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The Rate of Weakening of Paper Due to an Applied Stress

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THE RATE OF WEAKENING OF PAPER DUE TO AN APPLIED STRESS

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INTRODUCTION

When a load is applied to a sheet of paper, the paper may break immediately or it may support the load for some period of time. It is recognized that the paper, while under a stress less than that required to cause immediate break, is weakened until it is finally unable to support the stress. Since in the normal use of paper the stress to which paper is subjected is less than that needed to cause immediate break this weakening is an important factor in many cases.

A few examples of such cases are the winding of the paper onto the reel of the paper machine during manufacture, the use of paper in bags, and possibly most important of all the running of paper through a printing press.

Since approximately 90 per cent of all paper is printed by some means or another, and during the printing process the paper is subjected to stresses, the subject of weakening while under stress is very important. Should the paper be weakened to the breaking point in the printing operation, many costly shutdowns and wastes of materials could result.

FACTORS CONTRIBUTING TO PAPER STRENGTH

Paper strength is a vague term and is meaningless if not accompanied by an understanding of the particular strength property desired and a means of determining this property.

Paper strength is dependent upon many factors, some of which are better understood than others, and are believed to contribute more than others. The factors considered to be the most important to paper strength are: (1) the strength of the fibers of which the sheet is made, (2) the strength of the fiber-to-fiber bonds, (3) the number of bonds, and (4) the formation of the sheet.

Casey(1) claims that fiber-to-fiber bonding is the most important single factor affecting the strength of paper and that deficiencies in the strength of paper must be attributed to deficiencies in bonding, and not to a lack of intrinsic fiber strength. Forman (2) says that the total bonded area and the strength of the fiber-to-fiber bonds are major contributors to the strength of a sheet of paper.

Van den Akker, Lathrop, Voelker, and Dearth (3) have shown that fiber strength is not unimportant in sheet strength. It was found by them that fiber strength has a very significant influence in sheet strength. In their investigation of the relative importance of fiber failure and bond breaking in sheet failure, they found that by using a technique of tagging

(dying) a small fraction of the fibers making up the paper it could be shown that a substantial percentage of the tagged fibers were broken or pulled apart during tensile failure of the paper even when the degree of beating was moderate.

Ratliff (4) postulates that, at least during the early stages of beating, the amount of fiber bonding fairly well determines the sheet strength. As the total strength of the fiber bonding approaches the strength of the fibers themselves, fiber strength may increasingly become the limiting factor. He believes that other limiting factors may be the specific strength of the fiber bonds and increased concentration of stresses at weaker spots as fiber bonding is increased.

The degree of bonding which is present between fibers in a sheet of paper is dependent upon a great number of factors. Among these are the nature of the fiber surface and the way in which the fibers have been formed into the sheet. The area of the fibers in contact and the number of bonds formed is a result of the formation of the sheet. The treatment which the fibers receive in beating shows an effect upon the degree of bonding because of the effect of fiber surface and the flexibility of the fiber.

Emerton (5) believes that the flexing of the fibers which takes place during beating breaks bonds within the fiber and makes it more flexible. This flexibility is termed conformability and allows a fiber to bond with other fibers. Thode

and Ingmanson (6) believe that this flexibility gives less fiber damage and therefore results in a more efficient beating operation.

Casey (1) says that in the beating operation one of the first things which may be accomplished is the rupture and partial removal of the primary wall, thereby exposing the secondary wall of the fiber. Once this is accomplished, the bruising and rubbing action of the beater causes the fibers to fray out into fine fibrils which increases the amount of exposed surface area of the fibers, and at the same time makes the fibers increasingly flexible. The increased specific surface obtained increases the magnitude of the surface tension forces drawing the fibers together and also makes it possible for an increased area of fiber surface to come into contact during sheet formation, thereby increasing the adhesion between fibers.

Nissan (7) claims that the ultimate effect of the beating operation on fiber bonding is to (1) rearrange the bonds from within the fibers to bonds between them, and (2) to increase the number of bonds per unit volume, or compact the paper, while the total number of bonds per unit mass is not materially affected.

Forman (2) points out that on beating a pulp, the fiber area may be increased by fibrillation, hydration, and cutting, and the bonded area in a sheet therefore tends to increase as

the surface area of the pulp increases.

Ingmanson and Thode (8) believe that the "total" area available for bonding is not determined by the specific surface developed, but is a constant which is determined only by the surface area of the original unbeaten fibers. They believe that the fibrils on the surface of the fibers and the fines generated by beating are bonded back to the surface of the fibers, and therefore their area is not available for bonding.

Casey (1) suggests that fiber flexibility is increased by reduced lignin content, increased fiber length, as well as by increased beating. Ratliff (4) found that kraft pulps which were delignified with chlorite exhibited greater strength at a range of 40-50 per cent yield and that an increase in strength was came about as the yield lessened from 50 to 42 per cent. Keeney (9) found that the specific bonding strength (bonding strength divided by the percentage bonded area) increased as the lignin was removed in a semichemical kraft pulp.

Casey (1) believes that fiber length does not have a great effect upon fiber bonding, but fiber length is a property to be considered, because after a maximum of fiber bonding has taken place, the strength of paper depends principally upon the length of its component fibers.

McDonnell (10) states that inter-fiber bonding strength of paper is improved by bleaching because of the increased

surface area, possible better fiber flexibility, and increased efficiency of utilization of the available surface area which resulted from exposing better bonding surfaces. It was shown in this study that in a particular system, the level of strength is defined by the balance between bonding and fiber strength, but the maximum achievable strength is limited by whichever of the two factors is the weaker, relative to the other.

When dealing with the total bonding strength it must be realized that this strength is dependent upon the bonded area, the strength of the bonds, and the way in which these factors are distributed (11). In measuring bonded areas difficulty arises and the most recent discussions of this measurement have been done by Ingmanson and Thode (8) and by Swanson and Steber (12).

Parsons (13) made use of the specific surface measurement and the Kubelka and Munk equation in the determination of the area of optical contact. Ratliff (4) showed that the area of optical contact is a function, not a direct measure, of the area of fiber-to-fiber bonding.

One of the first methods suggested for the measurement of bonding strength in a sheet of paper was that of Hoffman-Jacobsen (14). This suggested method was concerned with the ratio of ordinary tensile strength to zero-span tensile strength.

Van den Akker (15) suggests that bonded area contributes to sheet strength but may depend upon the internal structure of the bond. In this investigation, the stress applied to a sheet in a direction parallel to the plane of the sheet is mentioned and it is hypothesized that in a typical well-bonded sheet the individual fiber-to-fiber bonds are subjected to simple shear forces when this is carried out.

Ratliff (4) suggests that the hemicelluloses in pulp manifest their effects upon pulp properties by enabling a high specific surface and bonded area to be developed during beating without much decrease in fiber strength. This indicates that hemicelluloses do have an increasing effect on fiber bonding as their percentage increases.

