-1-6	1820	.360	.828	0	-.333	1540	.228	.440	-.200	-.233	1350	.227	.354	-.121	-.072
G-1-7(a)	2210	.736	-	-.300	-	1640	.405	.540	-.293	0	1590	.347	.533	-.316	.025
(b)	1900	.621	-	-.200	-	1730	.382	.526	-.185	0	1700	.354	.504	-.173	-.173

Specimen	4th. Step: Modulus of Elasticity (1000 psi)	4th. Step: Coefficient of Lateral Deformation, During Loading μ_R	During Loading μ_T	During Creep μ_R	During Creep μ_T	5th. Step: Modulus of Elasticity (1000 psi)	5th. Step: Coefficient of Lateral Deformation, During Loading μ_R	During Loading μ_T	During Creep μ_R	During Creep μ_T	6th. Step: Modulus of Elasticity (1000 psi)	6th. Step: Coefficient of Lateral Deformation, During Loading μ_R	During Loading μ_T	During Creep μ_R	During Creep μ_T
O-1-1	1710	0.176	0.448	0.000	0.067	1710	0.229	0.458	0.017	0.033	1710	0.285	0.442	0.012	0.025
A-1-5	1870	.227	.394	.158	.167	1850	.278	.410	.169	.191					
A-1-7	1720	.363	.493	.183	.343	1720	.432	.544	.214	.362					
A-1-4	2020	.346	.392	.120	.280	1940	.392	.408	.204	.309	1870	.392	.427	.297	.304
A-1-3(a)															
(b)	1940	.248	.456	.179	.243										
(c)	1870	.264	.423	.180	.260	1830	.258	.449	.234	.252	1830	.294	.564	.234	.295
M-1-2															
M-1-9	1400	.310	.592	.029	-.016										
M-1-3	1470	.215	.328	.041	.179										
M-1-10	1800	.505	.525	.080	.060										
M-14(a)															
(b)	1600	.293	.446	-.084	.364										
M-1-7(a)															
(b)	1520	.451	.475	.097	.170										
G-1-9															
G-1-5															
G-1-3	1430	.237	.444	-.052	-.161										
G-1-6	1280	.208	.344	-.033	-.078										
G-1-7(a)															
(b)	1700	.307	.493	-.164	-.171	1700	.260	.470	-.037	-.040					

(a) Values for 1st. cycle of loading.
(b) Values for 2nd. cycle of loading.
(c) Values for 3rd. cycle of loading.

Table 7 - MODULUS OF ELASTICITY AND COEFFICIENTS OF LATERAL DEFORMATION DURING UNLOADING IN STEP-BY-STEP MANNER AT SUCCESSIVELY LOWER STRESS LEVELS

Specimen	1st. Step					2nd. Step					3rd. Step					4th. Step					5th. Step					6th. Step				
	Modulus of Elasticity	Coefficient of Lateral Deformation				Modulus of Elasticity	Coefficient of Lateral Deformation				Modulus of Elasticity	Coefficient of Lateral Deformation				Modulus of Elasticity	Coefficient of Lateral Deformation				Modulus of Elasticity	Coefficient of Lateral Deformation				Modulus of Elasticity	Coefficient of Lateral Deformation			
		During Unloading		During Recovery			During Unloading		During Recovery			During Unloading		During Recovery			During Unloading		During Recovery			During Unloading		During Recovery			During Unloading		During Recovery	
	(1000 psi.)	μ_R	μ_T	μ_R	μ_T	(1000 psi.)	μ_R	μ_T	μ_R	μ_T	(1000 psi.)	μ_R	μ_T	μ_R	μ_T	(1000 psi.)	μ_R	μ_T	μ_R	μ_T	(1000 psi.)	μ_R	μ_T	μ_R	μ_T	(1000 psi.)	μ_R	μ_T	μ_R	μ_T
O-1-1	1800	0.264	0.464	0.000	0.000	1710	0.188	0.443	0.000	0.000	1740	0.169	0.531	0.000	0.000	1770	0.177	0.563	0.000	0.000	1740	0.243	0.504	0.000	0.000	1660	0.430	0.430	0.000	0.000
A-1-5	1580	.163	.302	0	0	1900	.194	.369	0	.140	1900	.194	.349	0	.140	1900	.186	.363	.100	.300	1900	.318	.342	.164	.176					
A-1-7	1780	.291	.384	.260	.200	1850	.405	.575	.325	.250	1750	.376	.500	.260	.340	1850	.410	.536	.253	.400	1750	.420	.500	.143	.097					
A-1-4	1910	.328	.382	0	.333	1900	.320	.341	.0	.200	1870	.343	.356	0	.280	1870	.330	.386	.0	.167	2060	.380	.392	.056	.333					
A-1-3(a)	1880	.292	.745	0	0	1940	.241	.450	0	0	2200	.241	.462	.030	.130															
(b)	1800	.301	.652	.150	.500	1830	.621	.650	.600	.600	1870	.560	.432	.400	.400	2040	.234	.445	.134	.155										
(c)	1800	.280	.602	.240	0	1800	.264	.429	.100	.233	1830	.241	.423	.060	.294	1760	.240	.416	0	.288	1800	.251	.508	0	.327	1800	.282	.542	.024	.331
M-1-2	1540	.406	.542	0	.300	1540	.384	.482	.100	.100	1600	.362	.461	.159	.188															
M-1-9	1240	.314	.536	.118	.259	1190	.297	.505	.042	.200	-	.142	.244	0	.023															
M-1-3	1350	.382	.424	0	.038	1370	.242	.368	.025	.025	1250	.234	.360	.026	.030															
M-1-10	1590	.480	.532	-.016	.308	1490	.494	.646	.064	.198	-	.354	.382	.046	.049															
M-1-4(a)	1600	.424	.461	0	.260	1600	.300	.451	0	.150																				
(b)	1610	.430	.452	0	.280	1410	.341	.392	-.043	.314	1450	.240	.421	-.031	.216															
M-1-7(a)	1640	.496	.521	0	0	1590	.424	.460	.520	.120	-	.388	.467	.670	.240															
(b)	1490	.490	.502	.025	.050	1440	.476	.492	.056	.139	1540	.463	.475	.224	.327															
G-1-9	1150	.386	-	.291	-	1270	.334	-	.050	-	-	.240	-	-.098	-															
G-1-5	1130	.211	.330	-.134	.028	-	.041	.218	-.258	.024																				
G-1-3	1390	.278	.401	0	.218	1370	.250	.416	-.045	.050	-	.101	.262	-.129	.013															
G-1-6	1220	.182	.292	-.074	0	1110	.135	.223	-.089	-.022	-	.101	.110	-.124	-.054															
G-1-7(a)	1500	.521	.564	-.240	.200	-	.400	.526	-.300	.300																				
(b)	1360	.489	.560	-.220	.170	1560	.440	.520	-.092	.049	-	.346	.482	-.088	.079															

