# A STUDY OF THE EFFECT OF REPEATED TENSION IMPACT LOADS UPON CERTAIN METALS USED IN AIRCRAFT CONSTRUCTION

Thesis

by

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## SUMMARY

A test method is developed for evaluating the Impact Endurance Limit of a material. The Impact Endurance Limit is defined as the energy per blow in tensile impact loading below which the specimen will withstand an indefinitely large number of blows without rupture and this value is given for ALCOA 24ST and 14ST, with and across the grain, and Dowmetals X and Z-1 with the grain. Evidence is presented that this value probably does not depend directly either on the energy absorbed in breaking in one blow or on the brittleness of the material.

The ability to absorb energy in failure under static loading is shown to decrease nearly linearly with dynamic strain, while the ability to carry design static load is not adversely affected by any amount of dynamic strain short of failure.

Some shortcomings of the present test methods are pointed out and a new machine is briefly described which will be used in further investigation of repeated tension impact.

# INTRODUCTION

With the current improvements in aircraft structural design methods, resulting in more efficient structures in which the material is worked at higher stresses, it is becoming increasingly more necessary to consider the effects of dynamic loading on the structure. These loadings are imposed by vibration and shock, the latter being most important in the landing gear and attaching structure. During the useful life of an airplane the dynamic loadings due to vibration are imposed many millions of times, but the number of heavy shock loads caused by hard landings will probably not exceed a few thousand. Failures caused by vibration generally occur as fatigue failures in bending. Shock failures, however, occur also in tension.

This investigation was undertaken for the purpose of determining the ability of various aircraft structural alloys to withstand impact stresses in tension and, if possible, to correlate this property with the other physical properties of the material, in order to give some basis for design of parts which are to be subjected to repeated impacts in tension. It was intended that the investigation should be extended to very large numbers of repeated impacts but the equipment now available did not permit doing this, and it was necessary to design an automatic machine to make these extended tests. This machine is now being built and will be installed at the Guggenheim Aeronautical Laboratory, California Institute of Technology, as soon as it is completed. It will be described in an appendix.

## TENSION IMPACT TESTING

In a paper by D. S. Clark and G. Daetwyler, presented at the Forty-first Annual Meeting of the American Society for Testing Materials, June 1938, there is described a method developed at California Institute of Technology, for determining force-elongation diagrams of metals under tension impact loads, (Reference b). The apparatus therein described is used in connection with a standard Tinius-Olsen Izod impact testing machine modified to hold specimens in a dynamometer and extensometer mounted on a very heavy anvil, as shown in Figs. 1 and 2. One end of the specimen is screwed into the dynamometer and a tee-shaped tup is screwed onto the other end of the specimen. The pendulum strikes this tup at the bottom of its swing and the impact force developed is exerted in tension on the specimen and dynamometer. Motion of the tup is communicated to the extensometer, and these two instruments control a cathode-ray oscillograph so that force-time and elongation diagrams can be recorded directly on a photographic plate. By comparison with a calibration of the machine these can be reduced and combined to give stress-strain diagrams.

Since this equipment was available at California Institute of Technology it was decided to develop a specimen for the repeated impact tests that could also be investigated by means of the oscillograph. This consideration determined the dimensions of the specimen with the exception of the gage diameter, which could be anything less than .375 inch. The capacity of the testing machine is 120 foot-pounds striking energy, with a maximum velocity of the pendulum at impact of 11.3 feet per second. The pendulum could not be accurately set to deliver less than about 6 foot-pounds. Since it was anticipated that it might be necessary to go to very low striking energies per unit volume of the test specimen this restriction made it desirable to keep the gage diameters of the specimens fairly close to the upper limit of .375 inch. The form and dimensions of a typical test specimen are shown in Fig. 3 and the manner of mounting in the testing machine in Fig. 1. Every effort was made to seat the threaded ends of the specimen solidly by tightening the clamp screw of the split tup and taking up on the lock nut on the dynamometer end.

It was realized that the form chosen for the specimen was an unfortunate one for the correlation of test results with other physical properties of the material. The gage diameter is only a little smaller than the root thread diameter of the ends and it was feared that a portion of the striking energy might be expended in deforming the threads. There was never any evidence that this was occurring under test however, and the consistency of the test results removed this doubt.

The shortness of the specimen is a more serious fault.

The threaded ends are held by forces parallel to the specimen axis and this shear must be transferred to the interior of the specimen. This results in a non-uniform stress distribution within the gage length of the specimen, since the stress tends to concentrate near the surface where the gage length is filleted into the threaded ends. Another objection to this short length is that measured elongations in the static tension test will be greater than the values quoted in the literature, which give elongation in percent for a 2 inch gage length.

Because of the considerations mentioned above it was decided to make a preliminary survey of the effect of variation, through a limited range, of striking velocity, specimen diameter, and gage length, replacing the heavy anvil in the Olsen machine with an adjustable and somewhat less rigid anvil which could be set to use gage lengths of 1, 2, or 3 inches. The results of this survey are shown in Figs. 4, 5, 6, and 7. The velocity investigation was made with an aluminum forging alloy 14ST, and with Dowmetal Z1, HTA, a new high-strength magnesium-silver alloy. No variation in energy absorption with striking velocity was found with either material over the range tested; 4.5 to 11.3 feet per second.

Duralumin 24ST cut from rod stock was used for the investigation of diameter variation as this was believed to be the most uniform material available. The curve of energy absorbed per unit volume of the gage length of the specimen plotted against specimen diameter, Fig. 6, shows a slight increase for diameters less than 0.20 inch but is nearly flat above this value. The maximum variation in energy per unit volume from a diameter of 0.20 to 0.35 inch is five percent, which is about the magnitude of the experimental error found in other tests.

Fig. 7 shows the variation in energy per unit volume with gage length, holding the diameter constant. It was expected that this curve would be hyperbolic in character, that is, that high energy absorption would accompany the short lengths, decreasing asymptotically to a constant value for greater lengths. The curve obtained is very peculiar and does not follow the expected law at all, although it might approximate it if it were extended over a greater range. The energy per unit volume drops off at a gage length of about one inch and this agrees with the results obtained by H. C. Mann in his investigation of the effect of notch length, (Reference e). Each point on our curve was checked twice, with very close agreement, and no reason can be suggested for its unexpected reverse curvature. It must serve as a warning that results obtained in this investigation are useful only for comparison. At least until further investigation of variations in form of specimen have been carried out it will be impossible to correlate impact values obtained with differently shaped specimens, and some standard will have to be selected in order to compare the impact resistance of different materials.