Campbell (16) points out that when fibers themselves are broken the result is a rupture of shear between bonded fibrils inside the fibers and that fibers are broken is evidence that the bonding of these fibers to neighboring fibers is stronger than whenever bonding takes place in the fiber itself and which may be due to primary chemical bonds or to hydrogen bonding or both. He also says that possibly a great deal of the bonded surface is broken in the earlier stages of loading while distortions take place in the course of setting up the continuous chains of bonded units which carry the final load.

HISTORICAL SURVEY OF THE EFFECT OF A TENSILE STRESS ON PAPER STRENGTH

If paper is subjected to a tensile stress it may break immediately or it may support the stress for a period of time. Rance (17) showed that a relationship exists between the load and the logarithm of the time period that the paper supports the load before the break occurs. The relationship he obtained is shown in Fig. 1.

Jacobsen (18) also found this relationship. This seems to show that within the sheet there is a stress-dependent mechanism which affects the sheet strength.

Griffin and McKinley (19) show that paper will break under a reduced load if the time of application of this load is increased and, conversely, state that the load required will be higher if the paper is broken rapidly. They attribute this to the flow in paper and to the time element involved in the separation of fibers just prior to rupture.

Doughty (20) says that ultimate tensile strength of paper is decreased with increasing basis weight. He attributes this principally to variation in fiber orientation, therefore showing that fiber orientation or alignment has an effect upon the response of paper to a tensile stress.

Schulz (11) points out that the manner in which stress is distributed within the sheet while supporting a load is a factor which must be considered. If stress is distributed uniformly the least strain will be realized. Because of the variety in the size and shape of the elements which compose the sheet it is not likely that this uniform distribution is ever present in paper.

Schulz (11) states that publications by Nordman, Gustafsson, and Olafsson and Sandborn show an increase in the light scattering coefficient of paper after it was subjected to

stress. A relationship between the change in scattering coefficient and the work done by the load on the paper was found. It is generally believed that the light-scattering coefficient varies directly with the unbonded area in the sheet, so a change in the internal sheet structure is indicated.

Schulz (11) also says that Maynard and McKee showed changes in the thickness of paper while supporting a load. It is believed that the breaking of fiber-to-fiber bonds is responsible for this change in thickness.

PRESENTATION OF THE PROBLEM

It has been shown by Rance (17) and Jacobsen (18) that when paper is subjected to a load there is a relationship between the load and the logarithm of the time period that the paper supports the load.

This implies a stress-dependent mechanism within the sheet which affects the strength of the sheet. The weakening of paper until it is finally broken has been attributed to the breaking of fiber-to-fiber bonds in the sheet.

This work involved a study of the relationship between the weakening of paper to the time under load at periods of time less than that required for sheet rupture. Two objectives were to be served. First, it was proposed to obtain results which would enable an accurate prediction of the tensile strength of paper after it had been subjected to a load for a period of time. The second objective was an attempt to show that this weakening is due to the breaking of fiber-to-fiber bonds in the sheet.

EXPERIMENTAL PROCEDURES

PREPARATION OF HANDSHEETS

DESCRIPTION OF PULP

The pulp used in this work was a Weyerhauser softwood alpha pulp obtained from the Hawthorne Paper Company in Kalamazoo, Michigan and used by them in their daily operations. The pulp was obtained in bale form and was stored at room conditions. The pulp was refined in a Valley laboratory beater according to TAPPI Standard T 200 m-45. Before beating, the pulp was soaked in water for four hours and was defibered in a Williams Standard pulp disintegrator. The pulp was beaten with a load of 5500 g. on the bedplate. The results of the beater evaluation are shown in Table I.

TABLE I

BEATER EVALUATION OF PULP

Beating Time Minutes	Freeness ml. CSF	Basis Weight g./sq m	Average Thickness 1/1000 in.	Average Tensile lbs.	Average Burst psi	Fold MIT
0	729	62.6	5.8	1.55	1.9	0
15	550	61.2	3.9	7.92	18.3	19
30	260	59.5	3.4	10.93	24.1	37
45	101	60.0	3.1	11.12	24.9	91

STUDY OF THE REPRODUCIBILITY OF HANDSHEETS

This study was made to enable the preparation of handsheets

without great variations in physical properties, in order that further work would be free from error because of deviations in handsheet properties. It was evident that to obtain reproducible handsheets from this pulp, a study of this kind must be carried out because of variations in handsheets observed during the beater evaluation.

In studying the reproducibility of handsheets made from this pulp two areas were considered as major variables. First, a study of the reproducibility of sheet properties at different degrees of beating was made.

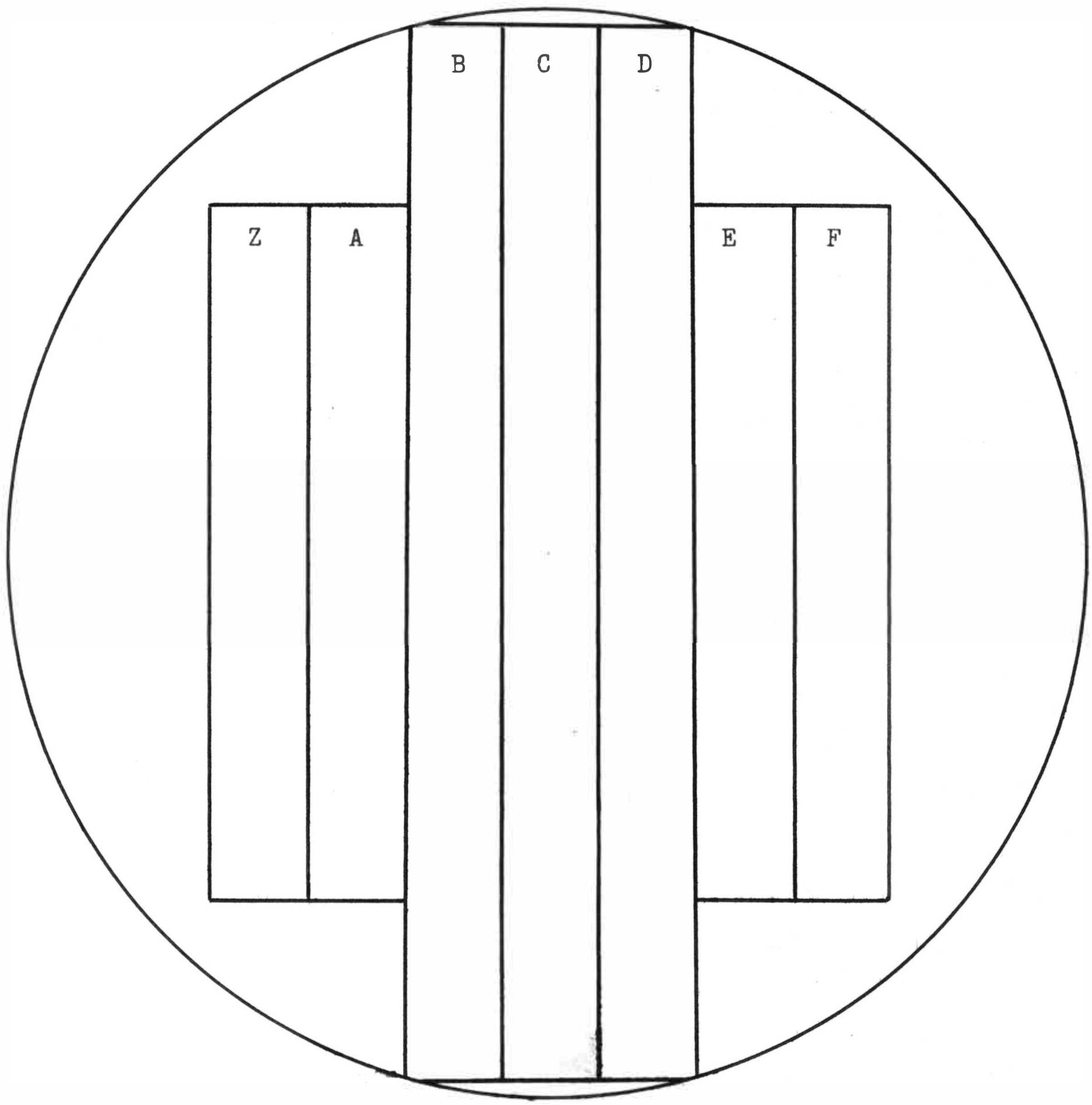
The second area of study was that of the reproducibility in properties of handsheets of different basis weights.

