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Abstract

The stress-strain behavior of parachute cloth, MIL - C - 7020, I, was measured for different rates of load increase (1 - 450 lbs/sec), at creep conditions (70 - 95 % of nominal breaking load), and at fatigue tests under a sinusoidal load (0.1 - 60 cps, different amplitudes and upper load limits). The machine used and test procedure is described and explained in detail. Test results are given in list and graphical form to show the decrease in strength under dynamic loading conditions.

CONTENTS

1. SYMBOLS

σ_{Bo}	lbs/120 threads	nominal breaking strength
σ_{max}	lbs/120 threads	maximum stress at cycling loads
σ_{min}	lbs/120 threads	minimum stress at cycling loads
ε_B	%	breaking elongation
ε_{max}	%	maximum elongation at cycling loads
ε_{min}	%	minimum elongation at cycling loads
t	sec	time
t_B	sec	breaking time

2. INTRODUCTION

Maximum stress, stress distribution and stress history of an inflating parachute canopy is still unknown. Theoretical and analytical attempts to calculate the stresses in a canopy have failed because of the problem and the complete lack of experimental data.

The detection of static or dynamic stresses by the measurement of strain, which is made so easy by the use of strain gages for metals and other elastic materials, has not yet been applicable for nylon cloth. Parachute cloth is elongated about 30 % of its original length before it breaks. None of the existing strain gages has this quality. Even if the elongation would be less a strain gage applied to the cloth would change the strain at the point of measurement and yield false results.

Another reason why strain measurements are not very meaningfull is the viscoelastic behavior of nylon material. The stress-strain curve does not follow a simple linear law like Hookes law. It is not linear and dependant upon time. Nylon elongates under a constant load, it creeps, and it does not reach its original length again, when the load is taken away. Even it the measurement of strain would be possible the evaluation of the actual stresses from these data would be very difficult. The whole loading history of the nylon would have to be registered. But such a method does not promise to be very successfull when loading histories with random frequencies and amplitudes in a highly dynamic process like a parachute inflation have to be expected.

Another experimental way for the detection of stress in an inflating parachute canopy has been tried by the author [1,2,3] by measuring the pressure distribution and its history during the inflation. Using these experimental data in the stress-analysis method of Heinrich and Jamison [4] resulted in stress values in the order of only 10 % of the nominal breaking stress, even for cases where the canopy was overloaded and broke.

The reason for this discrepancy in actual and calculated values is probably mainly due to the assumption made in the stress analysis method that the nylon material is elastic and its stress-strain behavior follows Hookes law.

Again the need for the investigation of the unknown stress-strain behavior of nylon parachute cloth appeared. This report contains the results of a program that should answer mainly the 3 questions:

1. How is the stress-strain behavior of nylon parachute cloth under dynamic loading conditions?

2. Is the breaking strength under dynamic loading conditions less than the nominal breaking strength?

3. Can strain gages or any other method for the measuring of strain be applied to determine the stress in a parachute canopy?

3. THE TESTING MACHINE

To cover the whole range of parachute application a testing of the cloth up to 60 cps frequency for fatigue tests was wanted. It should be possible to apply high rates of load increase from zero loading to breake up to 450 lbs/sec, which responds to a breaking time of 1/10 of a second. Because of the high elongation of nylon a stroke of ± 1 inch should be performed at 5 cps, at 60 cps still ± 0.1 inch.

Sine wave, square wave, and ramp functions should be produced and load or stroke be controllable.

These specifications were met by the MTS closed-loop,electro-hydraulic, expanded range materials testing system. It consists of 3 units (Fig. 1): the hydraulic power supply, the control console, and the load frame with the electro-hydraulic actuator.

The hydraulic power supply produced 3 gallons per minute at 3000 psi by a water cooled piston pump driven by a 6.25 hp electric motor.

The 3 column frame was rated at ± 50 000 lbs dynamic and ± 100 000 lbs static tension and compression. A load cell (Lebow fatigue load cell), range ± 2000 lbs, was mounted at the mounting screw of the upper crosshead. Later the upper grip was attached to the bottom screw of the load cell.

The lower grip was attached to the piston rod of the electro-hydraulic actuator, called Servoram. It is designed for a long stroke of 4 inches, a high speed up to 1150 in/min at 2000 lbs load and a 5 gpm servo valve, and high frequency fatigue testing, performing more than the required 60 cps. The servoram model 204.11 is rated at ± 2500 lbs dynamic tension and compression. It has a built in LVDT type, stroke displacement transducer.

A line tamer rated at 20 gpm was added between pump and actuator to provide hydraulic filtration and suppression of line pressure fluctuations in the high response actuator supply and return hoses as well as any instantaneous surge requirements demanded by the sevo valve.

The control console contains a function generator, a counter panel, a transducer donditioner module, a recorder, an oscilloscope, control panel, recorder input selector and the closed-loop control unit, named Servac.

The Servac is an integrated, solid state, electronic servo-controller. It is the main component of the MTS system. It controls the electro-hydraulic servo valve which regulates the flow of the hydraulic fluid to and from the hydraulic actuator. The controller compares the program value of the controlled parameter (load, stroke or strain) with the actual value which is read by a transducer and sends a correction signal to the servo valve which in turn controls the actuator to establish the desired value.

The function generator could provide sine, square, triangle and sawtooth waveforms from 0.001 to 1100 cps. It also generated ramp functions with rise times between 0.005 and 500 seconds.

The built in recorder was a Brush model, mark 280, a 2-pen, high speed, strip chart recorder. It provided a permanent ink record, 80 mm maximum response with an accuracy of 0.5 % up to 35 cps. Higher frequencies could be recorded with the same accuracy at lower amplitudes.

The built in oscilloscope was a Hewlett-Packard model 130 C.

4. TEST PREPARATIONS

Gripping of the specimen

The testing machine was delivered without grips but with adapters for Instron webbing capstan grips, model G-61-11F. These grips were purchased from Instron but proved to be to heavy for the dynamic testing system, when we used the low load range 0 - 200 lbs. The weight of the grip (20 lbs) on the actuator piston did not permit good sine or other wave forms and caused vibrations in the whole test frame. These vibrations were transmitted to the upper grip on the load cell which caused a load reading. It was found that the weight of the grips should be not more than 1 lb to eliminate the mass effects. The grips shown in Figures 1, 4, and 5 were fabricated in the University machine shop and weighed less than 1 lb.

The width of the specimen was chosen with 1.0 inch. Since this definition was not exact, a number of 120 threads was chosen, which comes very close to 1 inch for the used Ripstop material.

For the gripping the ends of the test specimen was glued between two aluminium plates on each end (Fig. 2). Shell Epon Resin 820 with curing agent V 40 was used in a 60 to 40 mixture.

The bonding was generally satisfactory only at frequencies of 10 or more cps and large numbers of cycles it was observed that the threads became loose and moved in the glue, probably only for a very short distance. But no increase of clamp breaking could be observed due to a frictional abrasion.

The large number of clamp breaks which occured sometimes during the first test series turned out to be due to not perfect alignment. When in the final test series the alignment was done with great care and perfection almost no clamp break occured any more.

The preparation of the specimen was done in the following way:

1. 24 strips of cloth, 8 inches long in the warp direction 1.4 inches wide were cutted out of one piece of cloth from the left side to the right side of the 36 inches wide roll of cloth. 1.5 inches on each edge was thrown away.

2. 4 jigs, each for 6 specimens, were used for the alignment and bonding to the metal plates (see Figure 3). First one layer of metal plates were fixed to the lower part of the jig (left in Fig. 3) and aligned with it. The same was done with the upper part of the jig (right) and then all plates were covered with glue. Second the specimens were clamped in the clamps of the middle part of the jig and also aligned properly. Finally all 3 parts of the jig were put together and loaded with a 10 lbs weight. It needed about 12 hours for proper bonding.

3. The specimens were taken out of the jigs and the loose threads plus some more on both edges pulled out until 120 were left.

The jig permitted a free length of the specimen of 4 inches.

The amount of glue used was just that much that no surplus glue could be sqeezed out, but enough so that no threads could be pulled out from between the metal plates.

Great accuracy was necessary with the alignment of the specimens in the grips. First the threads were checked to be vertical and the horizontal threads were aligned with the edge of the upper grip with the help of a magnifying glass. Then the same procedure was done at the lower grip.

Figures 4 and 5 show one specimen before and after the test.

5. THE TEST PROGRAM

The specimens were tested in the wharp direction. The testing length was 4 inches, the width was 1 inch, or more exact 120 threads.

In so called "ramp" tests the rate of load was varied. The increase was always linear and the time from zero to breaking varied between 0.1 and 350 seconds.

The nominal breaking strength was defined from these tests as the average from a large number of tests made at breaking times of approximately 50 seconds, which is a rate of load of 1 lbs/sec.

Creep tests were made at constant loads of 95, 90, 85, 80, 75 and 70 % of the nominal breaking load. The load increased to these values in 0.1 seconds and was then kept constant by the control till fracture occured.

Fatigue tests were made with sinusoidal load functions. The upper load limit was varied between 95, 90, 85, and 80 % of the nominal load, the lower limit between 0, 50, 75, and 85. The combination can be seen from table 3. The frequency was mostly 10 cps, for the 0 - 85 % combination it was changed to 20, 40, 60, 5, 1, and 0.1 cps.

Creep recovery tests were made with low frequency square wave functions to measure recovery capability and constant elongation. The chosen frequency was 0.05 cps (0.005 cps was tried once), the upper load limit was varied between 90, 85, 80, and 75 %, the lower limit was always zero.

6. TEST RESULTS

The results are shown in tables 1 through 4 and figures 6 through 18.

a. Definition of nominal breaking strength

Values for the breaking strength of parachute cloth, as given for instance in the parachute handbook are gained by conventional testing machines which need a time between 30 seconds and 1 minute to make a stroke of 1 inch which is necessary to break a 4 inches long specimen.

It was therefore decided to call the strength value gained at a breaking time of 45 seconds with linear load increase "nominal breaking strength".

This value will always be an average from a large number of tests, since there is a scattering due to inhomogeneity in the material and to inaccuracy in preparing the test specimen and adjusting it in the grips of the testing machine.

The average from 11 tests with breaking times between 40 and 50 seconds was:

46.5 lbs = nominal breaking strength for MIL-C-7020, Type I

Tests where the fracture occured at the clamp were eliminated for the determination of the average, but their results are shown also behind the eleven good tests in table 1.

b. Influence of rate of load on breaking strength

In practice the load increase occurs much faster than under the nominal condition. In the "ramp" test series the rate of load was therefore increased by setting very short breaking times down to 0.1 seconds.

The results are shown in table 1 and fig. 6. In figures 7 and 8 several original recordings from tests with breaking times of 50, 5, 1, 0.5, and 0.1 seconds are reproduced. Four tests with extremely long breaking times of 350 seconds were made which resulted in a 10 % lower breaking strength. But at such a long time we have already a remarkable influence of creep which is responsible for the lower strength.

Down to shorter breaking times the breaking strength is slightly increasing. The increase amounts to about 10 % at breaking times of 1 or less seconds where it did not increase any more. It can be concluded that for breaking times longer than 1 second an influence from creep appears. This will be discussed in more detail under the creep test results.

Figure 6 shows all the results of the ramp tests from two test series.

The accuracy in the preparation of the specimens was not quite satisfactory for the first test series (specimen numbers below 200) what resulted in clamp breaks for 60 % (31 out of 51) of the tested specimens.

In the advanced test series (specimen numbers 200 and higher) the preparation of the specimen was done with more accuracy and no clamp break due to this fact seemed to occur any more. The 20 % (8 out of 39) clamp breaks occured all at the high loading rates with breaking times shorter than 0.5 seconds and probably have another reason like a dynamic effect. The fracture, however, did not take place always at the lower grip, which is moving, but also at the upper grip, which is at rest, so that an explanation can not be given.

The location of break is given in table 1, 5th column, in % of the specimen length from the bottom grip. Hence 0 % indicates a break at the lower clamp and 100 % a break at the upper clamp.

As figure 6 shows all the clamp breaks lie well within the scattering of the good tests. This scattering of breaking strength must be due to inhomogeneity in the material. The unequality probably gets in during the stretching process after the spinning of the filaments which is done to coordinate the molecules to give the material some elasticity. This stretching which is done to approximately 4 times of the original length does probably not occur in an even distribution over the length of the filament and results finally in a scattering of the break elongation. It can be seen very clearly from table 1 that low breaking strength goes together with low break elongation and vice versa.

Question 2, whether the breaking strength becomes less at higher loading rates, could be answered by the ramp tests: It is not the case, but the breaking strength can increase up to 10 %.

c. <u>The Influence of Creep</u>

It is possible to break the nylon cloth under lower loads than the nominal breaking load if the lower load is allowed to act for a sufficient amount of time.

This time is the shorter the closer the applied load is to the nominal load, for loads less than 70 % of the nominal value (46.5 lbs for the 1.1 oz MIL-C-7020 cloth) the breaking time came to the order of days and was probably close to a limit where the load was not high enough to cause enough creep for the breaking.

Tests were made with 95, 90, 85, 80, 75, and 70 % of the nominal breaking load. The results are shown in table 2 and figures 9 through 13. Figure 14 shows 4 copies of original creep test recordings. Four to eight tests were made under each condition, with exception of the 75 and 70 % where because of the long testing times only 2 and 3 tests were made.

The figures 9 through 12 are the elongation over time recordings. All parallel tests under equal loading conditions are put together in one diagram. All of them show a large scattering in breaking time and in breaking elongation. The times scatter by one power of ten and the elongations between 16.6 and 23.0 %, where normally the low breaking elongations go together with the short breaking times.

This again can be explained with inhomogeneity in the material and to some degree with the always remaining inaccuracy in the alignment of the specimen.

It could be observed that in some cases the first thread or single filaments of it broke very early. This very often caused the adjacent threads to break earlier too. In such cases the rate of elongation was higher and fracture occured at a shorter time.

In other cases where no early thread break occured and the rate of elongation was normal the specimen broke at a lower breaking elongation (compare for instance figure 12, specimen numbers 253, 254, 255) which resulted also in short breaking times. These cases did not have the high increase in rate of elongation some seconds before break (compare for instance figure 11, specimen number 246) but broke abruptly. It can be assumed for instance that the threads of this specimen had suffered another amount of prestretching during their fabrication.

From these considerations it can be infered that the specimen with the highest homogeneity in the material and the highest accuracy in preparation have the longest breaking times. Consequently the test with the longest breaking time was taken from each group and all together were plotted in figure 13. Here the curves arrange themselves in a significant manner. The breaking elongation seems to decrease with the applied load and increasing breaking times.