It appears from the work of H. C. Mann (Reference c) that there is a critical velocity of impact above which the energy to rupture decreases and that this velocity varies widely for different materials and alloys. It is, however, for all alloys tested by Mann, far above the velocities attained in these tests and it can reasonably be assumed that we are not much concerned here with any velocity effect.

It should be noted here that the difference between so-called static and dynamic loadings lies in the difference in time rate of change of strain, which has the dimension $(\text{time})^{-1}$, rather than in striking velocity. Suppose, for example, that a tensile test specimen is broken in a static tensile testing machine in one minute with an elongation of 17%; then the time rate of change of strain is of the order of magnitude:

$$\frac{\Delta \epsilon}{\Delta t} = .0028 \ \text{sec}^{-1}$$

In the dynamic test the whole phenomena takes place in a very much shorter time. Fig. 8 shows a force-time diagram for 1015 cold rolled steel with a calibration frequency of 10 kilocycles per second. Here the same breaking strain is reached in 0.0022 seconds and:

$$\frac{\Delta \epsilon}{\Delta t} = 77 \ \text{sec}^{-1}$$

This is 27,500 times as fast as in the static test.

It may be that this function, $\Delta\epsilon/\Delta t$ , or its average value up to the yield point, has a critical value which is more intimately connected with variations of energy in dynamic failure than the velocity of the striking pendulum.

## TESTING PROCEDURE

### Determination of Impact Endurance Limit:

If specimens of a material are struck until they break, varying the striking energy but keeping everything else constant, and number of blows to break, N, plotted against striking energy, E, we obtain curves resembling hyperbolae, as in Figs. 9, 10, and 11. Fractional values for N are obtained by adding to the number of non-breaking blows the quotient obtained by dividing the energy absorbed on the final blow by the initial energy of the blow.

It appears from examination of the trend of these curves that there must be some limiting value for the striking energy below which the specimen can withstand the blow indefinitely, or at least for a very large number of blows, and this limiting value should serve as a basis for comparison of the strengths under repeated impact of the various materials. A more convenient method of plotting the same data for determination of this limiting energy value is shown in Figs. 12 to 19, where N/E is plotted against N and the reciprocal of the slope of this line over the straight portion to the right is the Impact Endurance Limit, $E_L$, corresponding to the vertical asymptote of the curve in Fig. 9. These curves are plotted together for comparison in Fig. 20. Values of $E_L$ for all of the materials tested are noted on the curve for each material and in Table 1.

The Impact Endurance Limit, $E_L$, for 24ST rod was also determined using a 2 inch gage length, Fig. 15, in order to find whether any correlation of this value with specimen size existed. From Fig. 7, which shows the effect of variation in specimen length on energy absorbed per unit volume when the specimen breaks in one blow, it can be seen that the energy per unit volume with gage length of 2 inches is 82% of the energy per unit volume when the gage length is 1 inch. It was expected that the $E_L$ for the 2 inch length would be in approximately the same proportion, per unit volume, to the $E_L$ for the 1 inch length. However, the $E_L$ for the 2 inch length, 13.5 ft. lbs., is only 68% of twice the value for the 1 inch length, 9.87 ft. lbs., and no correlation can be made between specimens of different lengths. This is very unfortunate because unless this correlation can be made, the Impact Endurance Limit, as now determined, can not be regarded solely as a physical property of the material useful in design of structures, but also must be regarded as a function of the test conditions. In spite of this failure to establish a correlation, it is a very useful value for comparison of the endurance strengths of various alloys if it is determined under standardized test conditions.

A very interesting phenomenon should be noted here. Examination of Fig. 9, showing N vs E for Duralumin with and cross grain, reveals a crossing over of the curves, and the same crossing appears more markedly in Fig. 10

with the two Dowmetals. In both cases the material which absorbed the most energy to break in one blow, i.e., the more ductile, had the lower endurance limit, $E_L$. Table 1 gives these values. Compare especially the two Dowmetals, where Z-1 absorbed 51 foot pounds in one blow compared with 73 foot pounds with Dowmetal X, however, the $E_L$ value for the Z-1 alloy was 6.0 ft. lbs. and that for the X alloy was 4.0 ft. lbs. The fracture in Z-1 is of the brittle type, with no sliding along shear planes, while X shows the 45° failures characteristic of ductile materials. These are shown in Fig. 21.

From this it appears that the energy absorption in the single-blow tension impact test is not even approximately a measure of the resistance of the material to repeated tension impacts, and further, that stronger and less ductile materials which designers have generally avoided in parts subjected to impact, may actually be much superior to softer materials in their ability to withstand repeated blows of small energy.

The process of strain progression under repeated impact is shown in Fig. 22. The diameter of the specimen across the smallest cross-section was measured after each blow and sectional area plotted against number of blows. It would have been preferable to plot elongation rather than sectional area but it was difficult to measure elongations accurately without removing the specimen from the machine. It can be seen that the area reduction is quite rapid in the first few blows, then slows to a nearly constant value until near failure, when necking-down becomes very rapid. It is probable that a similar curve for an impact energy below the Endurance Limit of the specimen would approach a horizontal asymptote as N became large and strain hardening raised the proportional limit.

Fig. 23 shows the method of obtaining energy absorbed in breaking a specimen in a single blow when this energy is greater than the capacity of the machine. N vs E is plotted on log-log coordinates and appears as a straight line over its lower portion. This is extrapolated down to N = 1 and the breaking energy read. All values of $E_o$, energy required to break in one blow, greater than 120 foot pounds were obtained in this way.

Effect of Dynamic Straining on Energy Absorptive Capacity:

While investigating the effect of cynamic loadings it was thought that it might be of some interest to determine the effect of dynamic straining upon the energy absorptive capacity under static loads of an aluminum alloy. The alloy selected was ALCOA 24ST as this material is widely used in the aircraft industry. Our standard type impact specimen, Fig. 3, was used in this study. The specimens were made up in the cross-grain direction as this gives the most conservative results. They had a gage length of one inch and a diameter of 0.375".