In preparing handsheets for the study of various degrees of beating and its effect on handsheet properties, TAPPI Standard T 205 m-53 was followed, using a British sheet mold and a hydraulic press. Drying was carried out in a conditioned room using standard drying rings. After conditioning of the sheets, they were cut into strips as shown in Figure 2. The cutting of these strips was done with a razor blade to permit a very accurate size to be obtained.

Strips A, E, F and Z (see Figure 2) were used to determine zero-span tensile strength, while strips B, C, and D were cut to a length of 150 mm, weighed and the tensile strength determined. Strips A, E, F and Z were cut to a length of 100 mm, weighed, and then reduced to 40 mm to enable easier handling. All strips were cut 15 mm wide.

Figure 2

Handsheet Division



The basis weight, tensile strength, and zero-span tensile strength of each strip was determined and calculations made to give breaking length and zero-span breaking length by use of the following formulas:

$$\text{Breaking length} = \frac{30{,}240\ p}{r}$$

where p is the tensile break load in pounds on a 15 mm strip and r is the moisture-free basis weight in grams/square meter

$$\text{Zero-span breaking length} = \frac{30{,}240\ p}{r}$$

where p is the zero-span tensile in pounds on a 15 mm strip after correction for the weight of the zero-span upper jaws and knurled screw and r is the moisture-free basis weight in grams/square meter

After the zero-span tensile strength was determined, the line of rupture was examined under a microscope to observe the type of break which had occurred and it was found that as the beating time increased up to 45 minutes, the line of rupture became increasingly sharper.

The data obtained in this study are shown in Tables II and III.

From the data in Tables II and III, a measure of the variations in sheet properties was calculated by dividing the "range" of values of breaking length and zero-span breaking length obtained at each degree of beating by the average value of breaking length and zero-span breaking length at each degree of beating, and multiplying by 100. The value of the "range" was obtained by subtracting the lowest reading obtained from the highest reading.

TABLE II
EFFECT OF DEGREES OF BEATING ON REPRODUCIBILITY OF HANDSHEETS

Beating Time Minutes	Breaking Length Meters	Zero-span Breaking Length Meters	Beating Time Minutes	Breaking Length Meters	Zero-span Breaking Length Meters
0	593	8201	30	5222	10634
	578	7087		5155	10343
	575	7081		5188	10132
	572	7079		4990	9820
	547	7093		4950	9712
	524	7025		4924	9689
	520	6970		4900	9573
	496	6845		4900	9539
	481	6703		4832	9378
	494	6769		4701	9375
	466	6551		4558	9271
	441	6351		4534	9214
15	3712	11449	45	5832	10476
	3707	11209		5707	9950
	3648	10193		5640	9693
	3598	10135		5607	9673
	3548	10118		5542	9518
	3543	10086		5444	9440
	3541	9916		5427	9223
	3528	9906		5364	9223
	3476	9848		5355	9122
	3471	9838		5138	9072
	3461	9793		5135	8756
	3402	9356		4744	8302

TABLE III
AVERAGE AND RANGE VALUES FROM DEGREE OF BEATING
STUDY ON REPRODUCIBILITY

AVERAGES			RANGES		
Beating Time Minutes	Breaking Length Meters	Zero-span Breaking Length Meters	Beating Time Minutes	Breaking Length Meters	Zero-span Breaking Length Meters
0	524	6807	0	152	1850
15	3553	9983	15	310	2093
30	4898	9585	30	688	1420
45	5413	9159	45	1088	2174

This measure of variation is termed variation percentage, and the values for it obtained at the degrees of beating studied are shown in Table IV.

TABLE IV
VARIATION PERCENTAGE AT VARIOUS DEGREES OF BEATING

Beating Time Minutes	Variation Percentage Breaking Length	Variation Percentage Zero-span Breaking Length
0	29.0	27.2
15	8.7	20.9
30	14.1	14.8
45	20.3	23.7

Upon examination of Tables II, III and IV, it can be seen that a great deal of error was present at each degree of beating. At a beating time of 30 minutes there seemed to be the greatest reproducibility and this degree also seemed to give the best handsheet formation upon visual examination.

In studying the reproducibility of handsheets of different basis weights, pulp beaten for 30 minutes was used. Handsheets were formed on a British sheet mold and pressing done on a hydraulic press. Drying was carried out in standard drying rings and in a conditioned room. Handsheets were formed in the above manner weighing approximately 2.0 and 3.3 grams per sheet. These handsheets were divided into strips according to Figure 2, cut in the same manner as those used in the study of the effect of degrees of beating on handsheet reproducibility, weighed, and tested for tensile strength and zero-span tensile strength. Calculations of breaking length and zero-span breaking length were made and are presented in Tables V and VI.