It is assumed that after long loading times with a high constant load, as well as with high cycling loads some changes in the physical structure of the material take place which cause kind of a hardening effect. This effect decreases the rate of elongation and by this extends the breaking time. But this is only an assumption and can not be proved by the results.

The result of the creep tests is the statement that the cloth can break already at 70 % of the nominal load if the load acts constantly for about 10 minutes.

d. Fatigue test results

The influence of cycling loadings was investigated by applying sine wave loadings. For one test series the frequency was kept constant with 10 cps and the upper load, σ_{max}, and lower load, σ_{min}, varied.

The set-up is described in table 3, column 1. σ_{max} was set 80, 90, and 95 % of σ_{Bo}. σ_{min} was set once close but some lbs higher than zero, and than at 50 %. For the σ_{max} = 85 % setting σ_{min} was also set at 75 and 85 %. The last setting with 85 - 85 % was identical with a 85 % creep test.

In a second test series the setting σ_{max} = 85 % and σ_{min} close to zero was kept constant but the frequency changed between 0.1, 1, 5, 10, 20, 40, and 60 cps.

Again a large scattering in the numer of cycles to break can be seen which will be caused by the influences of inhomogeneity and inaccuracy which were already mentioned with the creep and ramp test results. But if we take the highest numer of cycles reached for each condition, the results are arranged again in an orderly manner. For the 0 to 80, 85, 90, 95 % series the cycles to break are approximately 34 000, 16 000, 3 000, 700.

When we raised σ_{min} to 50 % the lifetime of the specimen got higher to 39 000, 18 000, 5 000, 1 300 cycles and still higher (55 000 for σ_{max} = 85 %) when we raised σ_{min} to 75 %.

It is hard to find an explanation for this result. One would have expected that the lifetime decreases the higher σ_{min} gets and the less recovery is granted.

When we increased σ_{min} to a zero amplitude of the wave, thus having a 85 - 85 % setting, which responds to a 85 % creep test the lifetime did not increase further but was remarkably shorter with only 500 seconds (corresponding to 5000 cycles). This value corresponds very well with the results from the creep setting.

When the frequency was raised from 10 to 20, 40, 60 cps (see table 4) the number of cycles increased from 16 000 to 24 000, 97 000, 225 000 cycles, and also the breaking times from 1 600 to 1 200 (no increase), 2 400, 5 600 seconds.

Down to 5 and 1 cps the breaking times were much shorter with 100 and 400 seconds but at 0.1 cps with 2 500 seconds again very high so that no clear impression can be gained.

These results are demonstrated graphically in figure 15.

The breaking elongation scattered again in the known way with lower values for shorter times.

A ratio $\xi = \sigma_{min} / \sigma_{max}$ was defined and one plotting made to look for the influence of ξ (figure 16A). It is very hard to read an influence, the curves lie close together.

The plotting was made with σ_{max} over the logarithm of the breaking time and indicates by the straigth line that a logarithmic dependancy exists.

While in this figure only the tests with the highest time were plotted another diagram was made (figure 16B) using all test results from settings which had a ξ of about 0.18. The line drawn through the points almost coincides with the one for $\xi = 0.18$ on the figure before and shows that the spreading of time down to lower values can be larger. An explanation for the spreading was already given in the chapters before.

Figure 17 shows copies of 3 original recordings with one 15 - 85 %, one 15 - 95 %, and one 75 - 85 % setting. In the first recording the paper speed was increased twice by the factor of 100 to show the load and strain wave forms.

e. Creep-recovery test results

How does parachute cloth recover after being exposed to a certain loading and how is the stress-strain behavior at a new exposure after a certain time of rest? To answer these questions a square wave setting was used and a frequency of 0.05 cps chosen. This gave 10 seconds of constant loading and 10 seconds of rest at zero loading. Again loadings of 90, 85, 80 and 70 % of σ_{Bo} were investigated. Cycles to break were 4, 44, 75 and 425 with corresponding breaking times of 53, 660, 1485 and 8440 seconds (see table 5).

Compared with the creep tests the breaking times here are higher, but they do not reach twice the value of the creep tests or even more what should be expected when a recovery is granted from time to time.

One test was made with a frequency of 0.005 cps, what is a 100 seconds loading + 100 seconds rest cycle. Here the total time was much longer, but no conclusions can be formed from only one test.

The recordings show also that the recovery time has only very little influence. Figure 18 is the recording from the 200 seconds/cycle (0.005 cps) test. σ_{max} was 37.4 lbs (80 %), $\sigma_{min} = 0$. Roughly seen if the recovery was 1 scale the elongation at the next loading starts only 1/10 of a scale lower than it ended the time before. The rate of elongation was a little lower than at a corresponding creep test and the breaking elongation was 0.6 % higher compared with test number 269. Both deviations may be responsible for the breaking time which was 3 times the time of test 269.

The 20 seconds/cycle tests, however, have a slightly higher rate of elongation or no difference to the creep tests and no systematic behavior is indicated.

As a first approximation one can say that recovery has no effect on the elongation history and that the elongation depends only upon the loading history neglecting the times of rest.

7. SYMMARY, CONCLUSIONS, RECOMMENDATIONS

We have gained information about the stress-strain behavior and the breaking strength of a nylon parachute cloth under different static and dynamic loading conditions.

The stress-strain curve is non-linear and the nylon material not elastic. A linear law like Hookes law can not be applied for these reasons, because of the second reason not even in a first approximation. Not only the amount of load but also the load history has to be considered.

The nylon cloth creeps under load and the stress relaxes when a constant elongation is kept. A permanent elongation remains after the load is removed (compare with figure 18 and see table 5). It is getting higher after each loading as long as the maximum elongation increases. The difference $\varepsilon_{max} - \varepsilon_{min}$ remains rather constant during a cycling test with a constant $\sigma_{max} - \sigma_{min}$ setting. $\varepsilon_{max} - \varepsilon_{min}$ is dependent upon this stress limit setting and upon the frequency. It decreases with increasing frequency.

The breaking strength decreases with decreasing loading rates because of creep influence and it decreases generally with increasing loading times because of the creep effect.

When we consider the scattering in breaking elongation to be due to inhomogeneity in the material and inaccuracy in the specimen alignment we can conclude that breaking occurs when a specific elongation is reached. For our nylon cloth this value was approximately 20 %.

Since creep contributes to the elongation this influence or generally time has to be considered in all stress-strain measurements or calculations.

The results from the cycling loadings in the fatigue test can not be considered to explain a fatigue characteristic of the material, it is again a creep effect that causes the fracture.

The number of cycles per second has no significant influence on the breaking strength. That the breaking time increases with the number of cycles per second may have other reasons and can not be explained. It is guessed that kind of a hardening effect in the material causes a flattening of the elongation increase.

It has to be concluded from these results that the detection of stress by the measuring of strain by means of strain gages is impossible. A method might be found to measure strain, but at a filling parachute with its very complex loading history the calculation of stress from a measured strain history of the nylon cloth will be impossible. A direct measurement of stress should be attempted, but with any method it has to be watched that the threads are not prevented from elongation or the stress is concentrated or diluted at the point of measurement.

One influence could not be investigated during these tests: the influence of weaving, i. e. the interaction of fill and wharp threads. It was observed during the tests that the specimen constricts under load in the middle. At breaking load this constriction amounted up to 10 % of the original width.

It can be concluded from this observation that an interaction between fill and wharp threads exists, and it is assumed that at cycling loading conditions the breaking strength is affected. The investigation of this problem of interaction would be another step to a better understanding of the stress events in a filling parachute canopy.

It can be presumed that other types of nylon cloth have a similar characteristic behavior to the one that was investigated. They should be tested however in the same manner to gain exact information and the possibility for comparison, to verify the existing results.

8. REFERENCES

[1] H.D. Melzig, F.K. Schmidt, Parachute Canopies During Inflation, AD 631 777, Sept. 65

[2] H.D. Melzig, P.K. Schmidt, Pressure Distribution During Parachute Opening, Phase 1: Infinite Mass Operating Case, AFFDL-TR-66-10, March 1966

[3] H.D. Melzig, The Dynamic Pressure Loading on Parachute Canopies, AIAA Aerodynamic Deceleration Systems Conference, Houston, Texas, Sept. 1966

[4] Heinrich H.G., Jamison L.R., Parachute Stress Analysis during Inflation and at Steady State, Journal of Aircraft, Vol. 3, No. 1, Jan. 1966

9. BIBLIOGRAPHY

The following list resulted from a study of technical abstract bulletins and bibliographies. Most of them could not be released to the author due to University regulations. Therefore, no reference could be made in the text of this report to possibly existing similar or other results of interest.

1. Baker, A. and Swallow, J. E., Impact Testing of Textile Yarns, AD 232 617, RAE TN CHEM 1381

2. Williams, R. B. and Benjamin, R. J., Analysis of Webbing Impact Data and Determination of Optimum Instrumentation to be Used in Conjunction With the Impacting of Webbing, AD 237 171, WADC TR 59-694

3. Bickford, H. J., Kuehl, D. K. and Rusk, J. L., The Development of High Strength Nylon Parachute Fabrics, AD 101 948, WADC TR 55-465

4. Chu, C. C., Coskren and Morgan, Investigation of the High-Speed Impact Behavior of Fibrous Materials, AD 247 493, WADD TR 60-511

5. Chu, C. C., Kaswell and Doull, Development of High Tenacity-Heat Stable Dacron Parachute Items, AD 155 511, WADC TR 57-765

6. Coplan, M. J. and Block, M. G., A Study of Parachute Seam Design Criteria, AD 110 407, WADC TR 56-313

7. Klein, W. G., Lermond, C. A. and Platt, M. M., Research Program for the Development of a Design Procedure to Engineer Parachute Fabrics, AD 155 517, WADC TR 58-65

8. Klein, W. G., Lermond, C. A. and Platt, M. M., Development of Design Data on the Mechanics of Flow Through Parachute Fabrics, AD 131 055, WADC TR 56-576

9. Lavrakas, V. and Katz, A., The Effect of Surface Finishing on Friction and Fusion of Parachute Cloth and Line, AD 918 73, WADC TR 54-323

10. Krizik, J. G., Backer, S., Victory and Cheatham, Design Data on Biaxial Forces Developed in Parachute Fabrics, AD 142 208, WADC TR 57-443

11. McCardy, J. W., Handbook of Parachute Textile Materials and Properties, AD 891 71, WADC TR 55-264

12. Miller, C. R., A Study of Parachute Seam Design Criteria, AD 110 406, WADC TR 56-313

13. MIT, Textile Div., Impact Behavior of Mechanical Textile Materials, AD 139 272

14. McLean, W. L., Nylon Webbing Impact Load Tests, AD 801 612

15. Neff, R. J., Development and Evaluation of Webbing made from Nylon 6, AD 151 090, WADC TR 57-538

16. Lavrakas, V., The Effect of Fabric Structure on the Frictional Fusion of Parachute Materials, AD 90859, WADC TR 54-570

17. Corry, W. A., Some Principles of Parachute Fabric Construction, WCRT 54-181, WADC TN

18. London, A. L. and Tong, L. S., Heat Transfer and Flow Friction Characteristics of Woven-Screen and Crossed-Rod Matrixes, ASME paper, 56-A-124

19. Barish, L. Et. Al., Fine-Wire Multifilament Yarn, Metal Fabric, AFML-TR, 65-313

20. Development of Nylon Webbing Impact Load Tests, AD 801 612

21. Cash, B. A. and Drummond, W. W., Development of Textile Type Vitreous Silica Yarns, AD 238 371, WADC TR 59-699

22. Backer, S., Cheatham, R. G. and Shank, Textile Fibers in High Temperature Applications, AD 260 003, WADC TR 60-327

23. Morgan, Some Aspects of the Behavior of Textile Materials Under Impact Conditions

24. Smith, J. C., Characterization of Textile Yarns for Use Under Ballistic Impact Conditions

25. Blaudford, J. M., Shouse, P. J. and Smith, J. C., Stress-Strain Relationship in Yarns Subjected to Rapid Impact Loading

26. McCrackin, F. L., Schiefer and Smith, J. C., Stress-Strain Relationship in Yarns Subjected to Rapid Impact Loading

27. McCrackin, F. L., Schiefer and Smith, J. C., Characterization of the High-Speed Impact Behavior of Textile Yarns

28. Feustermaker, C. A., Shouse, P. J. and Smith, J. C., Stress-Strain Relationships on Yarns Subjected to Rapid Impact Loading

29. Bersch, C. F. Et. Al., Impact Testing of Textiles

30. McCrackin, F. L., Effect of Air Drag on the Motion of a Filament Struck Transversely by a High-Speed Projectile

31. Feustermaker, C. A., Shouse, P. J. and Smith, J. C., Behavior of Filamentous Materials Subjected to High-Speed Tension Impact

10. TABLES AND FIGURES

RAMP SETTING [sec]	LOAD [lbs/120 Thr.] σ_{Break}	ELONGATION [%] ε_{Break}	TIME [sec] t_{Break}	LOCATION OF BREAK % from bottom	SPECIMEN NUMBER
350	41.4	21.1	365	20	130
	42.8	21.7	367	40	131
	41.3	19.4	326	80	137
	42.2	22.6	343	40	138
50	43.6	17.1	41.0	70	200
	45.0	19.1	40.2	10	226
	46.2	21.0	46.8	70	227
	46.6	21.1	50.0	35	228
	46.2	20.2	49.5	75	229
	48.3	22.6	51.2	80	230
	48.3	21.8	51.8	50	231
	47.4	21.2	50.8	60	232
	47.1	21.8	50.6	20	245
	45.6	20.4	47.0	50	112
	47.2	22.6	41.7	50	132
	43.6	17.5	50.0	0	111
	45.5	20.4	45.8	0	113
	46.8	20.9	47.1	100	114
	39.7	16.5	40.4	100	115
	47.7	22.4	49.2	100	120
25	42.0	16.5	30.9	60	224
	45.7	17.3	18.1	80	225
	43.3	17.9	37.6	50	135
	43.4	19.0	35.6	80	136
	43.8	20.6	36.7	0	133
	44.7	19.5	38.7	0	134

TABLE 1 RAMP TEST RESULTS

RAMP SETTING [sec]	LOAD [lbs/120 Thr.] σ_{Break}	ELONGATION [%] ε_{Break}	TIME [sec] t_{Break}	LOCATION OF BREAK % from bottom	SPECIMEN NUMBER
10	51.0	22.2	11.9	10	241
	50.3	22.8	16.4	45	242
	49.9	22.7	10.1	25	243
	50.7	22.2	10.2	25	244
	46.0	17.9	7.7	40	167
	50.0	23.3	8.1	20	169
	46.7	20.1	12.9	100	116
	48.0	21.5	10.3	100	117
	48.0	19.2	7.9	100	118
	38.4	15.7	6.2	0	119
	49.1	21.3	8.1	0	166
5	48.1	21.0	4.3	90	201
	51.2	21.7	4.4	5	203
	51.4	21.8	4.4	50	204
	51.1	21.0	4.2	5	233
	48.0	20.8	4.0	60	139
	48.3	21.6	4.1	30	140
	42.9	16.6	3.4	40	144
	51.2	20.9	6.0	0	202
	48.6	20.2	3.9	100	141
	49.6	21.6	4.3	0	142
	49.8	22.9	4.3	0	143
1	53.5	22.0	0.94	5	235
	50.3	19.9	0.73	5	236
	52.5	22.7	0.94	20	237
	53.2	22.8	0.94	20	238
	52.0	22.7	0.94	90	239