The dynamic straining was accomplished in the impact machine using a striking energy of 10 ft. lbs. per blow. Eight specimens were subjected to a varying number of blows as indicated in the following table:

| Specimen Number | Number of Blows |
|---|---|
| 1 | 0 |
| 2 | 1 |
| 3 | 2 |
| 4 | 4 |
| 5 | 20 |
| 6 | 30 |
| 7 | 50 |
| 8 | 79 |

Specimen number eight failed after 79 blows. The first seven specimens were broken in tension in a standard static testing machine. The load-elongation curves for these seven specimens are plotted in Fig. 24. Each curve is offset to the right an amount equal to its dynamic straining. By integrating the area under the various curves the amount of energy absorbed in static rupture can be determined. The ratio of energy absorbed in static rupture after dynamic straining to energy absorbed in static rupture after no dynamic loading vs. the ratio of dynamic strain to total strain is plotted in Fig. 25.

The effect upon the yield point stress was determined at the same time. This is given in Fig. 26 as yield point stress vs ratio of dynamic strain to total strain. The yield point stress was chosen as that stress which gave a permanent strain of 0.002. The original area before dynamic loading was used in calculation of all stresses.

Eight more specimens of the same material were given the same dynamic straining. Following this straining the

Rockwell hardness of the various specimens was determined in the following manner. First the average Rockwell hardness was determined around the periphery of each specimen at about the middle of its gage length. Then, the specimens were cut in half at the middle of their gage length and the hardness determined across the face. The dynamic straining appeared to have little or no effect upon the hardness as determined by the two methods. Of course, slightly higher hardness values were obtained when measuring in a direction perpendicular to the grain than when measuring in a direction parallel to the grain.

## GENERAL DISCUSSION

Table 1 shows the Impact Endurance Limits obtained for all the alloys tested, also this limiting energy as a percentage of the energy required to break in one blow. The latter value is roughly constant for all the more ductile alloys but is nearly double this average for Dowmetal Z-1, the only brittle alloy tested. It is not, however, a direct function of the brittleness. Compare 24ST with 14ST: the latter has a higher yield strength and less elongation; as might be expected it absorbs less energy to fail in one blow, yet its Impact Endurance Limit is also lower and the ratio of the two energies is nearly the same as for 24ST.

It is suggested that the Impact Endurance Limit of a material may serve to define its "toughness". This quality is rather loosely defined and is not now measured by any physical test. It is generally regarded as being indirectly associated with the brittleness or ductility, yet not measured by them. The repeated impact test seems to the authors to fit the generally accepted definition of the term well enough to serve as a measure of the property.

In the sixth column of Table 1 are tabulated the Impact Endurance Limits divided by the densities of the various materials, so as to give a figure of merit for each alloy on a weight basis. It can be seen that 24ST still appears the best of all the materials tested, the value for the forging alloy 14ST being rather disappointing in comparison. Dowmetal Z-1 appears to good advantage but its apparent sensitivity to stress concentrations as noted in the tests should have further investigation. All of the specimens of this material broke near the end of the gage length, at the beginning of the fillet, even after special precautions had been taken to make the fillets smooth. This did not, in general, happen with any other material. However, in the case of some of the other specimens which failed after more than 1000 blows, failure did occur near the ends. It is felt that in any further research larger fillets should be used.

Dowmetal X showed a tendency to open up fine circumferential cracks along machining marks invisible to the naked eye and at places other than where the break occured. Photographs of typical breaks of the two Dowmetals and 24ST cut from rod are shown in Fig. 21.

<u>Effect of Dynamic Straining:</u>

Two important effects of straining of the aluminum alloy 24ST are indicated by our results. These are;

(1) Rapid increase in yield point stress with amount of straining;

(2) Decrease in the energy absorption capacity with increase in straining.

In our tests the straining was accomplished by loading dynamically as mentioned in the description of the tests. It should be borne in mind that the original area based on a diameter of 0.375" was used in the calculation of stresses and not the reduced area following dynamic straining. The yield point stress vs ratio of dynamic strain to total elongation at rupture is plotted in Fig. 26. The rapid increase in yield point stress with amount of straining is clearly indicated. The force-elongation diagrams plotted in Fig. 24 also show the same phenomenon. As yield point stress increases, the material will absorb less and less energy in static rupture. This fact is indicated in Fig. 24 where the force-elongation diagrams are given. The area under the curve for 50 blows equals about 30% of the area under the curve for no blows. Even one blow, which produced an elongation of about 0.024" in one inch gage length, reduced the energy absorption capacity 14%. This effect is also indicated in Fig. 25. After a somewhat rapid decrease in energy absorption capacity with a small amount of straining our results indicate that with further straining the energy absorption capacity decreases linearly. However, since we actually tested only a few specimens our results, plotted in Fig. 25, can only indicate the general nature of the relationship.

Our results indicate that any part that has been dynamically strained in tension short of actual rupture can still safely carry its design static load even though some reduction in area has taken place.

## APPENDIX

It is well known that under repeated loading and unloading or reversal of stresses, failure can be produced by stresses smaller than the ultimate strength of the material as determined by the static test. The magnitude of stresses required to produce this failure decreases with increase in number of cycles or reversal up to a certain point. This weakening of the material is spoken of as fatigue, and the test for such stresses is called an endurance test. The stress which a given material will stand for an infinite number of reversals without failure is known as the endurance limit for that material. The endurance limits for practically all structural materials have been determined and are available; however, it should be borne in mind that a truly dynamic loading was not used in the determination of this endurance limit.

The European investigator R. Plank reported in Reference (a) that some materials appear to have a higher elastic limit and ultimate strength under dynamic loading than under static loading. He further stated that it would appear that materials could be divided into two groups. For one group, failure occurs at a distinct permanent strain. Such materials are soft, plastic, like soft steel which can stand large forces if they act for a short time so that no dangerous permanent strains can occur. This group exhibits greater strength under dynamic than under static loading. The other group appears to fail at a certain maximum allowable force, which of course under dynamic loading can occur at very small strains. Such materials are brittle and hard like glass, cast iron, and pitch. As a group these materials have lower strengths and absorb less energy under dynamic loading than they do under static loading.