TABLE V
EFFECT OF BASIS WEIGHT ON REPRODUCIBILITY

Sheet Weight g./sq. m	Breaking Length Meters	Zero-span Breaking Length Meters	Sheet Weight g/sq. m	Breaking Length Meters	Zero-span Breaking Length Meters
106.7	5060	11480	164.8	5190	10080
108.4	5275	11120	165.1	5130	9850
108.4	5025	11500	164.6	5100	9730
105.3	5490	11180	164.3	5250	9640
105.8	4875	10950	163.0	5175	10370
105.5	5100	10950	166.1	*4900	10410
108.2	5600	10660	162.6	5290	10250
108.0	5660	11000	161.4	5340	10070
108.9	5559	10300	162.5	5270	10650
107.9	5112	10800	164.8	5321	**9700
108.5	4958	11620	161.8	5364	10110
108.4	5040	11080	164.9	5226	9720
106.7	5481	11420	163.6	5120	**9490
107.3	5478	11100	164.4	5316	10890
108.4	5423	10300	164.1	5270	11130
106.9	5408	10800	164.9	5300	10290
106.0	5327	11010	164.3	5374	9890
106.2	5316	10350	163.6	5342	10890

* wood sliver found at point of failure

** jaws of zero-span tensile strength tester not at zero-span

TABLE VI
AVERAGE AND RANGE VALUES FROM EFFECT
OF WEIGHT STUDY ON REPRODUCIBILITY

AVERAGES			RANGES		
Sheet Weight g./sq. m	Breaking Length Meters	Zero-span Breaking Length Meters	Sheet Weight g./sq. m	Breaking Length Meters	Zero-span Breaking Length Meters
107.4	5288	10980	107.4	795	1320
164.0	5240	10180	164.0	274	1490

From the data in Tables V and VI, a measure of the variations in sheet properties was calculated by dividing the "range of values of breaking length and zero-span breaking length obtained at each sheet weight by the average value of breaking length and zero-span breaking length at each sheet weight, and multiplying by 100. The value of "range" was obtained by subtracting the lowest reading obtained from the highest reading. This measure of variation is termed variation percentage, and the values for it obtained at the sheet weights studied are shown in Table VII.

TABLE VII
VARIATION PERCENTAGE AT DIFFERENT SHEET WEIGHTS

Sheet Weight g./sq. m	Variation Percentage Breaking Length	Variation Percentage Zero-span Breaking Length
107.4	15.1	12.2
164.0	5.3	14.7

Upon examination of Tables V, VI, and VII, it can be seen that, in comparison with the deviation found in the study of the effect of the degrees of beating on handsheet reproducibility, the deviation has been reduced considerably. As the zero-span tensile strength test results are usually expected to vary considerably it can be said that a variation percentage of 5.3 for breaking length, as is the case with the handsheets of an average basis weight of 164.0 g./sq. m is very satisfactory for this type of work. Therefore, sheets of this weight were selected for use in further studies. The forming of heavier handsheets did not see to be justified once this variation percentage had been reached.

The tensile strength testing machine was periodically checked for accuracy by hanging different weights on the top jaw of the tester and reading the scale after allowing the tester to come to equilibrium. A check was also made to note the effect of using a 2-inch span while making the tensile strength test, but no significant variations were discovered by using this method.

EXPERIMENTAL RESULTS

STUDY OF THE RELATIONSHIP OF TIME TO BREAK VERSUS LOAD APPLIED

To meet the objectives set up for this work, it was necessary to make a determination of the relationship of the time to break versus the load applied to a sheet. To determine this relationship it was necessary to apply loads of different magnitudes to strips of paper and find the time required for the strips to break.

A timing apparatus and clamps in which to hold the strip while applying load were needed and these were designed and made by the author.

The timing apparatus, used to measure the length time the samples supported the load, consisted of an electric clock, a wooden base, an on-off push-type electric switch, a metal coil spring, and a wooden pedal with hinge attachment.

The procedure used to make this timing device was to drill into the base deep and large enough to allow the electric switch to be pushed off by a weight falling on the pedal without damage to the switch. The pedal was attached and the spring inserted between the base and the pedal to return the pedal to its original position after shutting the switch off. The clock was wired in connection with the switch so as to allow the switch to shut the clock off.

The clamps were made of a copper-brass alloy. Rubber used in the clamps was from an automobile tire inner tube and bolts were of stainless steel. These are shown in Figure 3.

The study of the relationship of time to break versus load applied was carried out in a conditioned room of controlled temperature and