Contd. TABLE 1 RAMP TEST RESULTS

RAMP SETTING [sec]	LOAD [lbs/120 Thr.] σ_{Break}	ELONGATION [%] ε_{Break}	TIME [sec] t_{Break}	LOCATION OF BREAK % from bottom	SPECIMEN NUMBER
	50.5	21.6	0.91	15	170
	50.0	20.1	0.85	15	172
	50.9	22.5	0.93	5	163
	49.5	21.3	0.86	100	164
	51.2	20.4	0.92	100	165
	49.8	21.1	0.84	0	171
.5	52.5	20.0	0.52	90	206
	51.4	19.6 (22.0)	0.46	25	208
	52.3	18.8	0.47	95	211
	51.2	22.4	0.52	80	145
	49.0	19.4	0.45	80	147
	45.0	16.7	0.34	50	151
	49.6	20.4	0.48	50	152
	52.1	20.1	0.48	0	205
	50.1	17.5	0.45	100	207
	49.9	17.8 (18.8)	0.46	0	209
	52.9	20.3	0.50	100	210
	52.1	20.8	0.44	100	146
	50.0	19.6	0.44	0	148
	46.4	16.7	0.39	100	149
	52.3	19.6	0.46	0	150
	52.0	22.2	0.50	0	154
	52.0	21.4	0.52	100	155
	50.0	21.9	0.48	0	156
	49.8	18.1	0.45	0	157
	48.4	18.5	0.41	0	158
	52.0	19.6	0.47	100	159
	50.0	21.3	0.46	0	160
	51.5	22.7	0.48	0	161
	52.0	20.8	0.48	100	162

Contd. TABLE 1 RAMP TEST RESULTS

RAMP SETTING [sec]	LOAD [lbs/120 Thr.] σ_{Break}	ELONGATION [%] ε_{Break}	TIME [sec] t_{Break}	LOCATION OF BREAK % from bottom	SPECIMEN NUMBER
.1	53.0	20.7 (21.9)	0.17	60	212
	50.0	17.0 (19.1)	0.13	5	214
	53.1	19.4 (21.4)	0.17	5	216
	53.4	21.6	0.29	95	234
	47.1	16.2	0.10	0	213
	52.9	20.5	0.15	0	215
	51.2	18.6 (18.9)	0.13	100	217

Contd. TABLE 1 RAMP TEST RESULTS

CREEP SET-UP	LOAD	ELONGATION		TIME	LOCATION OF BREAK	SPECIMEN NUMBER	REMARKS
	σ_{Break}	ε_{Break}	ε_o	t_{Break}	% from bottom		
[% of σ_{Bo}]	[lbs/120 Thr.]	[%]	[%]	[sec]			
95	44.5	22.8	16.7	33.5	30	264	
	44.4	20.5	16.9	32.6	70	265	
	44.3	22.0	16.5	31.5	5	266	
	44.1	19.9	16.4	3.7	95	267	
	44.5	23.0	16.6	10.6	75	268	
90	42.0	20.6	15.4	88.1	10	260	
	42.0	21.0	16.1	68.7	5	261	
	42.0	22.8	16.1	97.1	25	262	
	42.1	20.2	15.9	85.0	5	263	
85	38.5	21.3	15.4	385	85	246	
	39.0	21.5	15.7	546	40	247	
	39.8	19.0	15.6	103	60	248	
	39.6	17.7	15.8	39.5	25	249	
	39.6	17.2	15.3	44.0	80	250	
80	36.6	17.8	15.1	98.0	50	253	
	37.5	16.9	15.3	40.0	80	254	
	37.5	16.6	14.7	57.6	75	255	
	37.8	19.1	14.6	104	35	256	
	37.9	20.2	14.5	327	30	257	
	37.4	20.7	14.7	350	80	258	
	37.5	20.5	14.7	404	40	259	
	37.7	21.1		950	85	269	

TABLE 2 CREEP TEST RESULTS

CREEP SET-UP [% of σ_{Bo}]	LOAD σ_{Break} [lbs/120 Thr.]	ELONGATION ε_{Break} [%]	ε_o [%]	TIME t_{Break} [sec]	LOCATION OF BREAK % from bottom	SPECIMEN NUMBER	REMARKS
75		(20.0)	14.4	19,800	No	269	raised to 80%
	35.3	17.5		116	50	100	
70	33.2	19.3	13.3	700	75	251	
	(33.2)	(16.8)	13.4	(7,906)	No	252	No Break after 132 minutes
	32.6	17.5		10,000	70	101	

Contd. TABLE 2 CREEP TEST RESULTS

FATIGUE SET-UP [% of σ_{Bo}]	LOADING [lbs/120 Thr.]			ξ	ELONGATION [%]		CYCLES TO BREAK	TIME [sec]	LOCATION OF BREAK [%]	SPECIMEN NUMBER
	σ_{max}	σ_{mean}	σ_{min}	$=\frac{\sigma_{min}}{\sigma_{max}}$	ε_{Break}	$\varepsilon_{max} - \varepsilon_{min}$				
- 80	37.5	22.3	7.0	0.187	19.1	4.45	29,070	2,907	20	302
	37.6	22.3	7.0	0.186	17.5	4.4	34,500	3,450	0	300
	37.6	22.2	6.8	0.181	17.6	4.5	33,260	3,326	0	301
- 85	39.8	23.3	6.8	0.171	20.2	4.8	15,900	1,590	80	270
	39.8	23.7	7.5	0.188	20.0	4.7	10,900	1,090	75	271
	39.9	23.5	7.1	0.178	19.8	4.5	9,518	952	80	272
	39.9	23.5	7.1	0.178	18.8	4.5	4,936	494	80	273
	39.9	23.3	6.8	0.170	20.1	4.7	8,200	820	25	274
	39.9	23.6	7.3	0.183	19.8	4.6	4,150	415	75	275
	39.9	26.0	11.0	0.276	17.1	4.5	930	93	80	281
	39.0	23.0	7.0	0.179	19.7	4.9	2,220	222	85	289
- 90	42.3	24.8	7.3	0.172	21.2	4.8	1,660	166	15	294
	42.3	24.8	7.3	0.172	21.3	4.9	2,920	292	20	295
	42.3	24.8	7.3	0.172	20.4	4.9	2,087	209	20	296

TABLE 3   FATIGUE TEST RESULTS (Frequency 10 cps)

FATIGUE SET-UP [% of σ_{Bo}]	LOADING [lbs/120 Thr.]			$\xi = \frac{\sigma_{min}}{\sigma_{max}}$	ELONGATION [%]		CYCLES TO BREAK	TIME [sec]	LOCATION OF BREAK [%]	SPECIMEN NUMBER
	σ_{max}	σ_{mean}	σ_{min}		ε_{Break}	$\varepsilon_{max} - \varepsilon_{min}$				
- 95	44.6	26.1	7.6	0.170	20.6	5.0	714	71.4	75	297
	44.6	26.1	7.6	0.170	20.8	5.1	700	70.0	50	298
	44.7	26.2	7.6	0.170	20.2	5.1	732	73.2	95	299
50 - 80	37.6	30.6	23.6	0.629	16.9	1.3	39,030	3,903	No	307
50 - 85	39.9	31.7	23.4	0.587	18.7	1.5	18,030	1,803	70	303
	39.9	31.6	23.3	0.584	16.6	1.6	750	75.0	60	304
	39.9	31.6	23.3	0.584	16.8	1.6	2,310	231	10	305
	40.0	31.7	23.4	0.584	17.9	1.6	1,670	167	40	306
	39.9	32.7	25.4	0.638	20.3	1.3	12,350	1,235	85	189
50 - 90	42.3	32.9	23.5	0.555	19.0	1.6	1,980	198	95	308
	42.3	32.9	23.5	0.555	19.3	1.6	1,470	147	15	309
	42.3	32.9	23.5	0.555	20.0	1.6	4,400	440	5	310
	42.3	32.8	23.2	0.549	19.7	1.6	5,200	520	95	311

Contd. TABLE 3 FATIGUE TEST RESULTS (Frequency 10 cps)

FATIGUE SET-UP [% of σ_{Bo}]	LOADING [lbs/120 Thr.]			$\xi = \frac{\sigma_{min}}{\sigma_{max}}$	ELONGATION [%]		CYCLES TO BREAK	TIME [sec]	LOCATION OF BREAK [%]	SPECIMEN NUMBER
	σ_{max}	σ_{mean}	σ_{min}		ε_{Break}	$\varepsilon_{max}-\varepsilon_{min}$				
50 - 95	44.5	34.0	23.4	0,525	20.2	1.9	1,140	114	70	312
	44.6	34.0	23.4	0.522	20.2	1.9	1,300	130	95	313
	44.8	34.1	23.4	0.521	19.2	1.9	890	89.0	5	314
75 - 85	39.8	37.5	35.2	0.886	20.9	0.4	55,570	5,557	40	315
	39.9	37.5	35.1	0.880	20.7	0.4	17,020	1,702	20	316
	39.8	37.5	35.2	0.886	20.0	0.4	2,740	274	60	317
	39.8	37.4	35.0	0.880	20.2	0.4	40,360	4,036	5	319
85 - 85	39.8	39.8	39.8	1.0	21.3	0	(1,660)	166	95	318
	39.9	39.9	39.9	1.0	22.0	0	(4,670)	467	60	320
	39.8	39.8	39.8	1.0	22.0	0	(2,660)	266	50	321
	39.8	39.8	39.8	1.0	21.1	0	(1,950)	195	5	322

Contd. TABLE 3 FATIGUE TEST RESULTS (Frequency 10 cps)

FREQUENCY [cps]	LOADING [lbs/120 Thr.]			$\xi = \frac{\sigma_{min}}{\sigma_{max}}$	ELONGATION [%]		CYCLES TO BREAK	TIME [sec]	LOCATION OF BREAK [%]	SPECIMEN NUMBER
	σ_{max}	σ_{mean}	σ_{min}		ε_{Break}	$\varepsilon_{max} - \varepsilon_{min}$				
0.1	39.9	20.3	0.6	0.015	21.3	8.4	249	2,490	60	286
	39.6	24.9	10.1	0.253	18.5	3.7	127	1,270	5	288
1	39.9	21.0	2.0	0.050	20.2	7.6	391	391	25	283
	39.8	20.8	1.8	0.045	18.8	7.8	198	198	10	284
	39.9	20.9	1.8	0.045	19.5	7.8	201	201	15	285
5	39.9	22.3	4.7	0.118	18.7	5.8	580	116	40	282
10	39.8	23.3	6.8	0.170	20.2	4.8	15,900	1,590	80	270
	39.8	23.7	7.5	0.188	20.0	4.7	10,900	1,090	75	271
	39.9	23.5	7.1	0.178	19.8	4.5	9,518	952	80	272
	39.9	23.5	7.1	0.178	18.8	4.5	4,936	494	80	273
	39.9	23.3	6.8	0.170	20.1	4.7	8,200	820	25	274
	39.9	23.6	7.3	0.183	19.8	4.6	4,150	415	75	275
	39.9	26.0	11.0	0.276	17.1	4.5	930	93.0	80	281
	39.9	23.0	7.0	0.179	19.7	4.9	2,220	222	85	289

TABLE 4 FATIGUE TEST RESULTS (σ_{max} = 85% σ_{Bo} = const.)

FREQUENCY [cps]	LOADING [lbs/120 Thr.]			ξ	ELONGATION [%]		CYCLES TO BREAK	TIME [sec]	LOCATION OF BREAK [%]	SPECIMEN NUMBER
	σ_{max}	σ_{mean}	σ_{min}	$=\frac{\sigma_{min}}{\sigma_{max}}$	ε_{Break}	$\varepsilon_{max}-\varepsilon_{min}$				
20	39.9	25.2	10.4	0.261	19.7	3.4	18,810	941	70	276
	39.9	25.2	10.4	0.261	19.4	3.5	24,360	1,218	75	277
	39.7	25.1	10.5	0.264	18.8	3.7	3,740	187	80	278
	39.7	25.2	10.7	0.269	17.9	3.5	1,660	83.0	50	279
	39.6	25.3	10.9	0.279	16.6	3.5	570	28.5	20	280
40	39.9	22.9	5.9	0.149	20.0	2.4	96,670	2,414	75	291
	39.9	22.9	5.9	0.149	18.4	2.4	65,180	1,380	0	290
60	39.9	24.6	9.3	0.234	17.9	2.0	65,500	1,388	0	292
	39.9	24.3	8.6	0.216	20.1	2.0	224,715	5,618	100	293

Contd. TABLE 4 FATIGUE TEST RESULTS (σ_{max} = 85 % σ_{Bo} = const.)