Much more recently D. S. Clark and G. Daetwyler in Reference (b) report that under dynamic loading most structural materials, which have been tested to date, have higher yield and ultimate strengths and absorb more energy in rupture than under static loading. However, their investigations indicate that most materials do not have the same percent elongation under dynamic as under static loading.

H. C. Mann in Reference (c) reports the dynamic and static strengths of those materials tested by himself to be different. In general, he finds that the dynamic strengths are greater.

In the standard type of endurance test the frequency of application of the load appears to have some effect upon the endurance limit. J. Jenkin reports in Reference (d) that at frequencies of 60,000 and 120,000 cycles per minute he found a considerable increase in the endurance limit of mild steel over that found at lower frequencies.

In view of the apparent variation in ultimate and other strengths of a material with the type and rapidity of loading it would appear that an investigation of the effect of repeated impacts would be of interest. Such an investigation would have to be carried to a large number of impacts to give any information regarding the effect of dynamic loading on the endurance limit. As mentioned in the introduction, the authors have designed a machine which they hope will aid in the study of the reaction of materials to repeated dyhamic loadings. This design is illustrated in Fig. 27. Essentially it consists of a falling carriage which is guided by two vertical rails. Between the rails at the bottom is a heavy block or anvil with a vertical hole bored directly below the center of the falling carriage. The specimen to be tested is threaded on both ends. The upper end of the specimen is screwed into the base of the carriage, and onto the lower end of the specimen is to be screwed a block with any desired mass. When the carriage is released it drops striking the anvil. The specimen and its attached mass do not strike the anvil as they pass into the vertical opening in the latter. With the striking of the carriage on the anvil, the mass on the lower end of the specimen exerts a dynamic tensile force on the specimen.

The height of drop can be regulated from one to about eight feet. The latter drop should give a striking velocity of the order of 22 ft. per second if the sliding resistance between the guide rails and the hammer can be kept to a minimum. By controlling both height of drop and mass of the attached blocks striking velocity and striking energy can be made independent variables. This is not possible with prevailing types of pendulum impact machines. This feature will make it possible to use striking energies of such magnitudes that the specimen will not be plastically deformed by any one impact. At the same time the striking velocity can be varied over a range of from about 6 to 22 feet per second.

An electric motor with a built-in reduction unit drives the vertical chain. This continuously moving chain picks up the carriage by means of the "pick up" mechanism illustrated in Fig. 28. This mechanism is controlled by two pairs of guide slots. The one pair guides the chain drive while the other operates the "pick up" mechanism to release or drop the carriage at any desired height. At present the machine is designed to operate at a speed which will give five impacts per minute, however, methods of permitting faster operation will be provided. The reaction of certain materials to repeated dynamic loadings of the order of 10,000 times is of interest to the aircraft designer and should offer light on any definite trend. A larger number of loadings can be applied either by leaving the specimen in the machine for a protracted period or arranging for faster operation of the equipment. As stated previously, this machine is now being built at the Guggenheim Aeronautical Laboratory, California Institute of Technology. Upon its completion and calibration it will be used to study the effect of repeated dynamic tensile loadings on various materials used in the aircraft industry.

## REFERENCES


(a) Plank, R. : Betrachtungen Über Dynamische Zugbeanspruchung; Zeitschrift, Ver. Deut. Ing., Vol. 56, Jan. 6, 1912.

(b) Clark, D. S. and Daetwyler, G.: Stress-strain Relations Under Tension Impact Loadings. Paper presented at the Forty-first Annual Meeting of the American Society for Testing Materials, June 1938.

(c) Mann, H. C.: Relation Between Tension Static and Dynamic Tests; Proceedings, A.S.T.M., Vol. 35, Part Two.

(d) Jenkin, J. Proc. Roy. Soc., Vol. 109A, 1925.

(e) Mann, H. C.: A Fundamental Study of the Design of Impact Test Specimens; Proceedings, A.S.T.M., Vol. 37, Part Two.

# Table 1

| Material | Specimen | $E_o$ | $E_L$ | $E_L/E_o$ | $E_L/\rho$ | QUOTED VALUES yield stress | ultimate stress | elong. in 2" | $\sigma_y \div \rho$ |
|---|---|---|---|---|---|---|---|---|---|
| ALCOA 24ST | Rod, with grain | 155 | 9.87 | 6.37% | 98.7 | 40,000 | 62,000 | 14% | 400,000 |
| | Plate, with grain | 169 | 8.90 | 5.27 | 89.0 | | | | |
| | Plate, cross grain | 145 | 7.60 | 5.25 | 76.0 | | | | |
| ALCOA 14ST | Plate, with grain | 114 | 6.80 | 5.96 | 67.2 | 50,000 | 65,000 | 10% | 495,000 |
| | Plate, cross grain | 88 | 6.08 | 6.92 | 60.1 | | | | |
| Dowmetal X | Rod, with grain extruded, aged | 73 | 4.00 | 5.48 | 61.6 | 30,000 | 41,000 | 10% | 462,000 |
| Dowmetal Z-1 | Rod, with grain extruded | 51 | 6.00 | 11.75 | 88.2 | 42,000 | 58,300 | 8.0% | 618,000 |
| ALCOA 24ST | Rod, 2" gage length | 242 | 13.5 | 5.58 | 67.5 | | | | |

$E_o$ = Energy absorbed by specimen in breaking in one blow (foot pounds)

$E_L$ = Impact Endurance Limit (foot pounds)

$\rho$ = Density (pounds per cubic inch)

$\sigma_y$ = Yield stress (pounds per square inch)