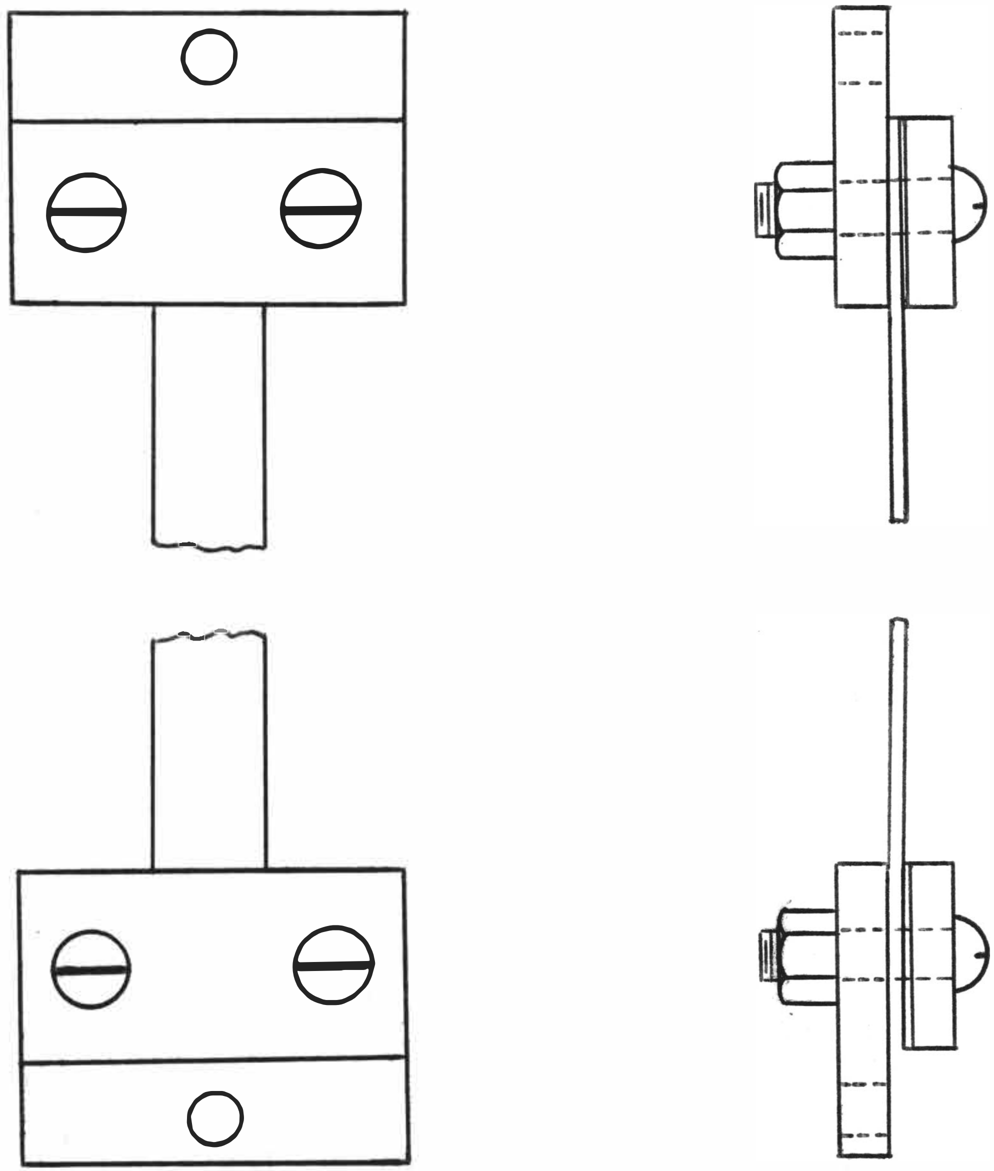


Figure 3. Clamps

humidity. The upper clamp was suspended and the lower clamp held the load. Loads used were 14.76, 13.73, 12.72, 10.89 and 9.90 pounds. Strips were cut 15 mm wide from selected handsheets and placed with a 4-inch span between the clamp jaws. The timing apparatus was located directly beneath the load in such a position that upon breaking the sheet, the weight would fall and shut the electric clock off. This arrangement is shown in Figure 4. The time of placing the strip under load was noted and with the clock being stopped upon sheet rupture, the time under load could be determined very easily.

The results of the study of the relationship between time to break and load applied is shown in Figure 5.

It is evident from this study that sheets will break at loads less than the maximum tensile load required for immediate rupture. From Figure 5, it can be seen that, for a period up to one week, the time to break increased with decreasing load applied. This relationship is linear between the logarithm of the time required for sheet rupture and the load applied, over this time period.

These data are useful because they verify the work of Rance (17), shown in Figure 1.

After sheet rupture occurred in the study of the relationship of time to break versus load applied, the zero-span tensile strength was determined. The results of these zero-span tensile strength tests are shown in Table VIII.