SET-UP [% of σ_{Bo}]	FREQUENCY [cps]	LOADING [lbs/120 Thr.]			ELONGATION [%]		CYCLES TO BREAK	TIME [sec]	LOCATION OF BREAK [%]	SPECIMEN NUMBER
		σ_{max}	σ_{mean}	σ_{min}	ε_{Break}	$\varepsilon_{max} - \varepsilon_{min}$				
0 - 90	.05	42.1	21.1	0	18.9	12.5	4	53	20	328
	"	42.6	21.3	0	18.7		0.5	6	60	329
0 - 85	.05	39.9	20.0	0	20.8	11.4	44	660	95	323
	"	39.9	20.0	0	20.0	11.5	15	284	10	324
	"	39.9	20.0	0	21.8	11.5	38	737	50	325
0 - 80	.05	37.6	18.8	0	21,3	10.1	75	1,485	10	326
	"	37.6	18.8	0	18.7	12.0	14	137	50	330
	"	37.0	18.5	0	19.4	11.2	37	362	50	331
	.005	37.4	18.7	0	21.7	11.2	29	6,220	30	332
0 - 75	.05	35.2	17.6	0	20.8	10.7	425	8,440	25	327

TABLE 5 CREEP-RECOVERY TEST RESULTS

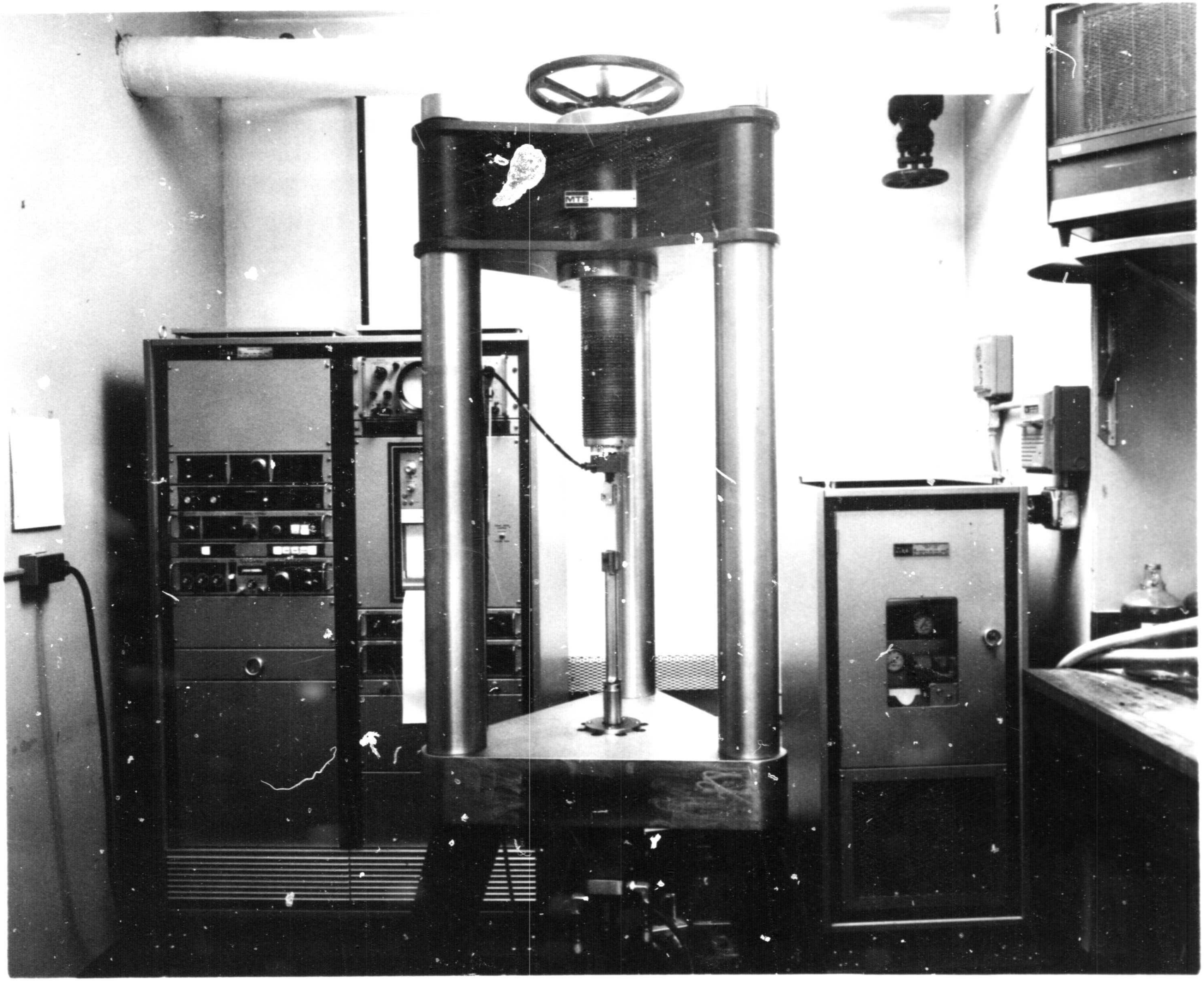


FIG. I TESTING MACHINE

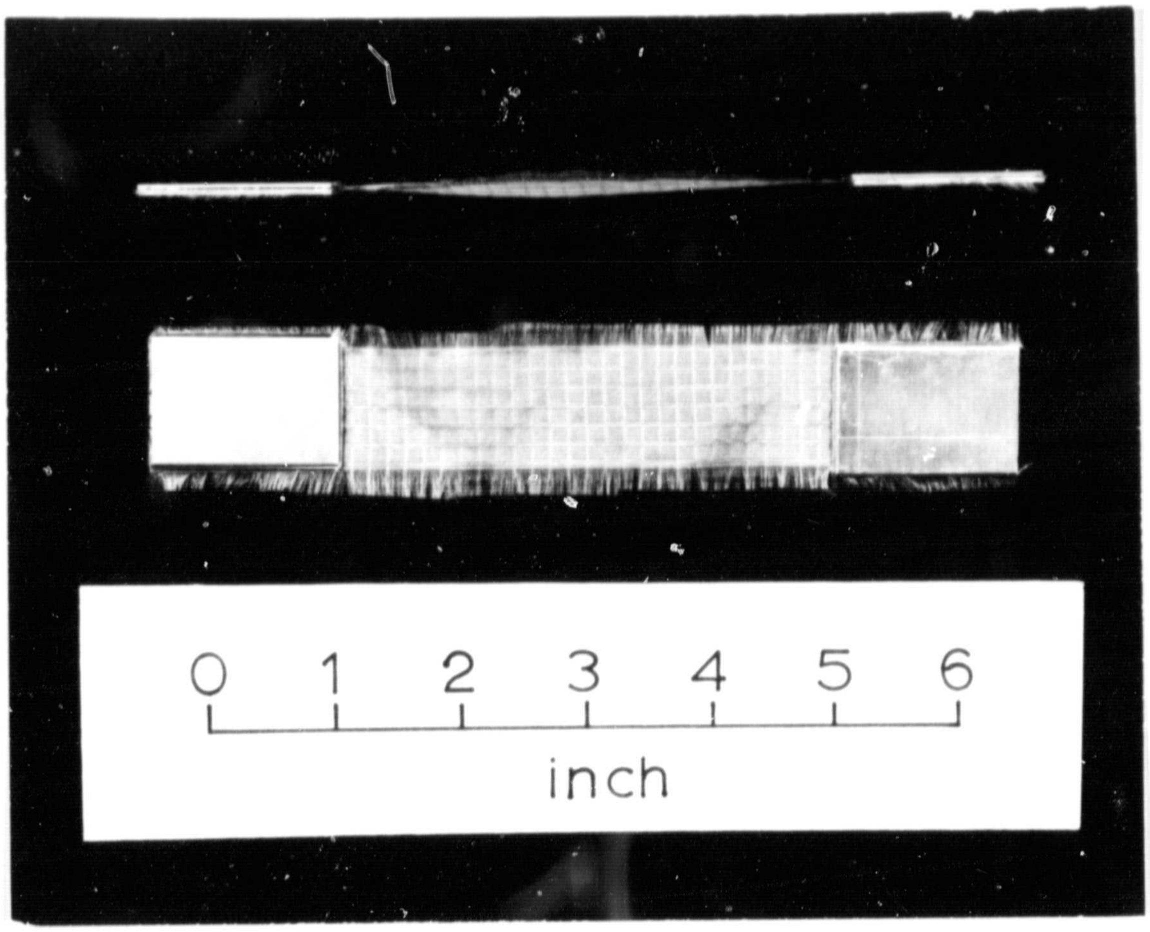


Fig. 2 Test specimen

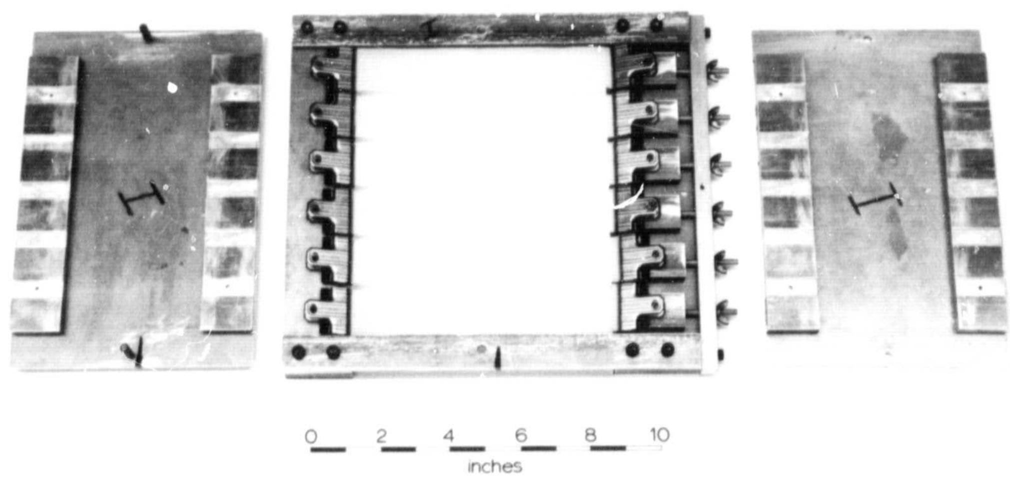


Fig. 3 Specimen jig

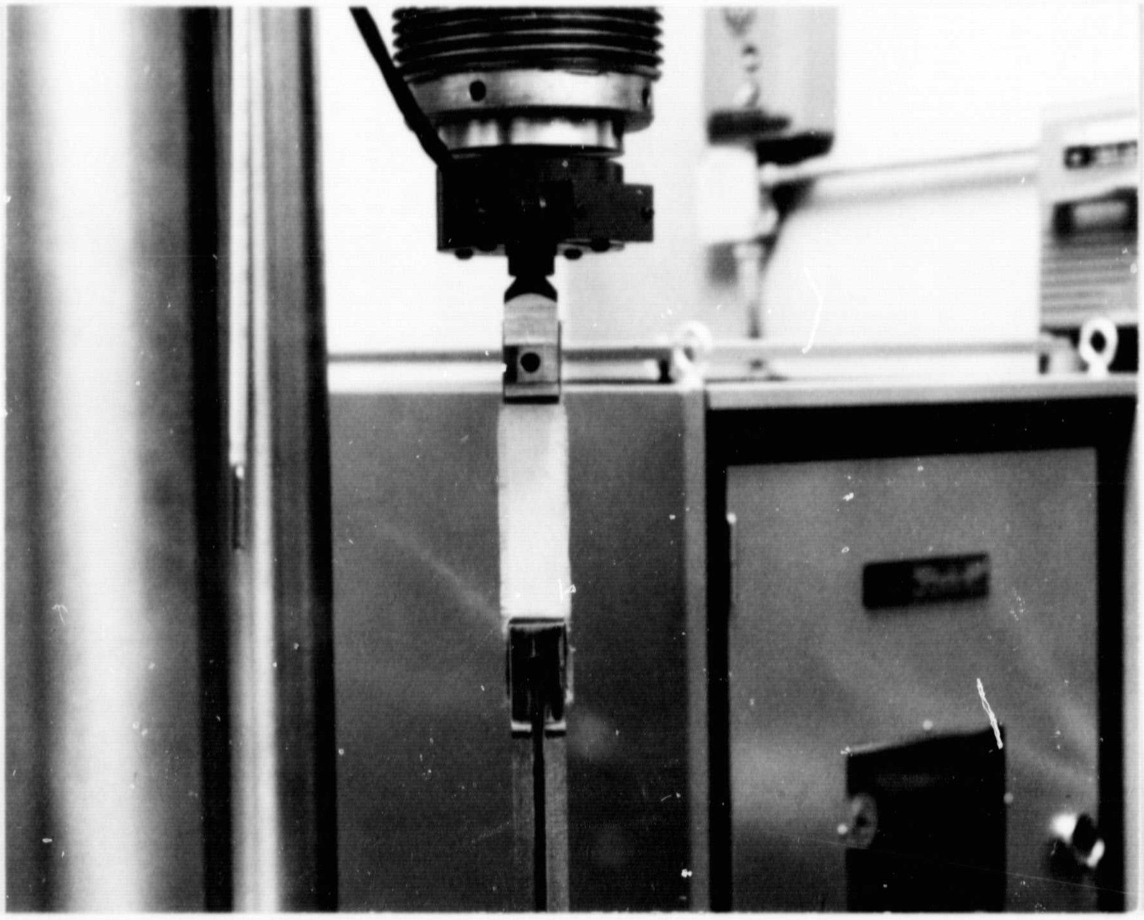


Fig. 4 Specimen in machine before test

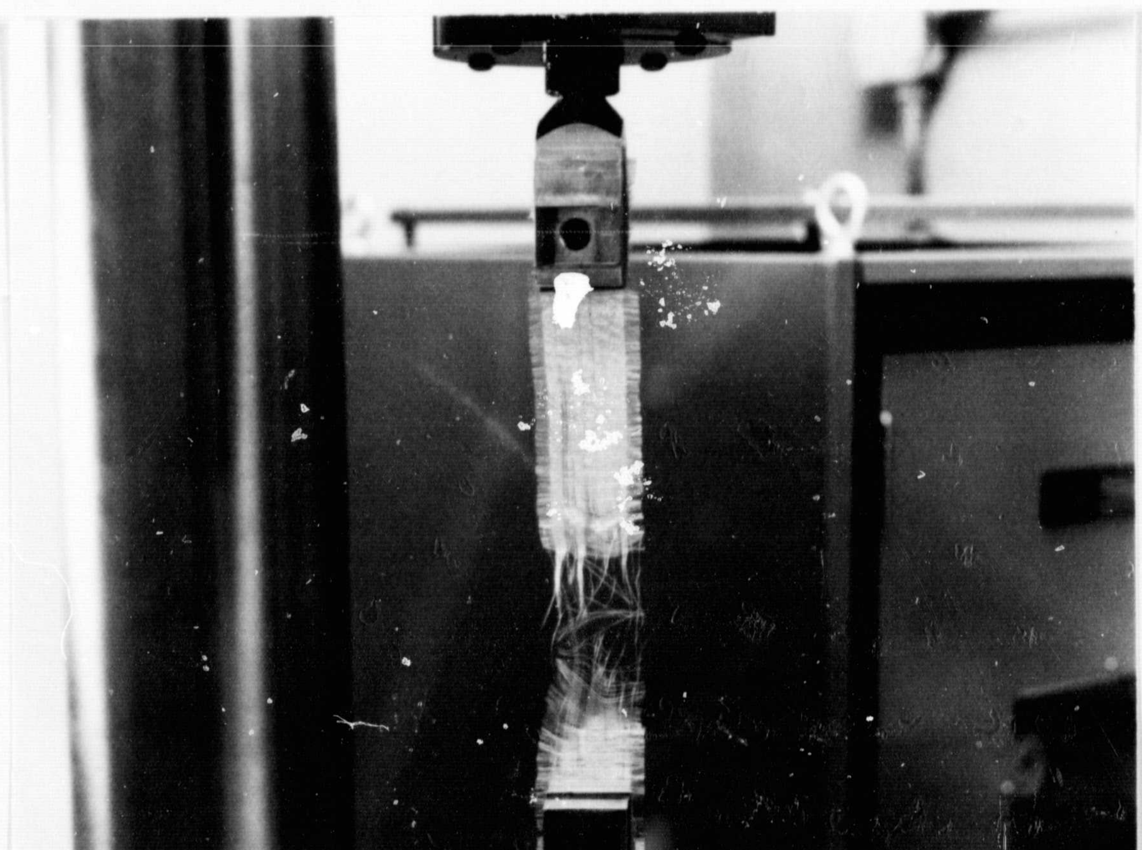


Fig. 5 Specimen in machine after test

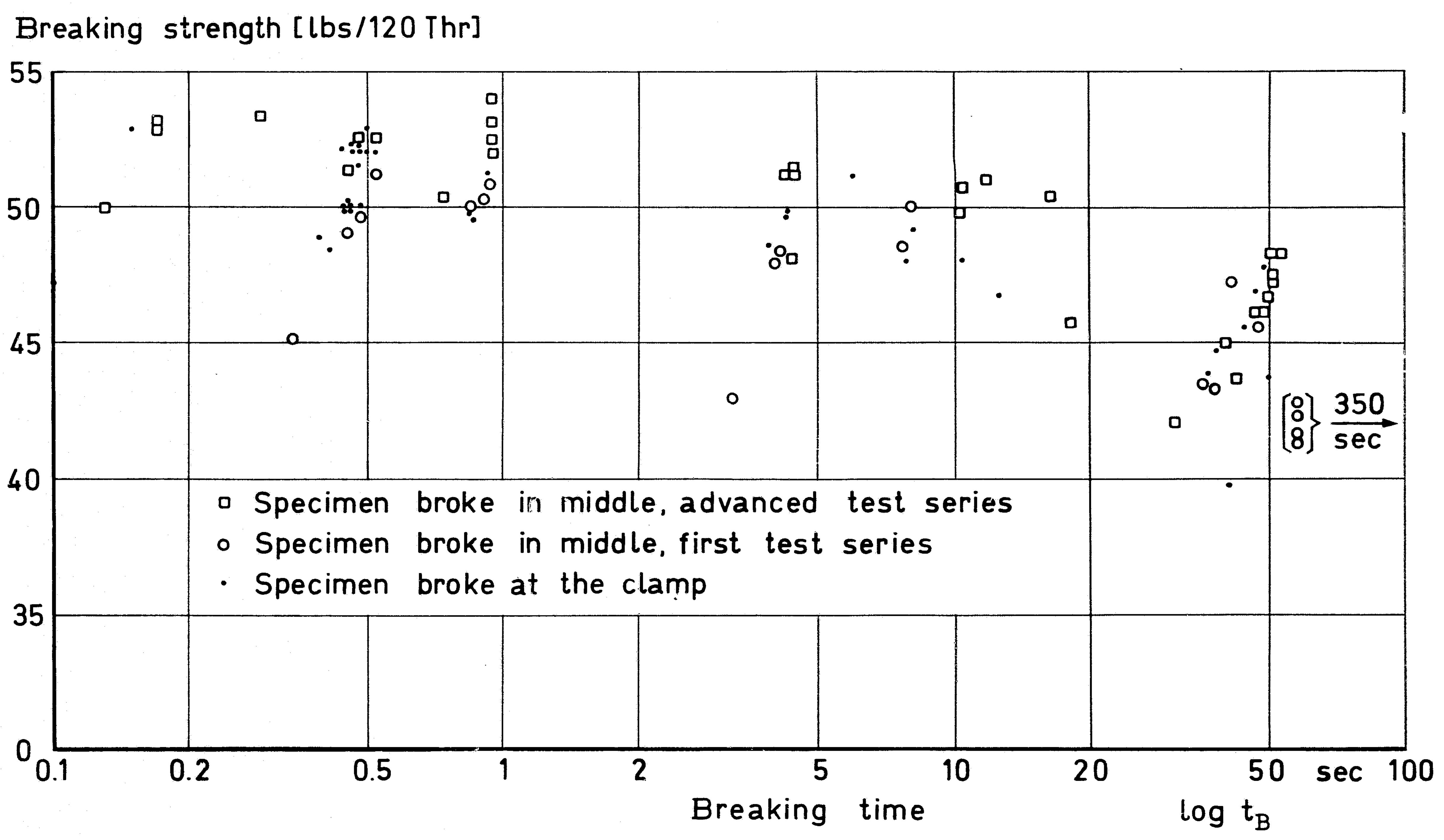


FIG. 6 BREAKING STRENGTH DEPENDANT UPON BREAKING TIME FOR LINEAR LOAD INCREASE