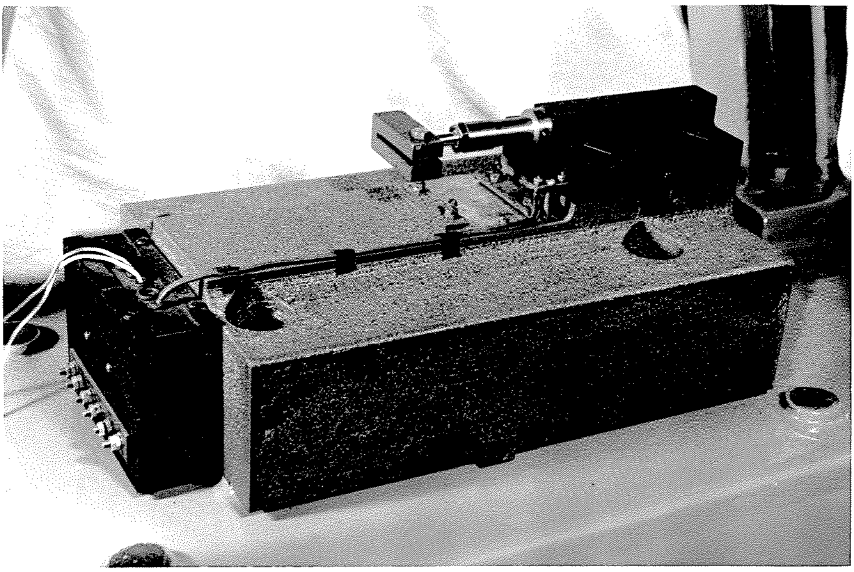


Fig. 1

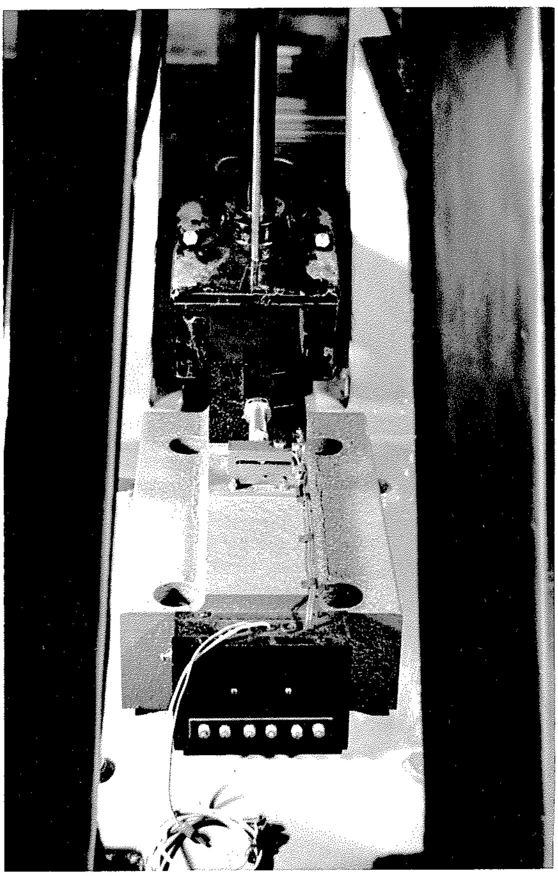


Fig. 2

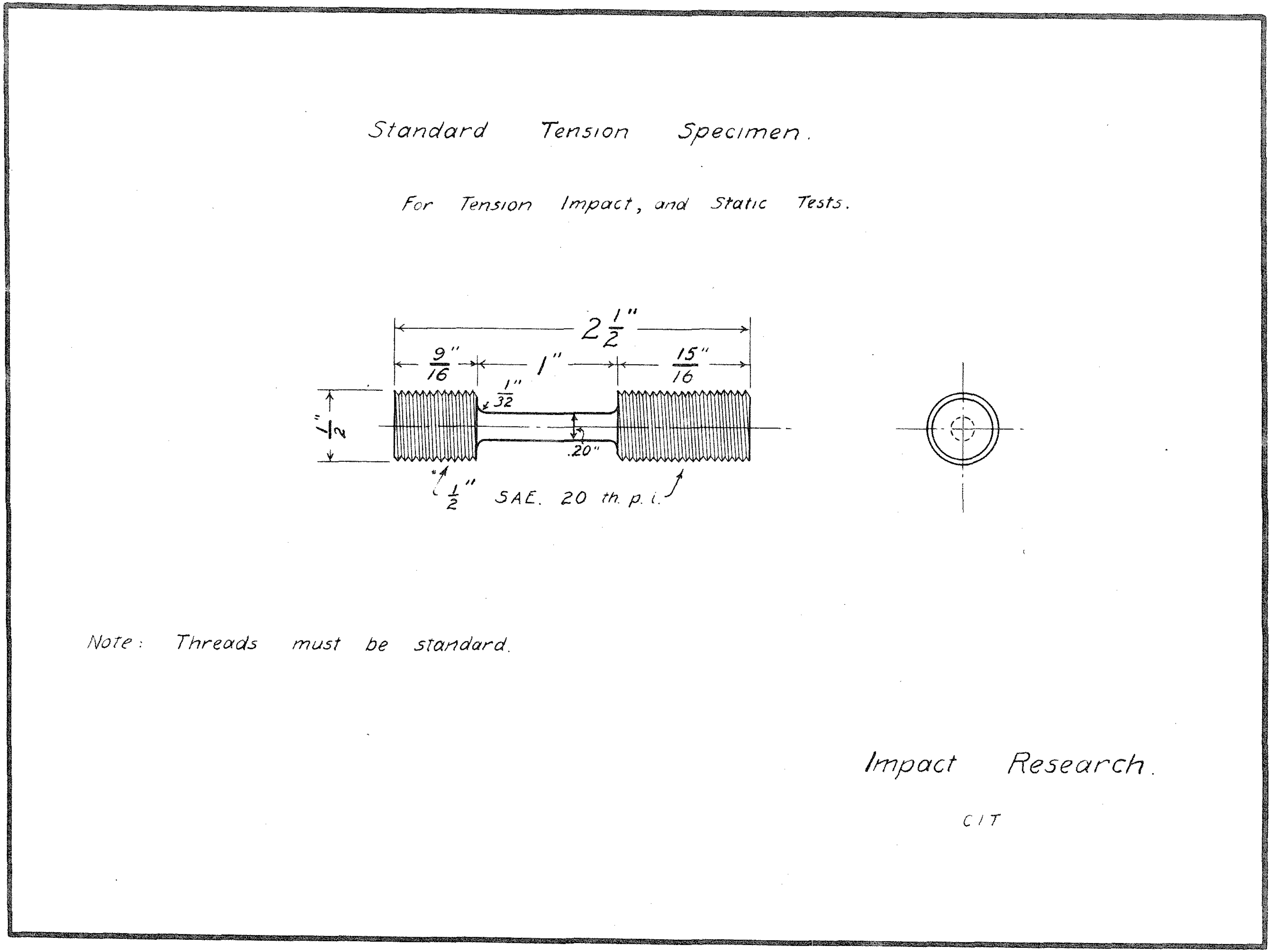

Standard Tension Specimen.
For Tension Impact, and Static Tests.
2 1/2"
9/16"
1"
15/16"
1/32"
1/2"
.20"
1/2" SAE. 20 th. p. i.
Note: Threads must be standard.
Impact Research.
CIT