(a) Values for 1st. cycle of unloading.
(b) Values for 2nd. cycle of unloading.
(c) Values for 3rd. cycle of unloading.

Table 8- VALUES FROM FINAL STATIC TESTS IN COMPRESSION PARALLEL TO GRAIN FOLLOWING CREEP-RECOVERY TESTS.

Specimen	Moisture Content (%)	Specific Gravity	Max. Stress (psi.)	Max. Strain (micro-in./in.)	Modulus of Elasticity (1000psi)	Poisson's Ratio	
						μ_{LR}	μ_{LT}
O-1-1	oven-dry	0.472	11,400	12,200			
CA-1-6*	9.6	0.497	7300	6000	1890	0.372	0.402
A-1-5	9.6	0.504	7860	7300			
A-1-7	10.2	0.541	7760	11,050			
A-1-4	9.3	0.492	7750	6700			
A-1-3	9.6	0.492	7600	6200			
CM-1-1*	19.9	0.491	4190	4400	1610	0.210	0.596
M-1-2	20.8	0.491	4400	4800			
M-1-9	20.3	0.518	3720	4720			
M-1-3	21.8	0.490	4400	5500			
M-1-10	20.0	0.541	4850	7900			
M-1-4	20.0	0.500	4180	4650			
CG-1-10*	63.0	0.547	4100	3850	2000	0.342	0.651
G-1-9	46.9	0.545	3290	4300			
G-1-5	60.5	0.498	3280	6240			
G-1-3	65.5	0.504	3320	4250			
G-1-6	62.1	0.499	3250	6600			
G-1-7	57.4	0.547	3900	4850			

* Control specimens were not subjected to creep-recovery tests.

Table 9- PERMANENT SET AND STRAIN RECOVERY OF DOUGLAS-FIR TESTED FOR CREEP

Specimen	Permanent Set			Strain Recovery
	Radial	Tangential	Longitudinal	Percentage of Axial Creep
	(micro-inches per inch)			
O-1-1	0	17	270	51.8
A-1-5	48	77	300	70.4
A-1-7	48	91	370	53.1
A-1-4	*	*	270	56.5
A-1-3(a)	*	*	0	100.0
(b)	*	10	40	87.3
(c)	*	232	700	55.5
M-1-2	-27	*	80	83.5
M-1-9	0	-16	750	77.7
M-1-3	-27	-127	490	79.9
M-1-10	138	29	1440	64.6
M-1-4(a)	-32	43	100	60.6
(b)	-32	40	160	81.9
M-1-7(a)	*	-6	50	78.2
(b)	34	-19	80	90.6
G-1-9	-30	*	220	82.1
G-1-5	60	-35	800	76.7
G-1-3	-22	-20	175	89.4
G-1-6	-67	-29	460	87.0
G-1-7(a)	*	*	30	89.3
(b)	*	60	180	88.8

* No values recorded due to accidental disturbance of the lateral deformation apparatus.
(a) Values of 1st. cycle.
(b) Values of 2nd. cycle.
(c) Values of 3rd. cycle.

Note:

Pages 46-67 oversized and are ~~contained in accompanying tube~~. see fly leaf.

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November 2nd, 1962.