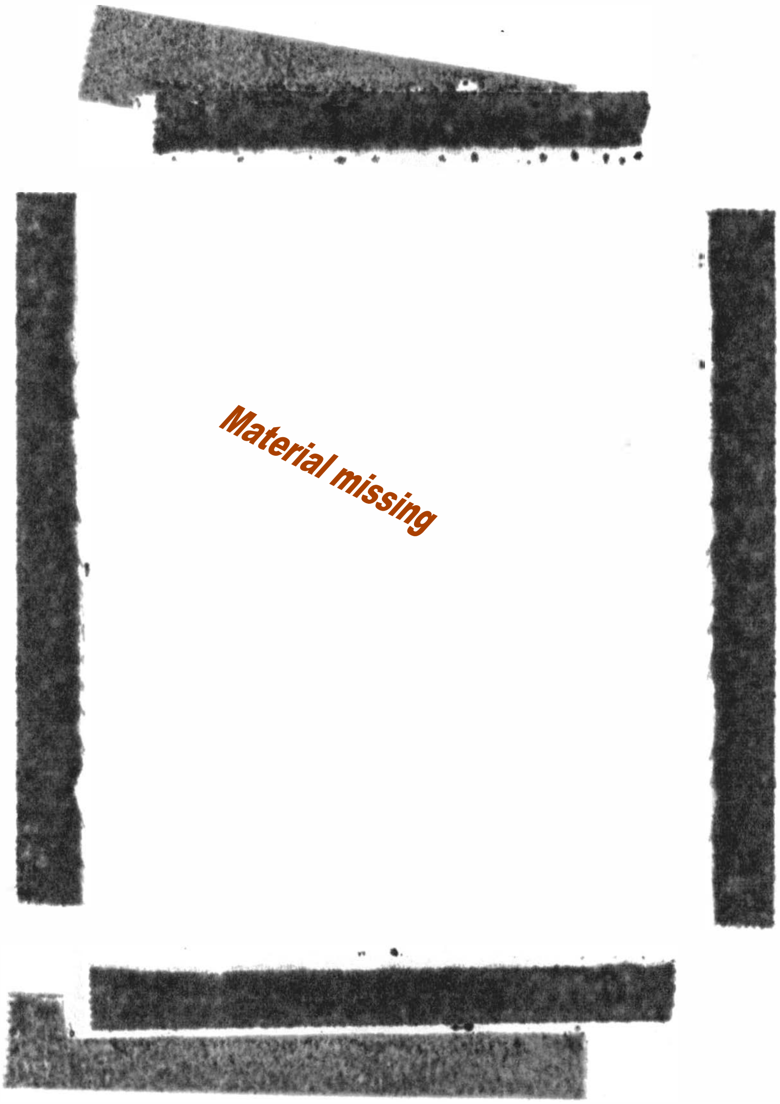


Figure 4. Assembled Apparatus

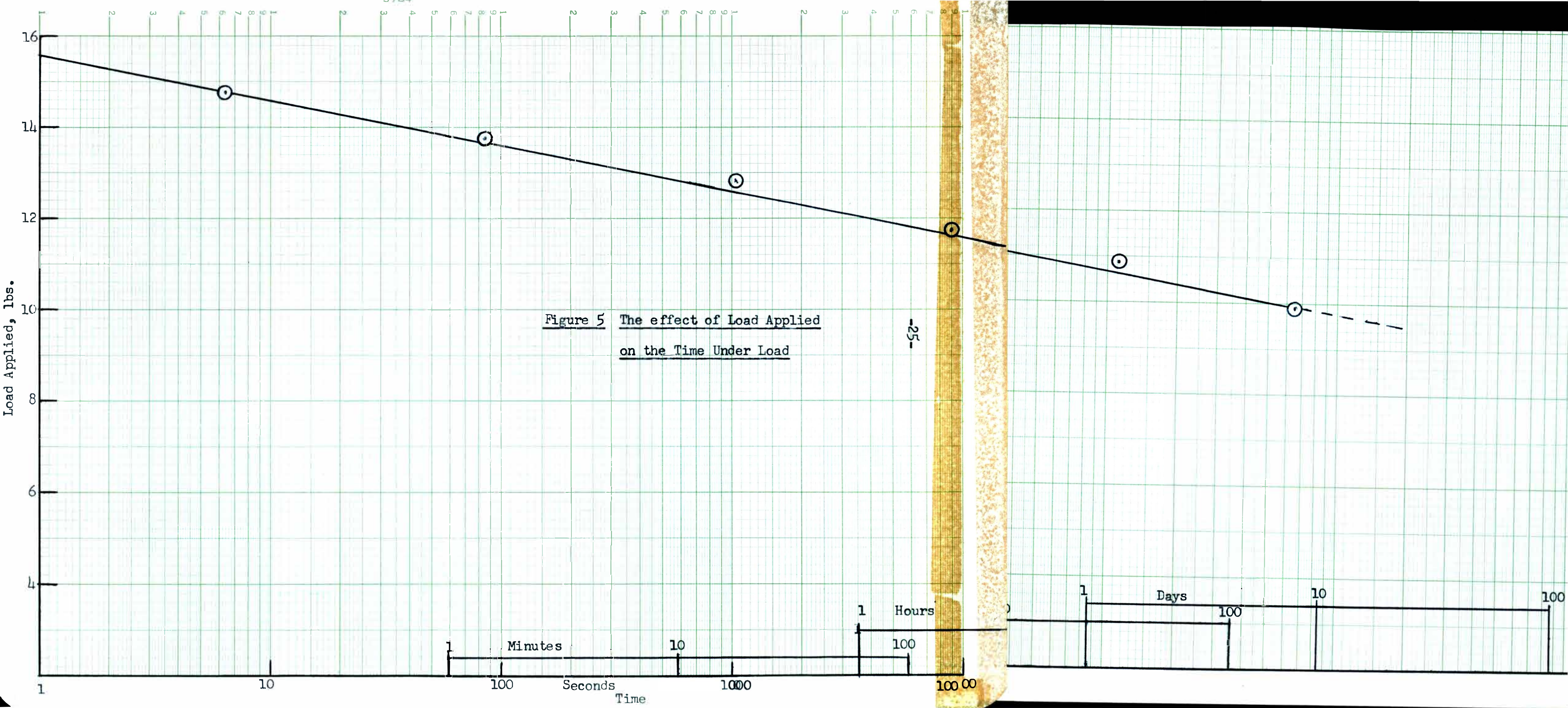


Figure 5 The effect of Load Applied on the Time Under Load

TABLE VIII

EFFECT ON ZERO-SPAN TENSILE STRENGTH OF APPLIED LOAD

Load Applied lbs.	Average Time to Rupture	Average Zero-span Tensile Strength lbs.
14.76	6.5 seconds	45.3
13.73	85 seconds	46.6
12.72	20 minutes	45.4
10.89	30 hours	46.0
9.90	1 week	45.2

From Table VIII, it can be seen that there is no change in the zero-span tensile strength that can be attributed to the weakening of the fibers of the sheet. The small differences are assumed to be due to experimental error, indicating that in the weakening of a sheet until it ruptures, by means of applying a tensile load, the breaking of fiber-to-fiber bonds within the sheet takes place. Also shown is that the intrinsic strength of the fibers is not affected during this weakening.

DETERMINATION OF THE RATE OF WEAKENING DUE TO AN APPLIED LOAD

It was found in the study of the relationship of time to break versus load applied, that in the time period studied, a sheet, when subjected to a tensile load less than that required for immediate rupture, is weakened continually until it finally fails. It was also indicated by this study, that this weakening is due to the breaking of fiber-to-fiber bonds within the sheet.

The determination of the rate of weakening due to an applied load was carried out to examine this weakening effect and determine the effect of different tensile loads and the time of application of these loads on the rate of weakening of a sheet.

In determining the rate of weakening due to an applied load, loads of 13.73, 12.72, 11.89 and 10.89 pounds were used. The time to break at each of these loads had been determined in the study of the relationship of time to break versus load applied.

These loads were applied at periods less than that required for immediate rupture and the tensile strength determined after removal of the load. The results of applying loads for less than the time required for immediate rupture is shown in Table IX and Figures 6, 7, 8, and 9.

TABLE IX

EFFECT OF LOAD APPLIED FOR VARIOUS TIME PERIODS ON TENSILE STRENGTH

Load Applied Previous To Tensile Strength Test-Lbs.	Time Under Load	Tensile Strength Lbs.
0	0	15.8
13.73	30 sec.	15.4
13.73	60 sec.	15.1
12.72	10 min.	14.3
12.72	15.min.	14.5
11.89	30 min.	14.6
11.89	60 min.	15.1
11.89	90 min.	14.4
10.89	8 hours	15.3
10.89	16 hours	15.1
10.89	24 hours	14.5

From examination of Table IX and Figures 6, 7, 8 and 9, it can be seen that the tensile strength will decrease because of an applied load continuously until rupture and that the tensile strength decreased as the time under load increased. There is also some evidence that the rate of weakening of a sheet increases as the time under load increases until rupture occurs.