Fig. 3

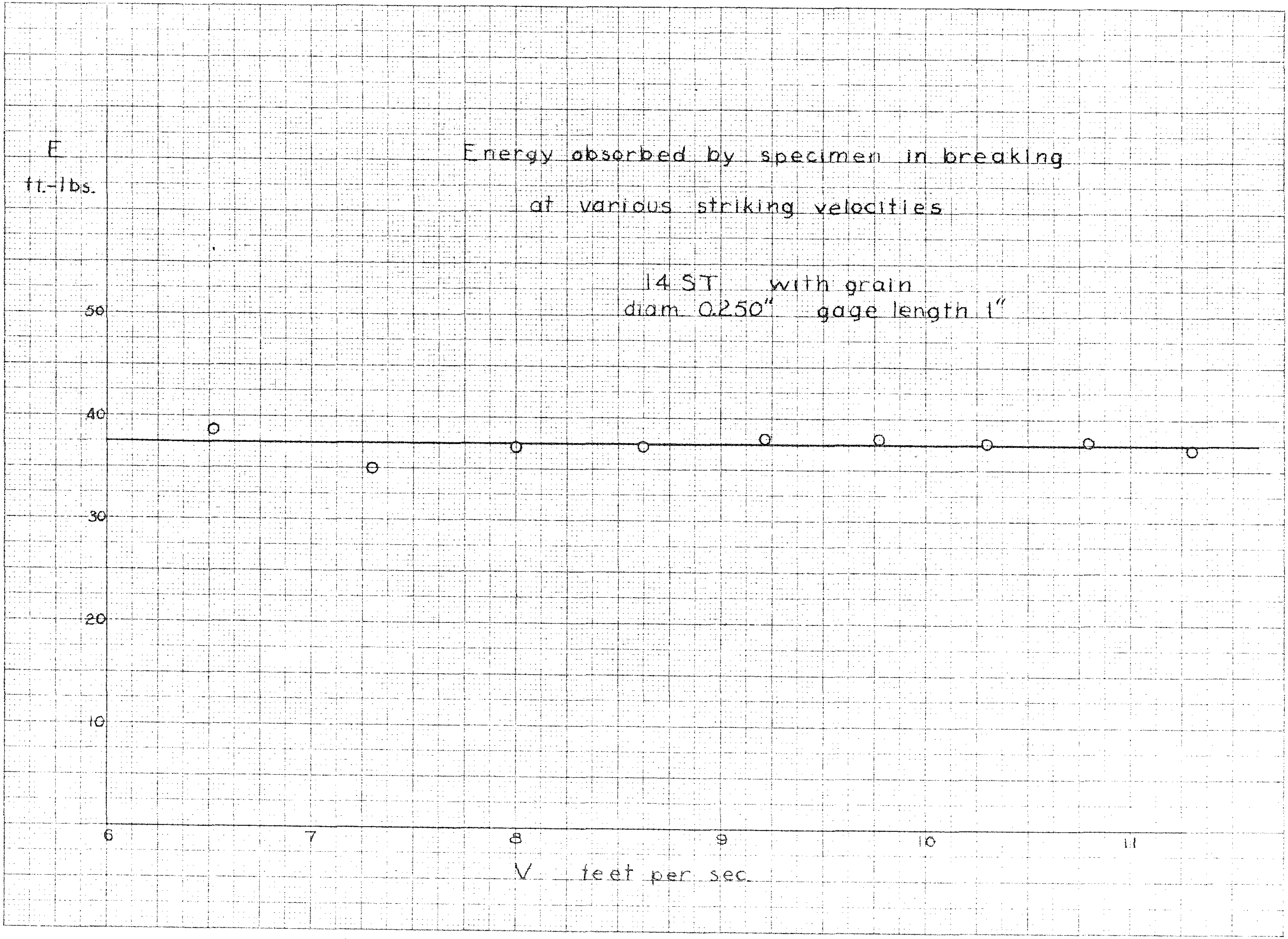

E
ft.-lbs.
Energy absorbed by specimen in breaking
at various striking velocities
14 ST with grain
diam 0.250" gage length 1"
50
40
30
20
10
6
7
8
9
10
11
V feet per sec