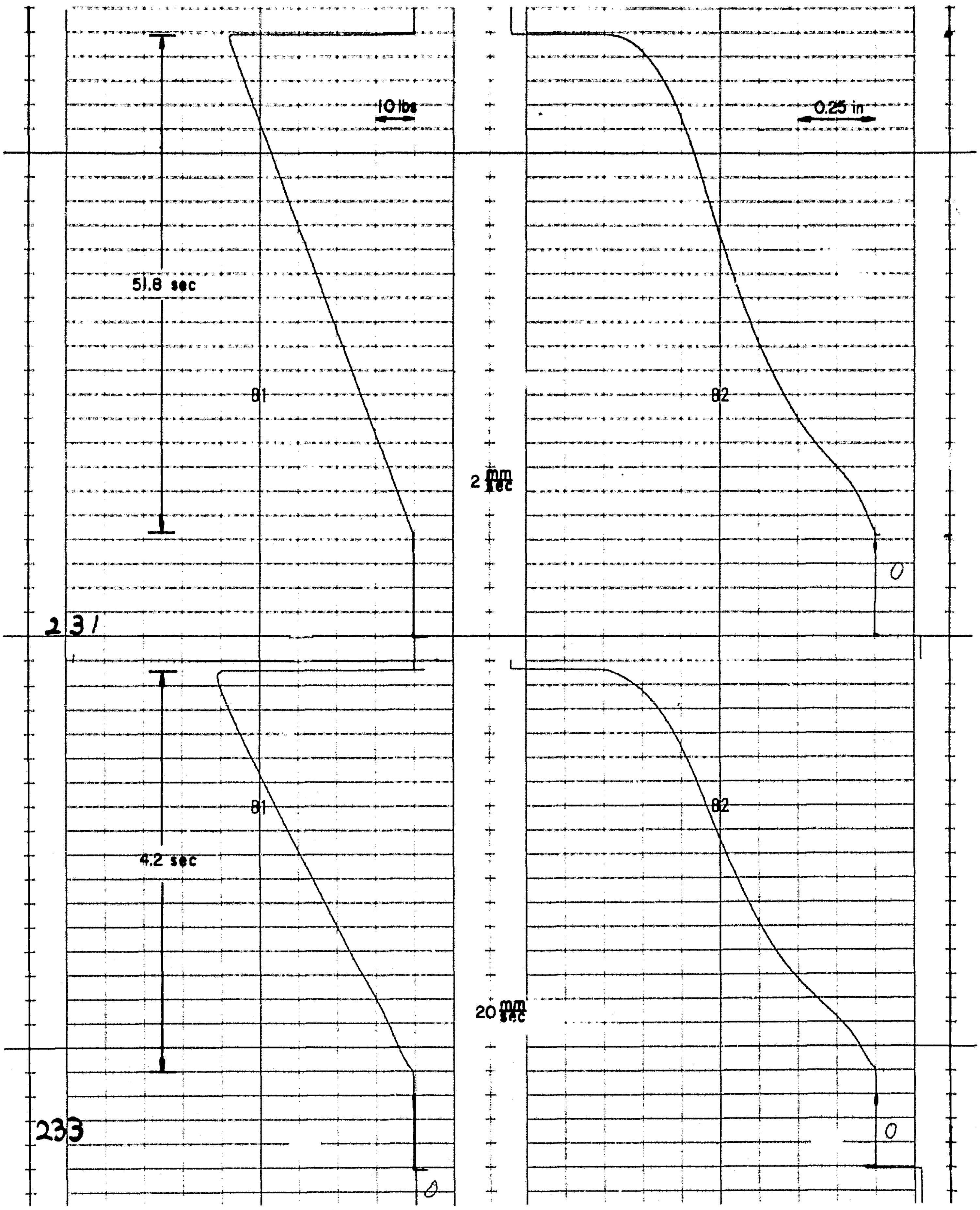


FIG. 7 ORIGINAL RAMP TEST RECORDINGS

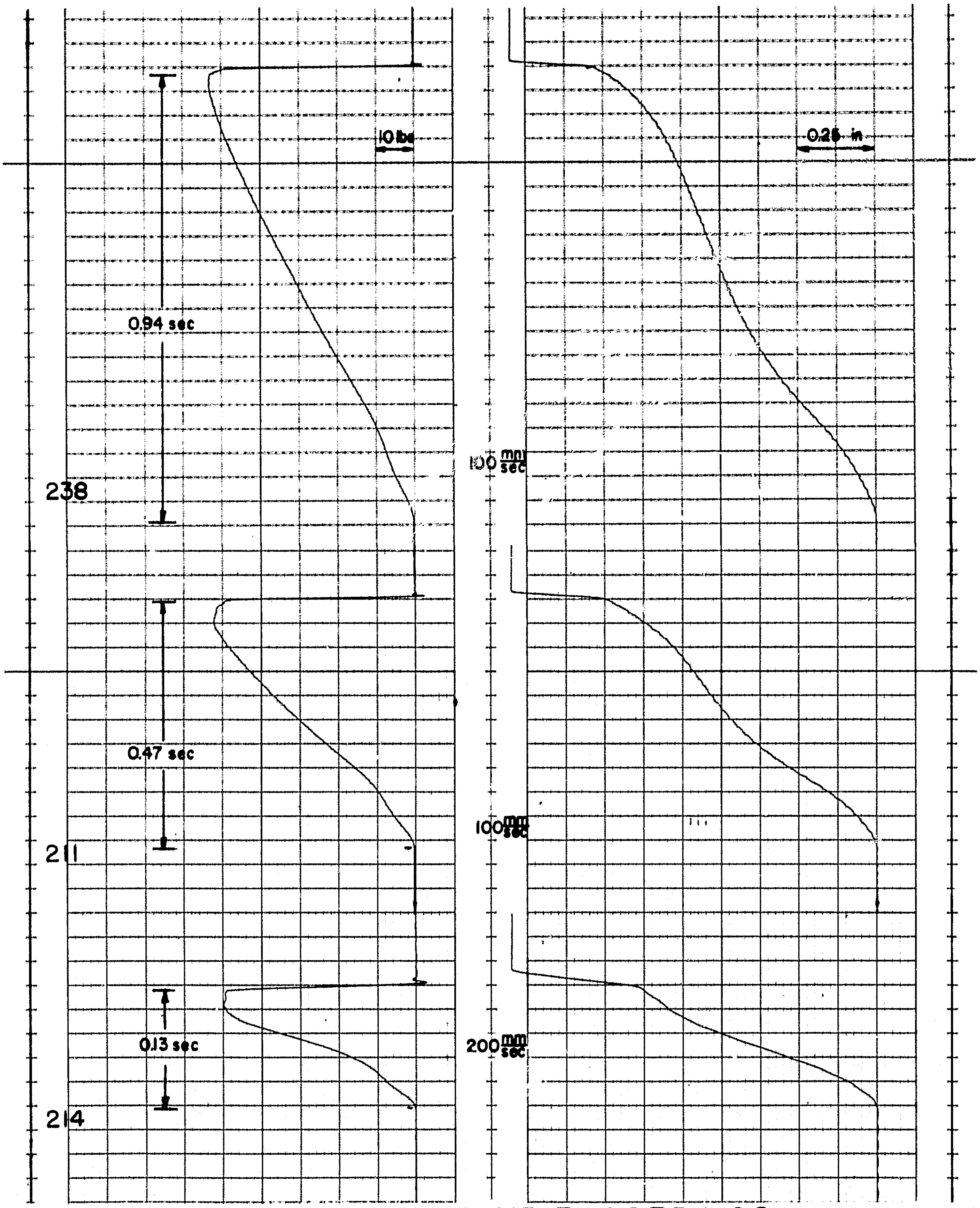


FIG. 8 ORIGINAL RAMP TEST RECORDINGS

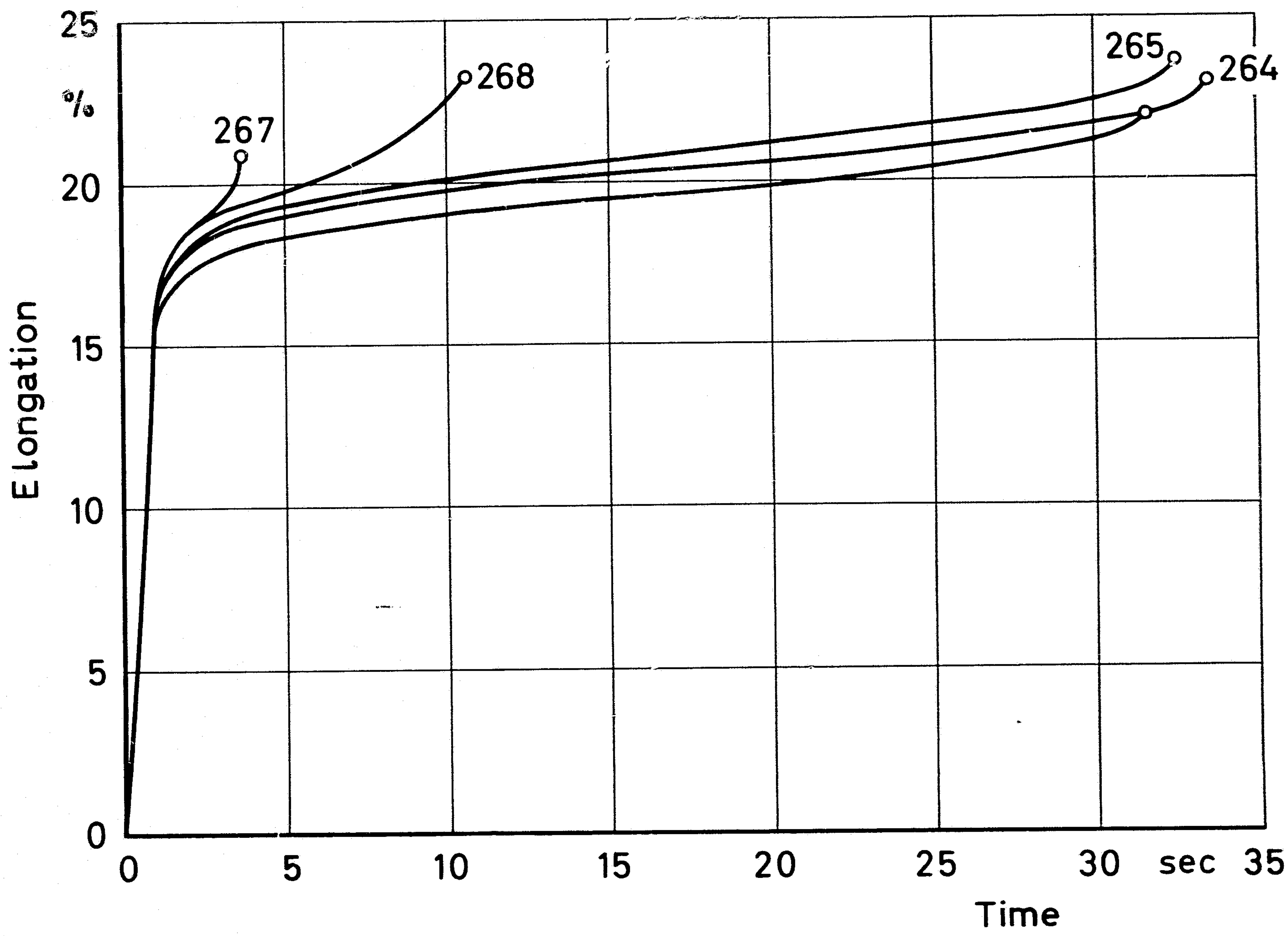


FIG. 9 CREEP ELONGATION AT A 95 % CONSTANT LOAD

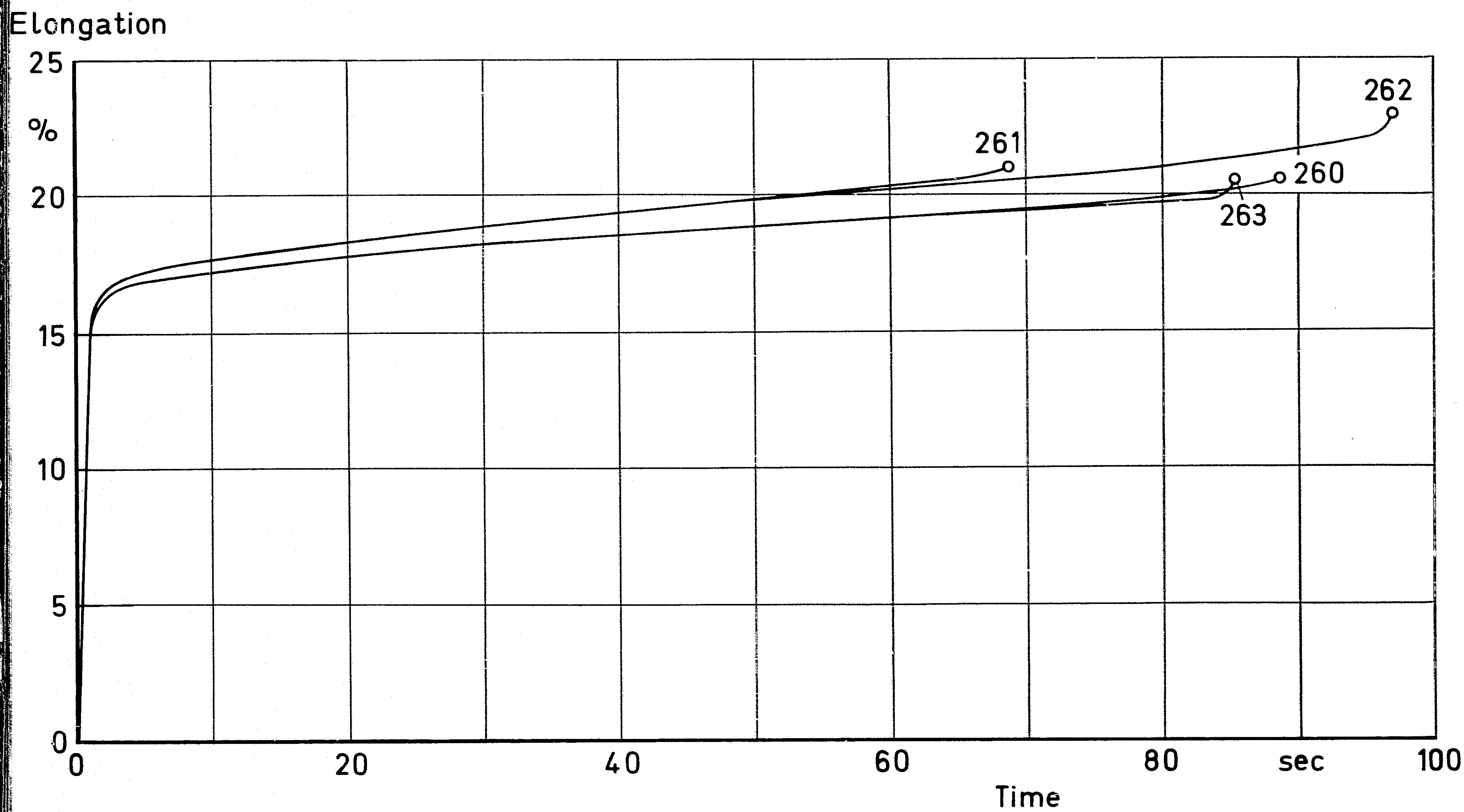


FIG. 10 CREEP ELONGATION AT A 90 % CONSTANT LOAD

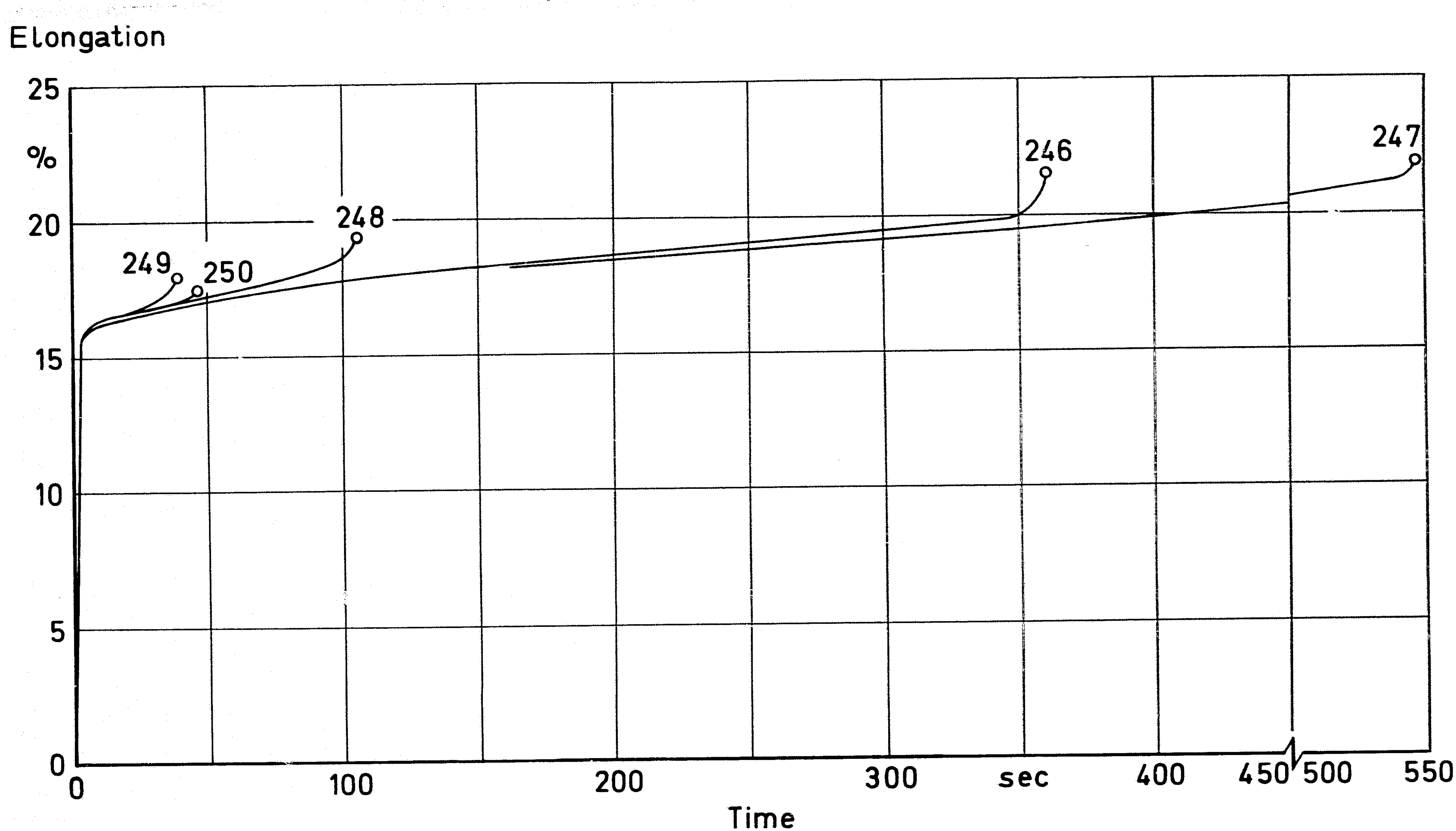


FIG. 11 CREEP ELONGATION AT A 85 % CONSTANT LOAD

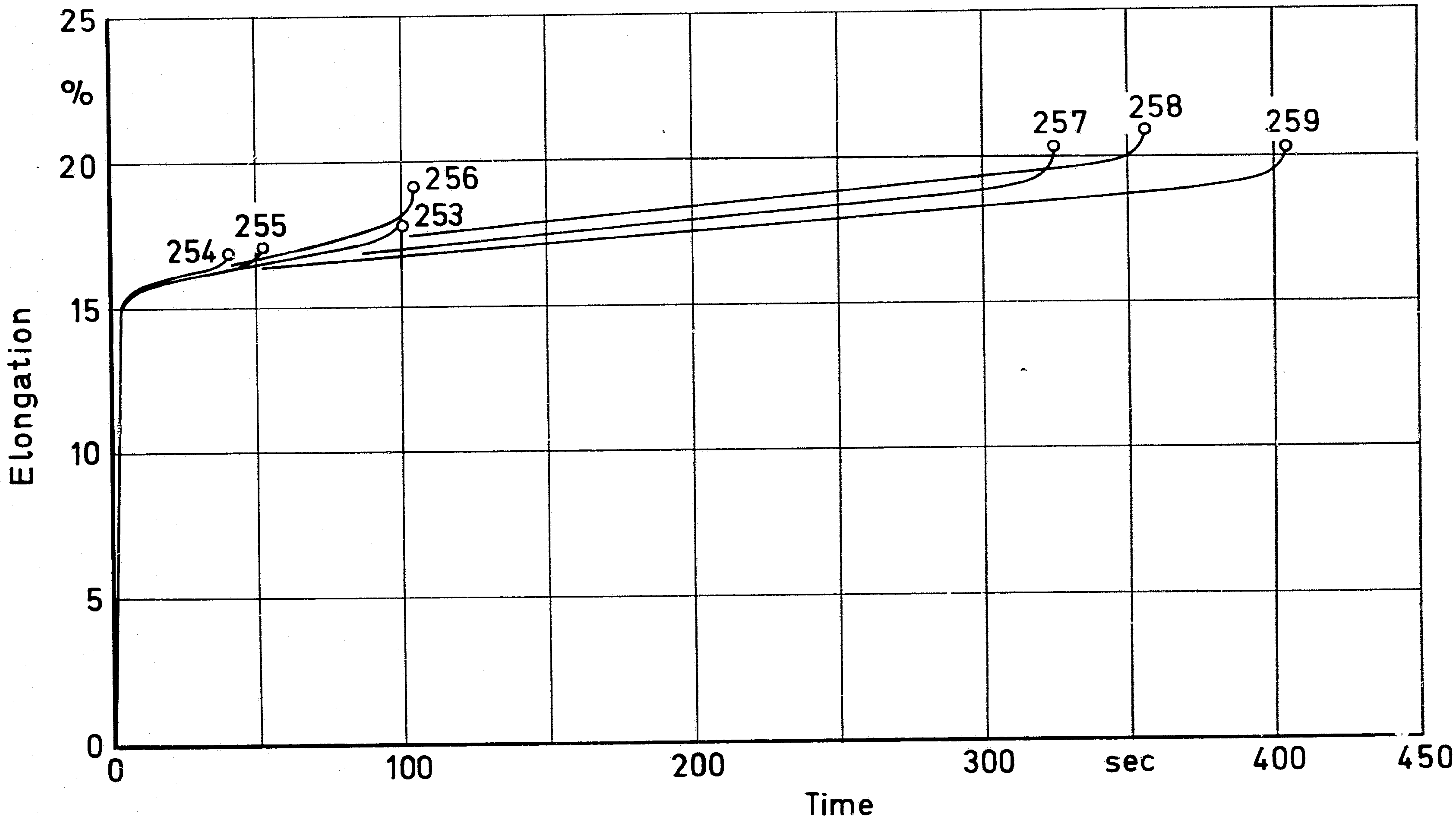


FIG. 12 CREEP ELONGATION AT A 80 % CONSTANT LOAD

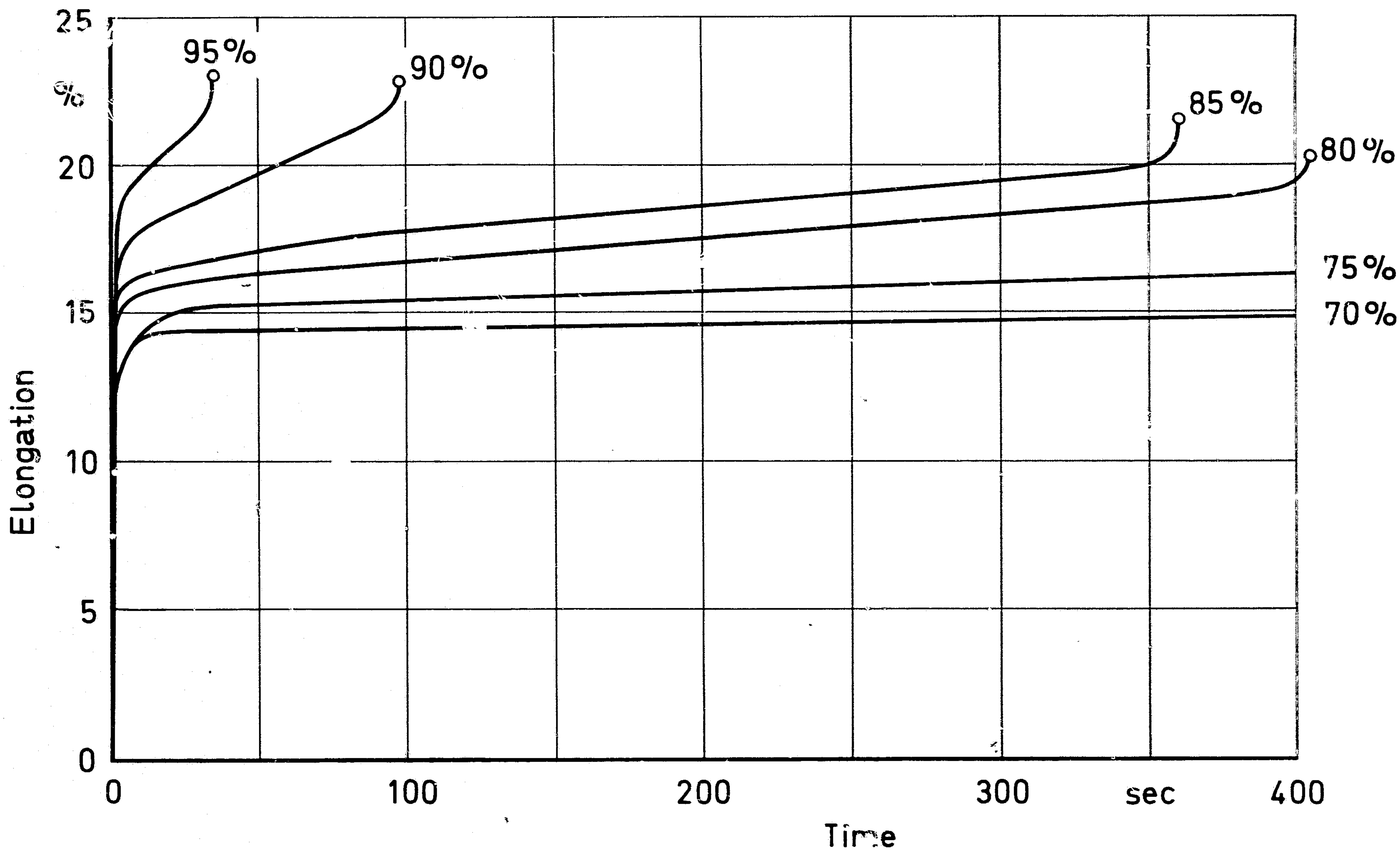
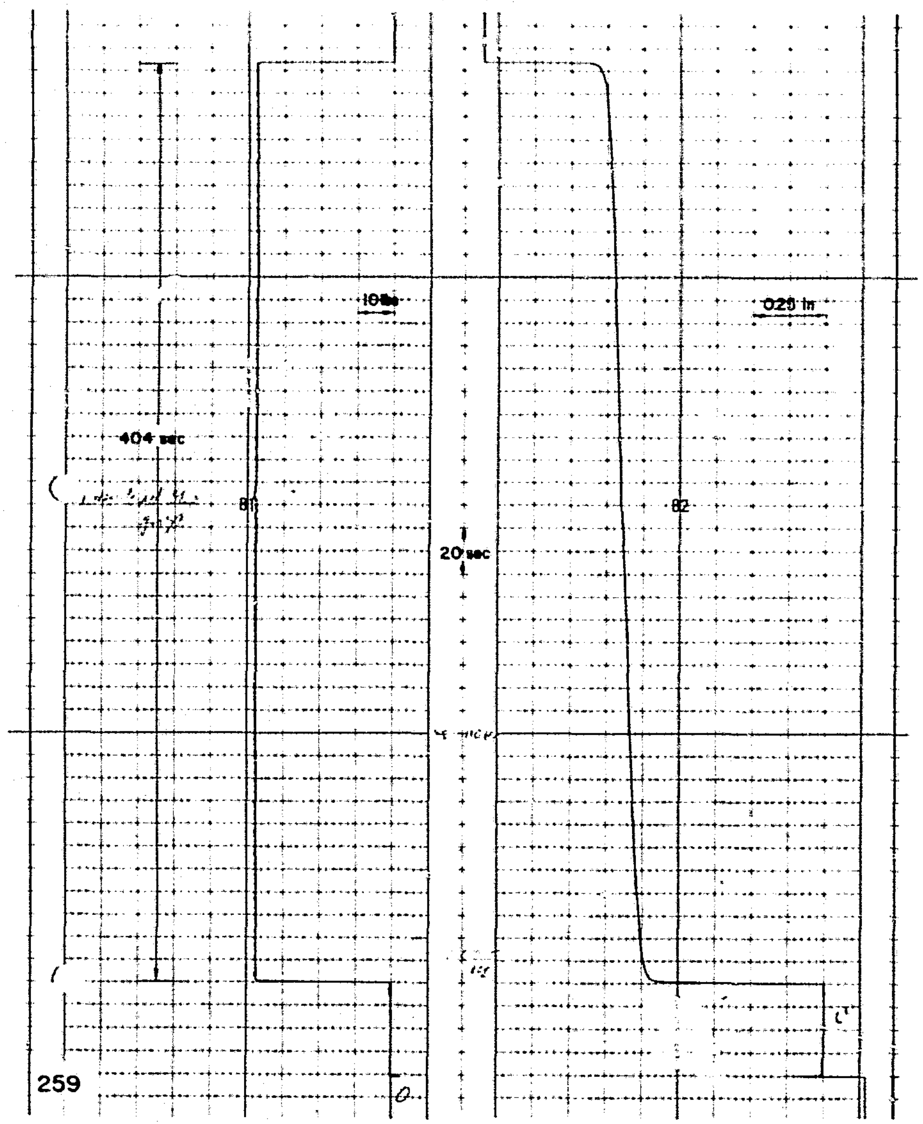