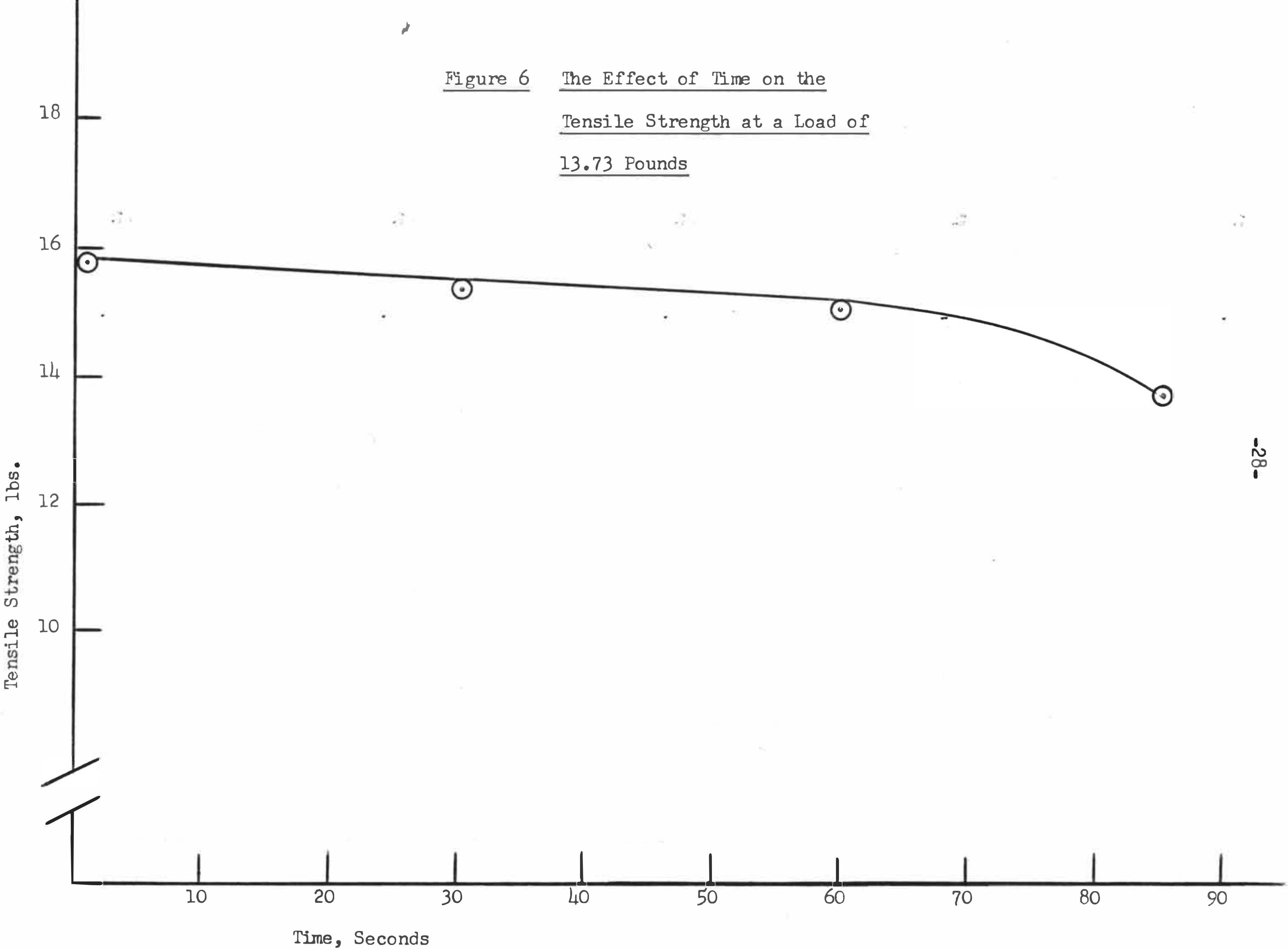


Figure 6 The Effect of Time on the Tensile Strength at a Load of 13.73 Pounds

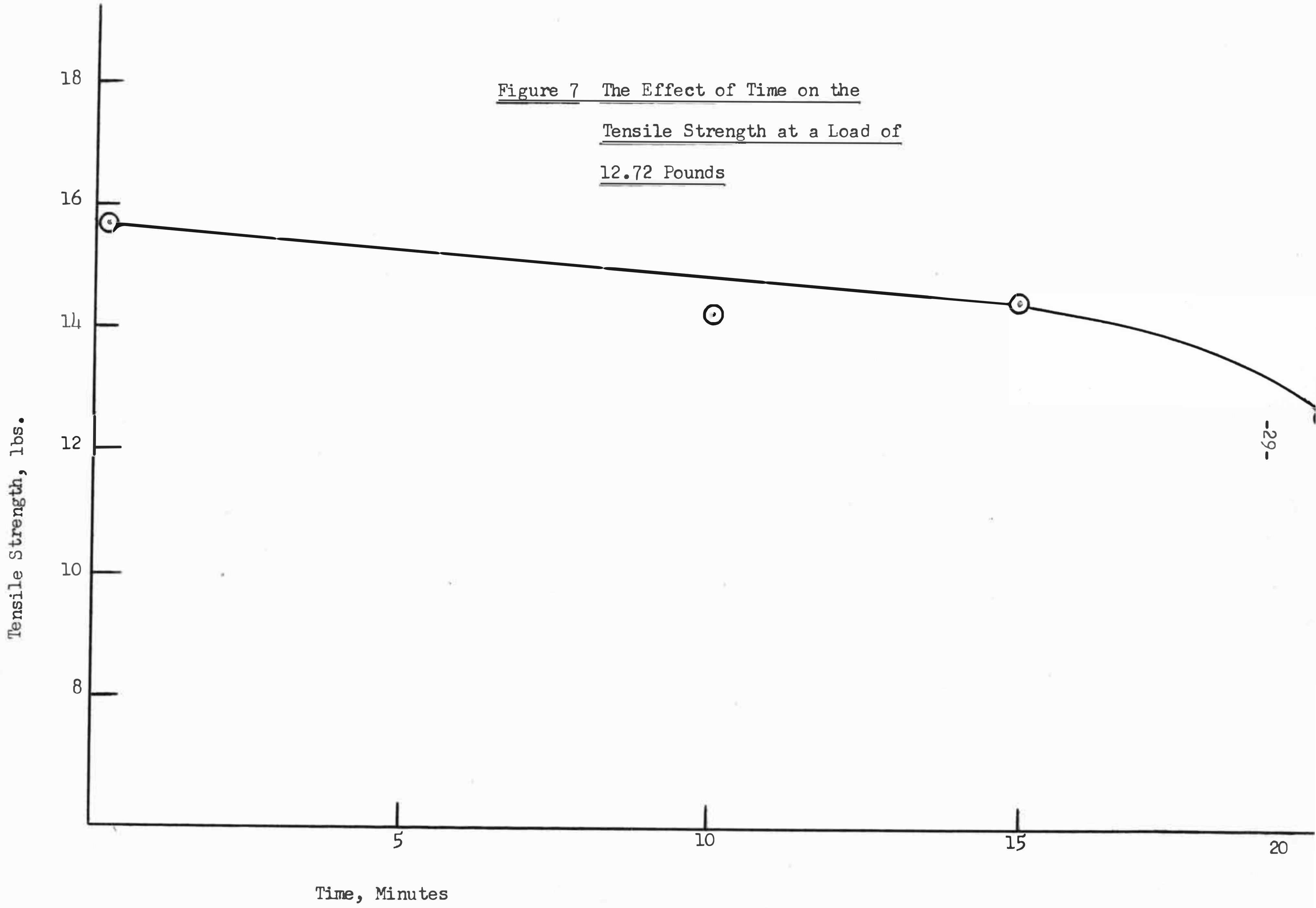


Figure 7 The Effect of Time on the Tensile Strength at a Load of 12.72 Pounds

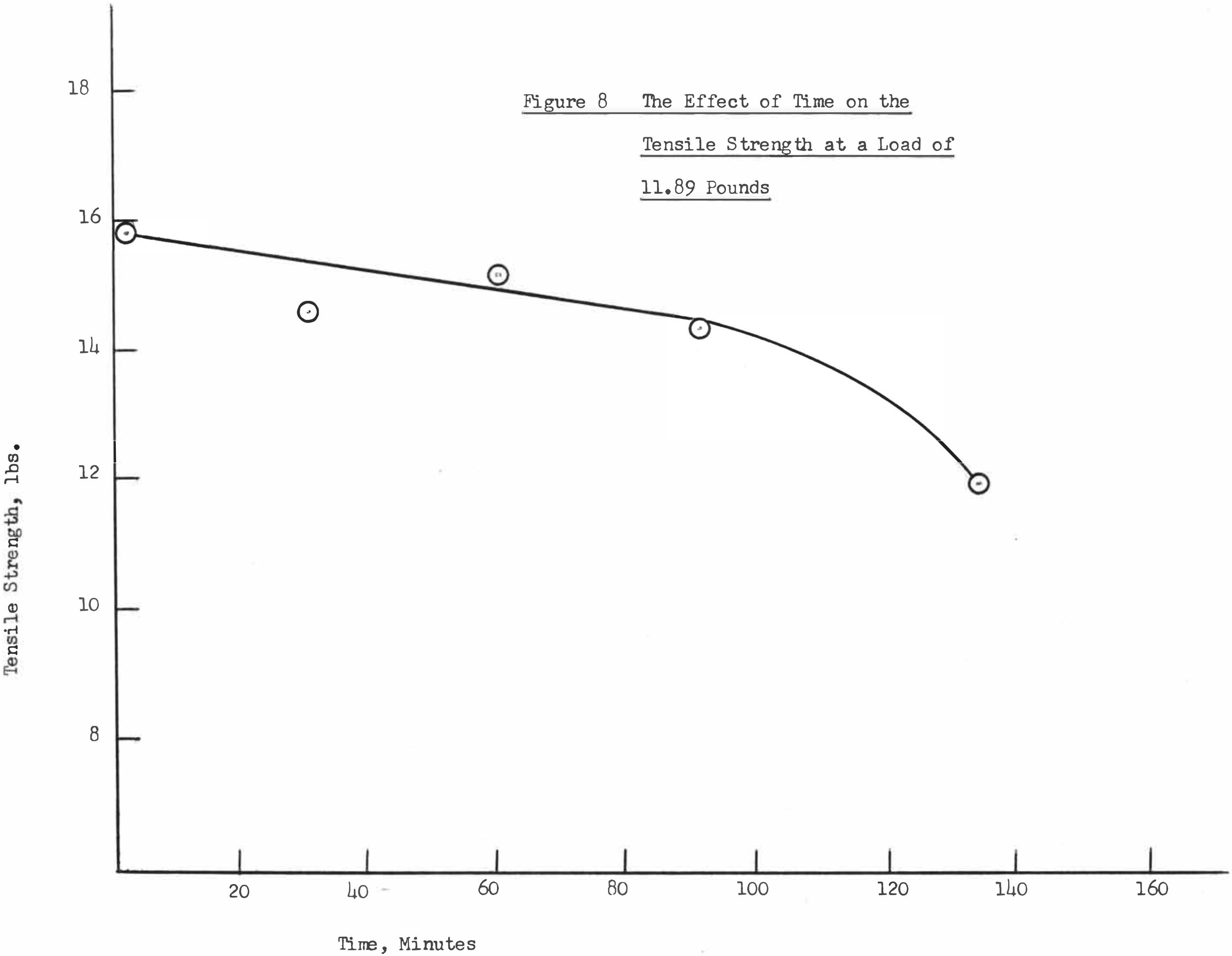


Figure 8 The Effect of Time on the Tensile Strength at a Load of 11.89 Pounds

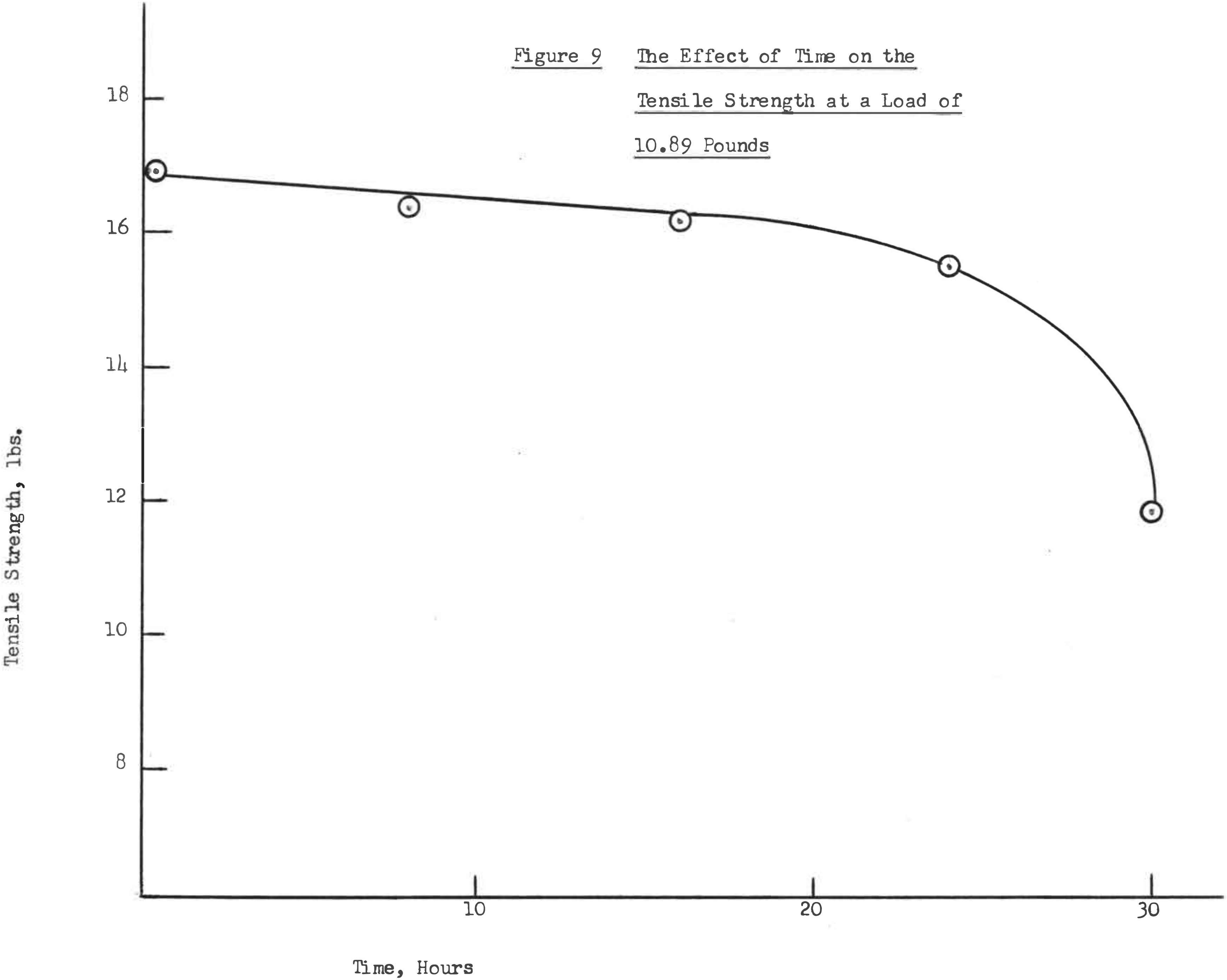


Figure 9 The Effect of Time on the Tensile Strength at a Load of 10.89 Pounds

SUMMARY AND CONCLUSIONS

Procedures and equipment were designed and constructed to determine the rate of weakening of paper and the factors which were effected by this weakening.

A softwood alpha pulp was used in all work. A study of handsheet reproducibility was carried out, followed by a study of the relationship of time to break versus load applied, previous to the determination of the rate of weakening.

From the work carried out it is evident, that a sheet will be weakened continually until rupture, because of an applied load. As the intrinsic fiber strength is not effected by the applied load, the weakening can be attributed to the breaking of fiber-to-fiber bonds within the sheet. As the load applied is increased, but less than the maximum tensile strength of the sheet, the time required for rupture decreased at periods up to one week. The rate at which a sheet is weakened will increase as the time under load is increased until rupture.

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