Fig. 4

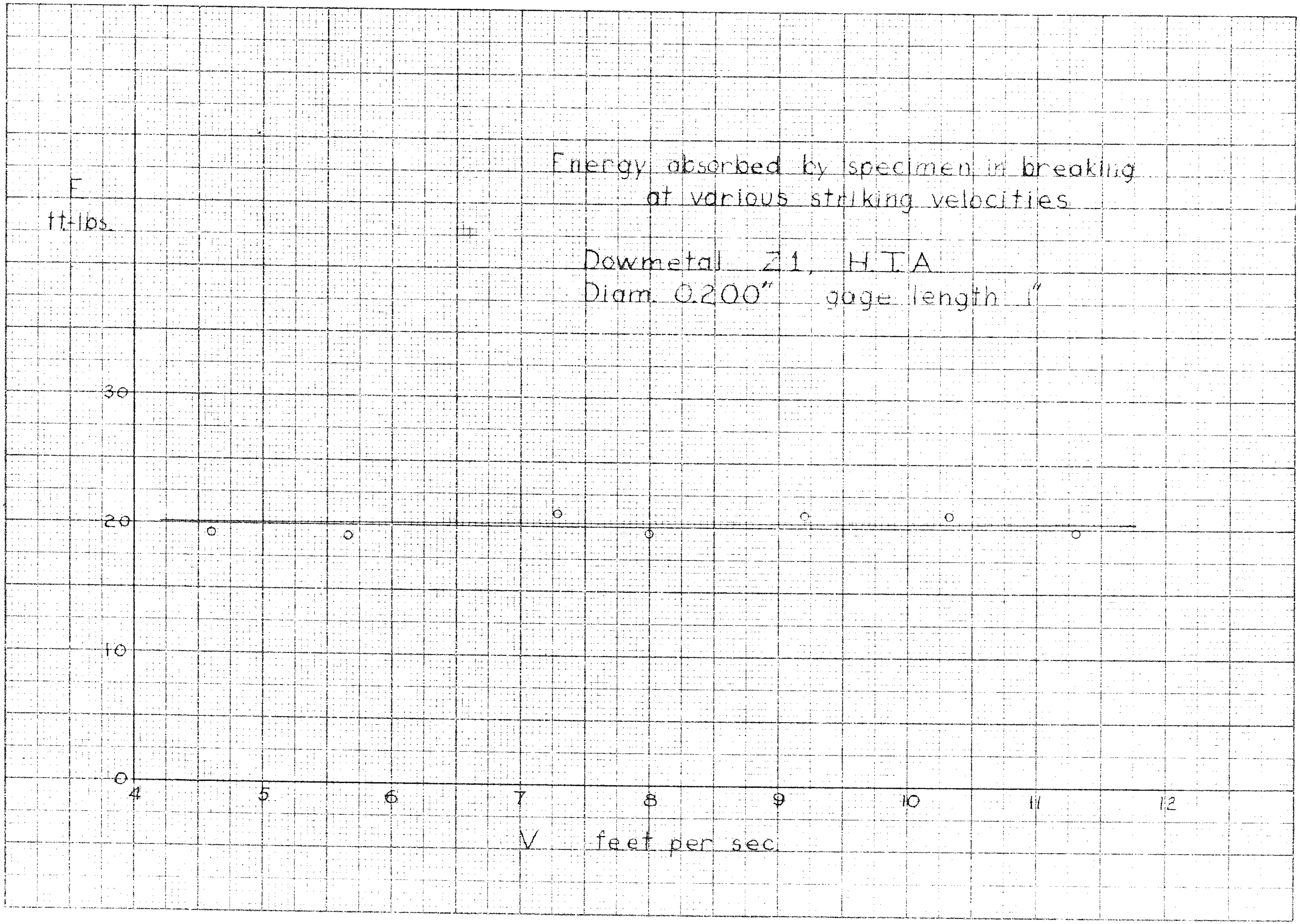
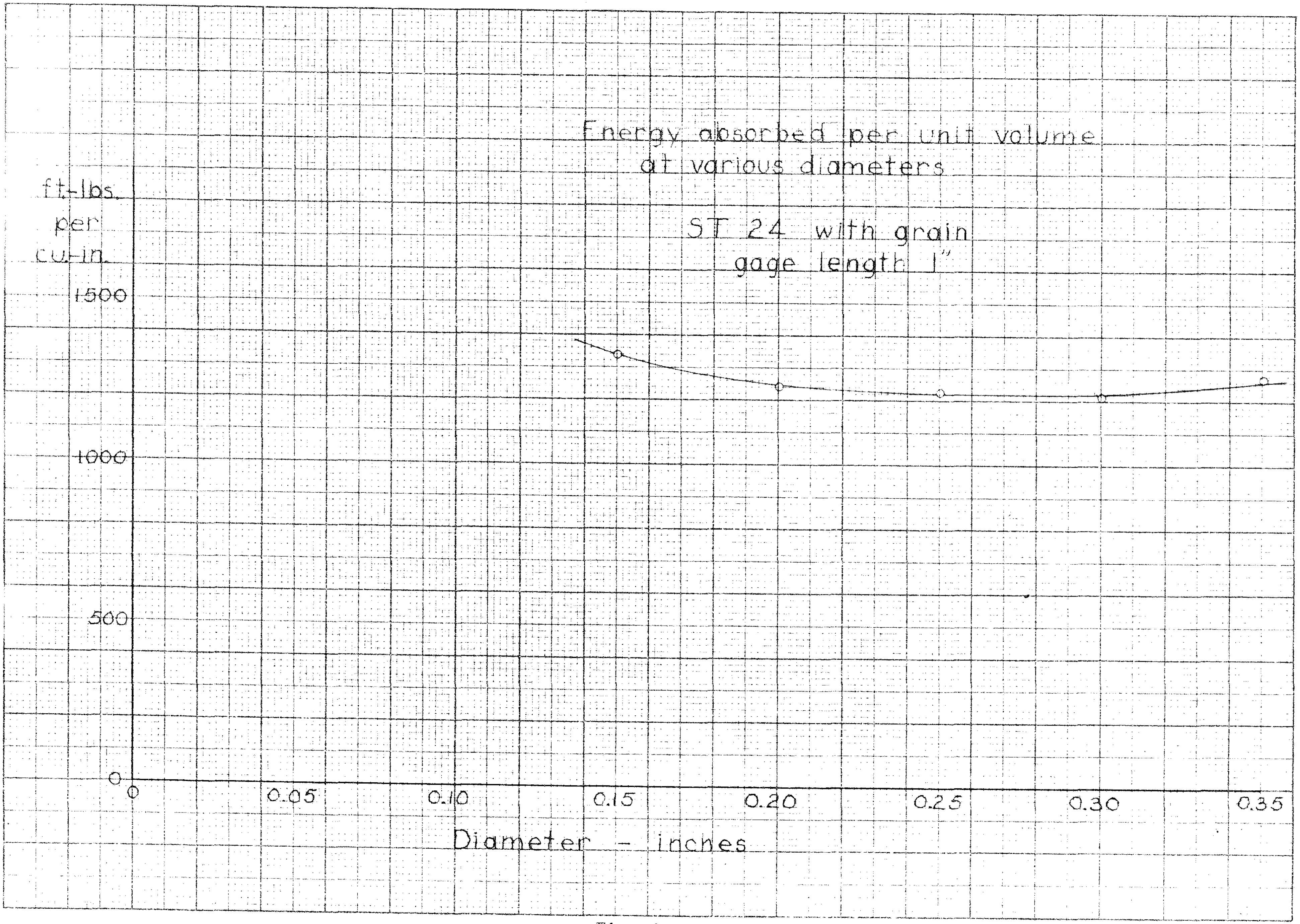