FIG. 13 COMPARISON OF CREEP ELONGATIONS AT DIFFERENT CONSTANT LOADS



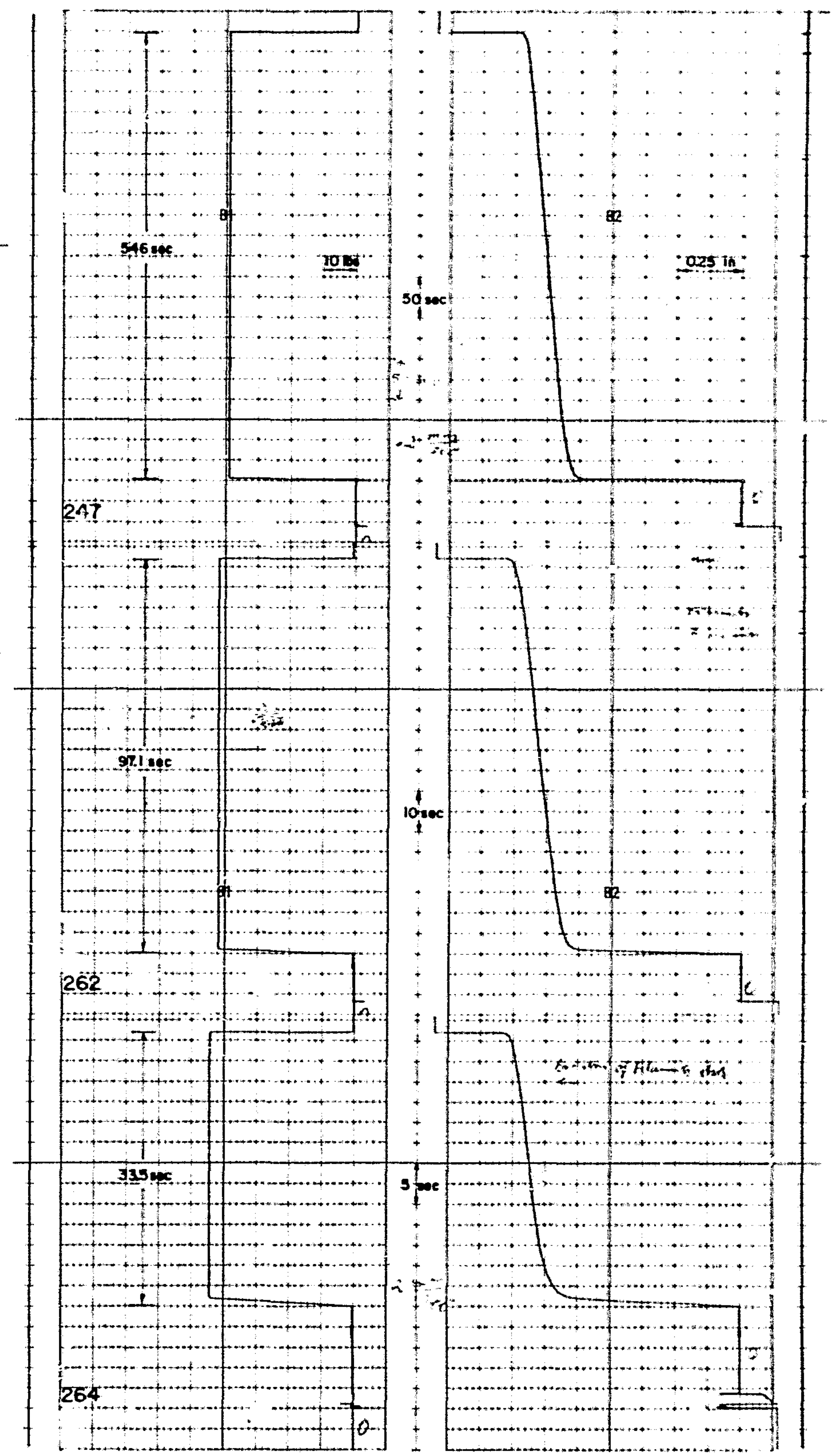


FIG. 14 ORIGINAL CREEP TEST RECORDINGS

259 37.5 LBS. = 80 % σ_{Bo}

247 39.0 LBS. = 85 % σ_{Bo}

262 42.0 LBS. = 90 % σ_{Bo}

264 44.5 LBS = 95 % σ_{Bo}

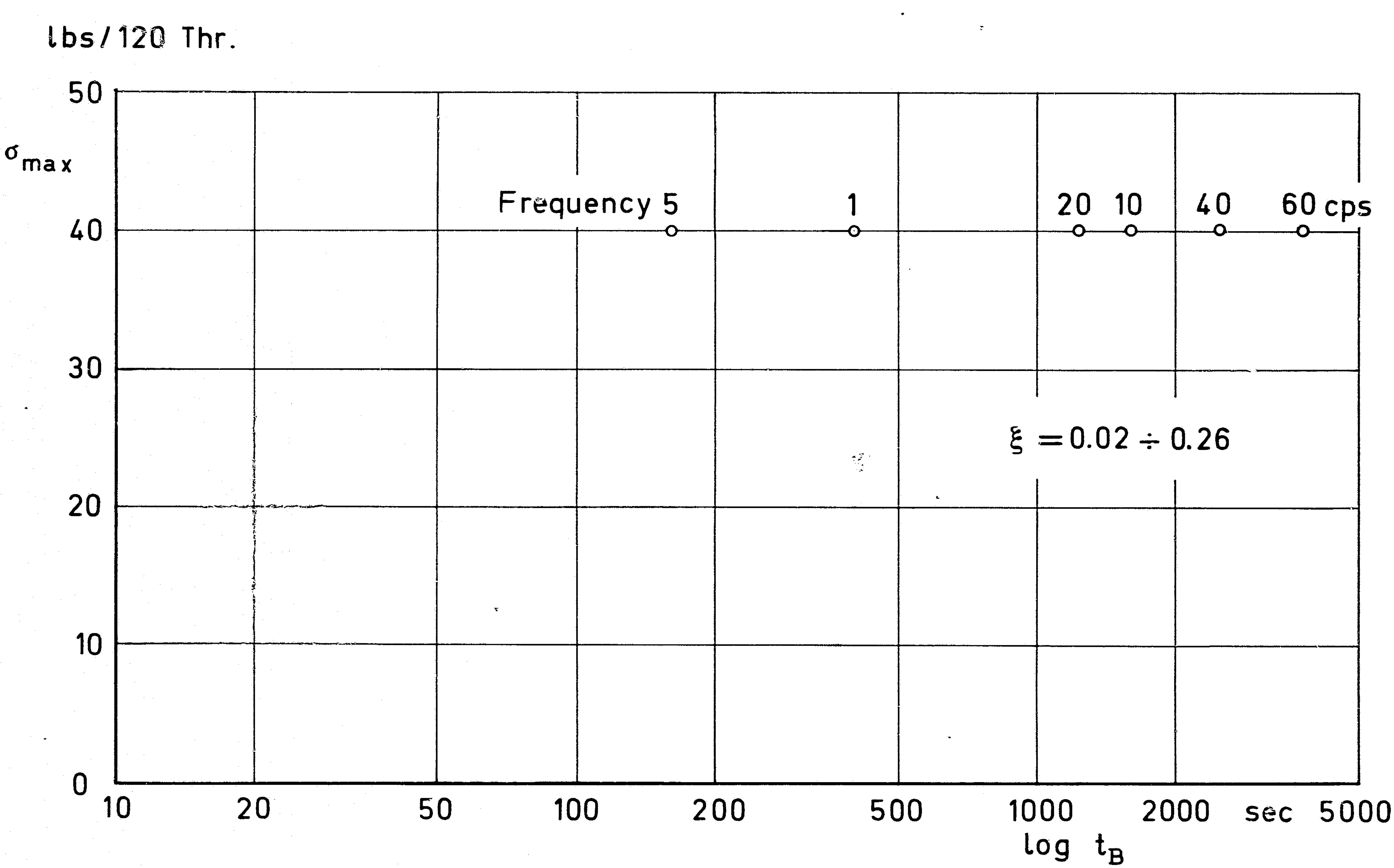


FIG. 15 BREAKING TIME FOR SINUSOIDAL WAVE LOADING - INFLUENCE OF FREQUENCY

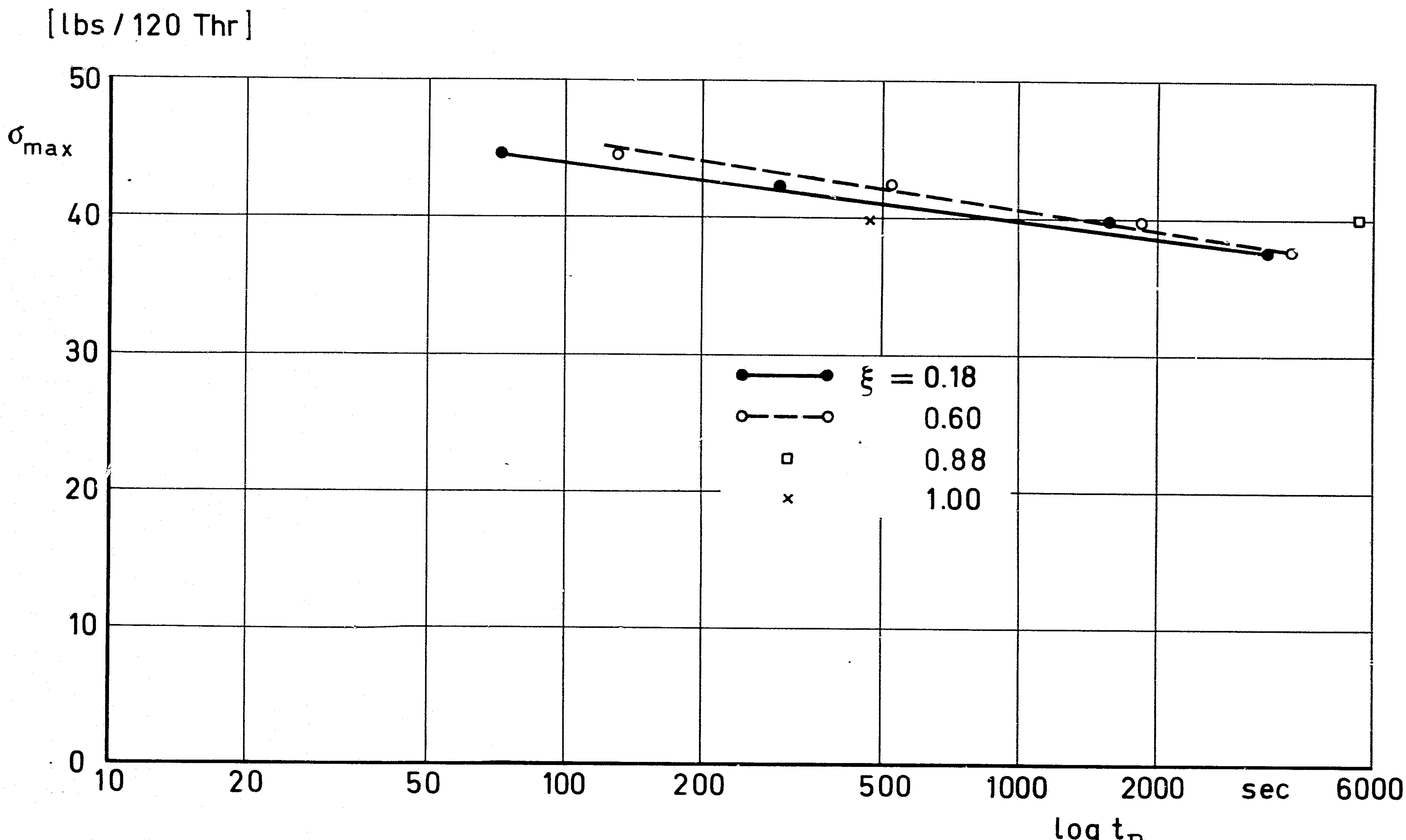


FIG. 16A BREAKING TIME FOR SINUSOIDAL WAVE LOADING OF 10 CPS - INFLUENCE OF ξ

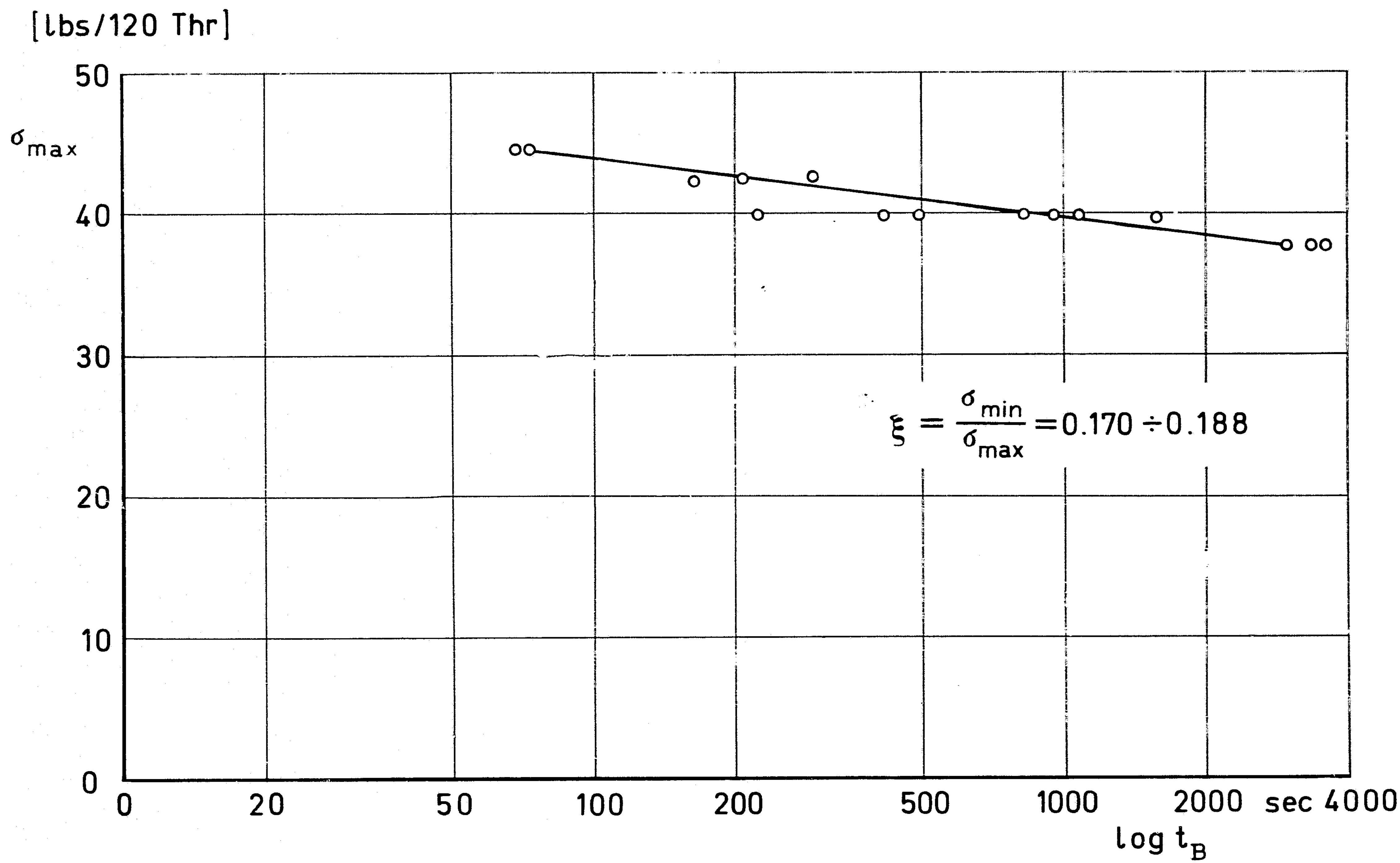


FIG. 16B BREAKING TIME FOR SINUSOIDAL WAVE LOADING OF 10 CPS - ξ = const.

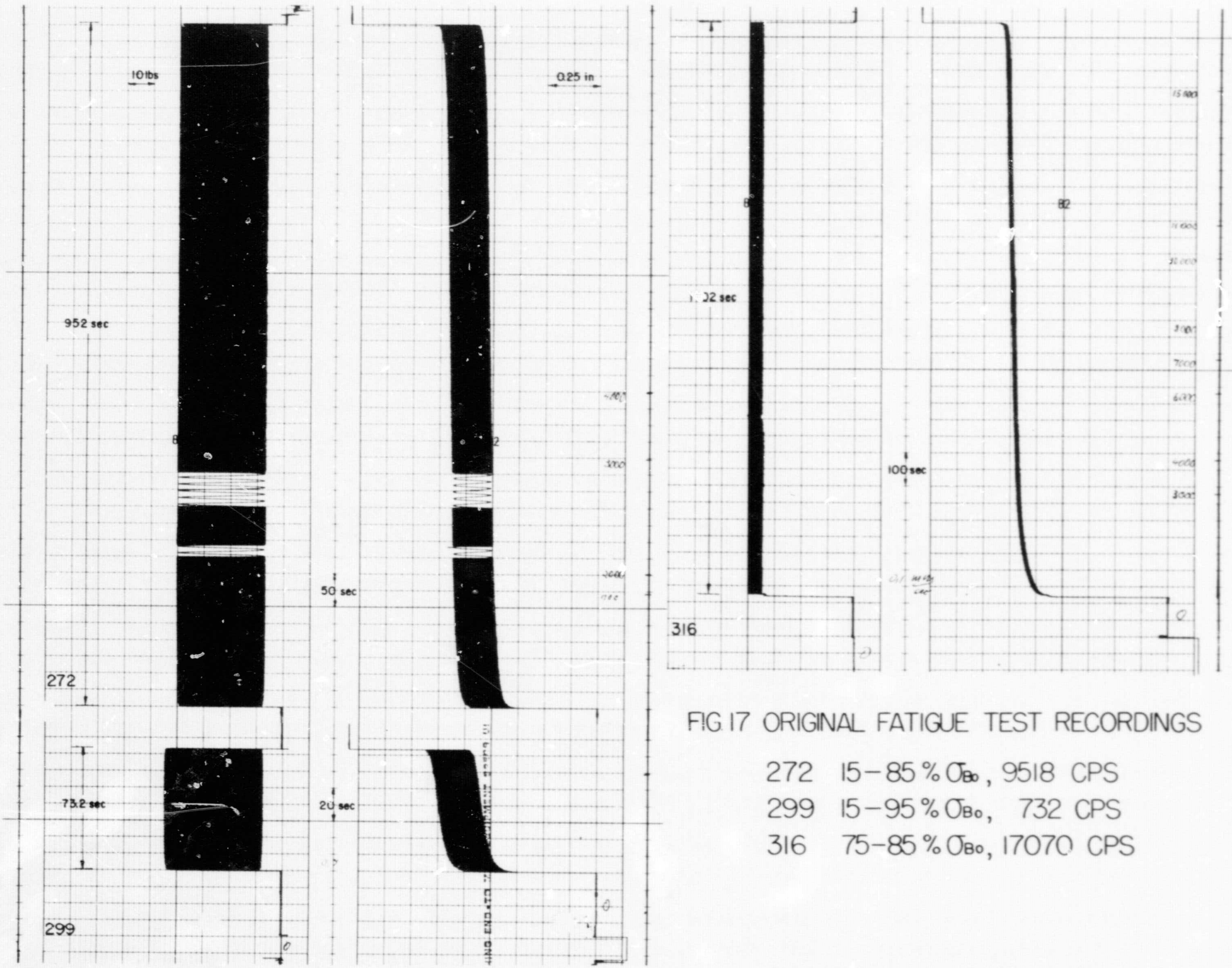


FIG. 17 ORIGINAL FATIGUE TEST RECORDINGS

272 15–85 % σ_{Bo}, 9518 CPS
299 15–95 % σ_{Bo}, 732 CPS
316 75–85 % σ_{Bo}, 17070 CPS

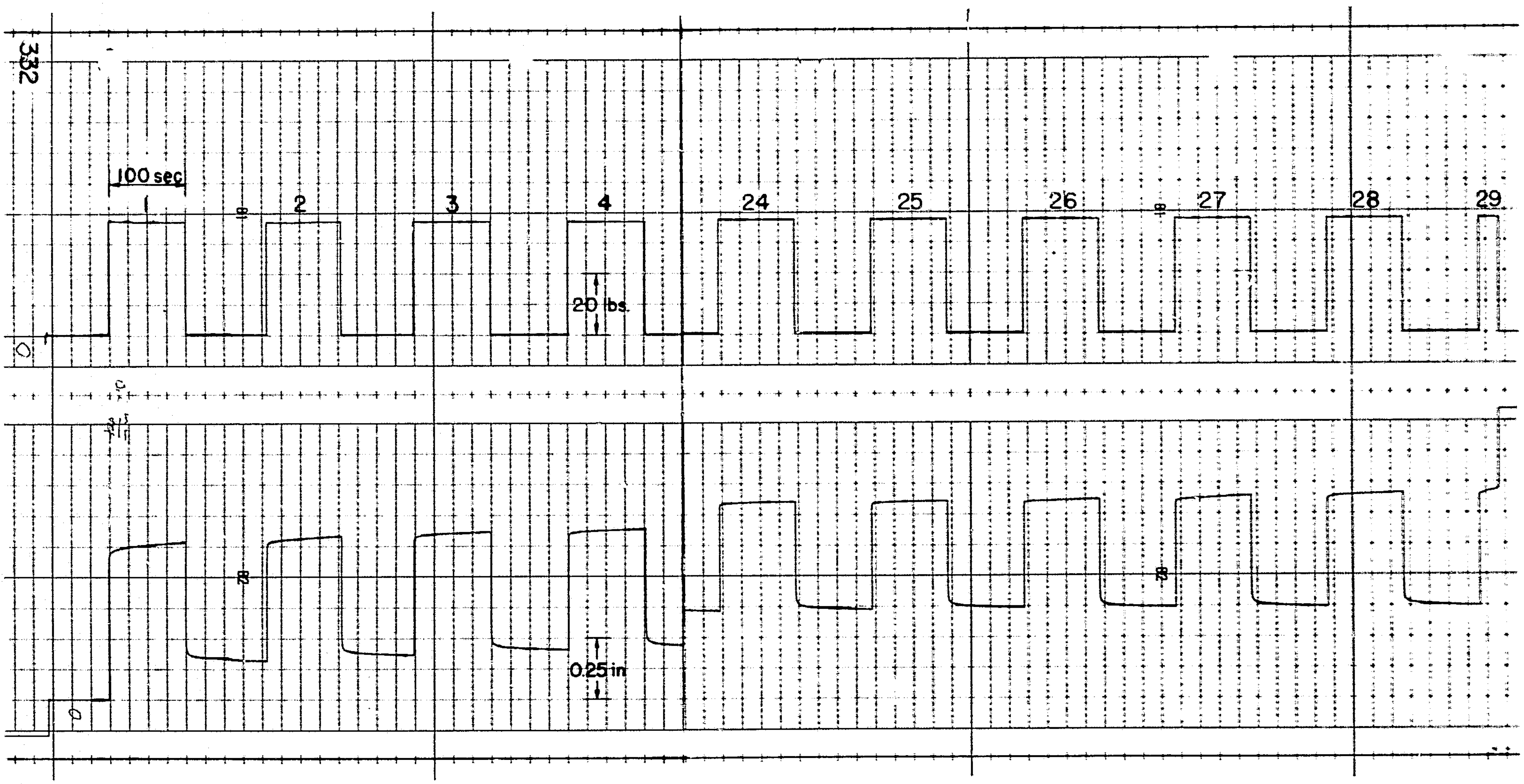


FIG. 18 CREEP RECOVERY TEST