Energy absorbed by specimen in breaking
at various striking velocities
Dowmetal Z1, H.T.A
Diam. 0.200" gage length 1"
E
ft-lbs
30
20
10
0
4
5
6
7
8
9
10
11
12
V feet per sec

Fig. 5



Energy absorbed per unit volume
at various diameters
ST 24 with grain
gage length 1"
ft-lbs.
per
cu-in.
1500
1000
500
0
0
0.05
0.10
0.15
0.20
0.25
0.30
0.35
Diameter - inches


Fig. 6

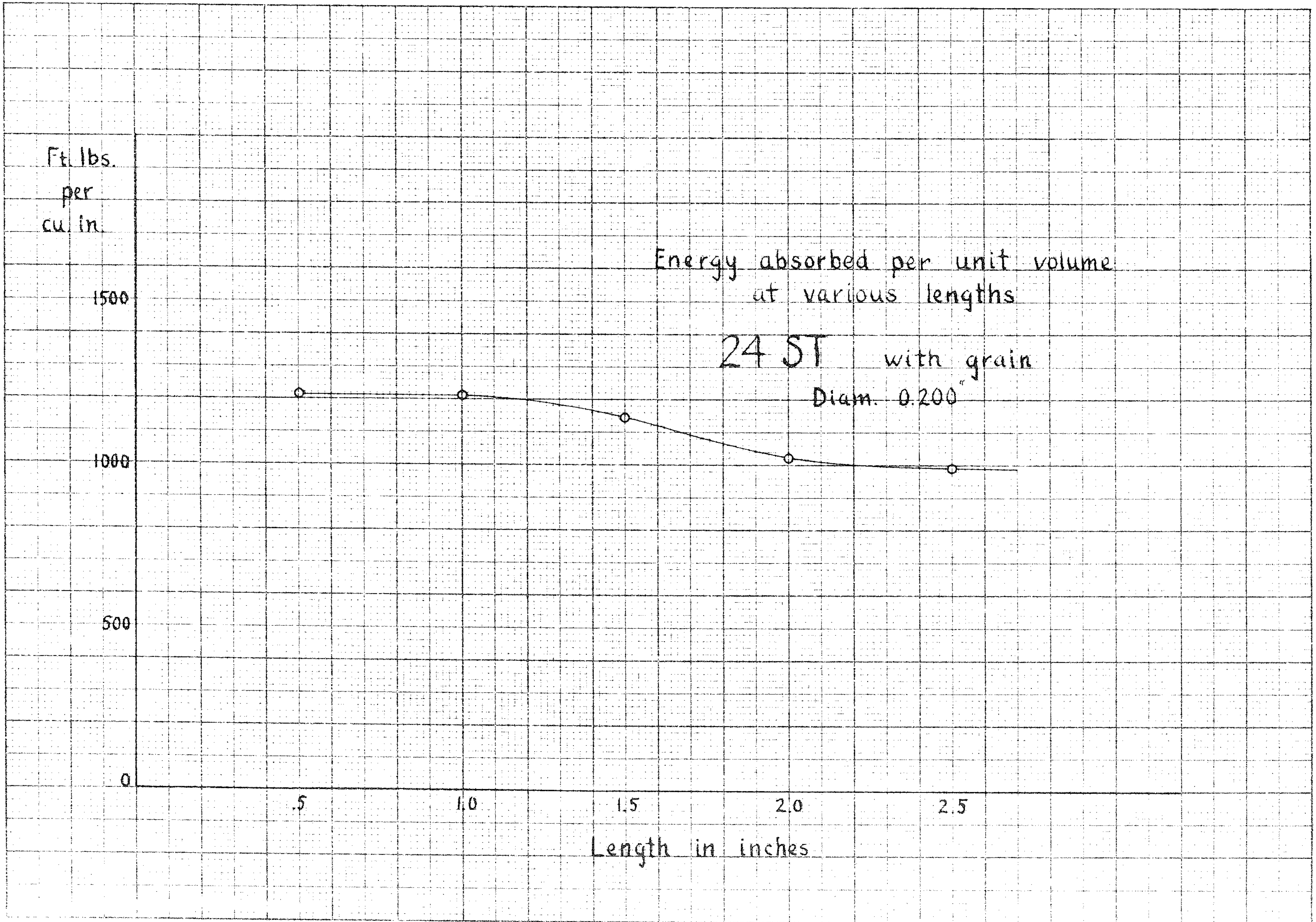

Ft. lbs. per cu. in.
1500
1000
500
0
Energy absorbed per unit volume at various lengths
24 ST with grain
Diam. 0.200"
.5
1.0
1.5
2.0
2.5
Length in inches

Fig. 7

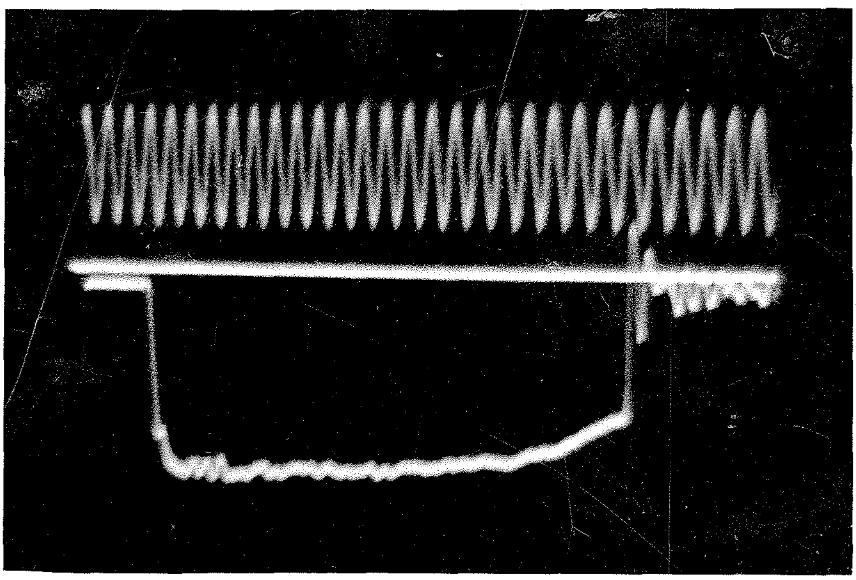
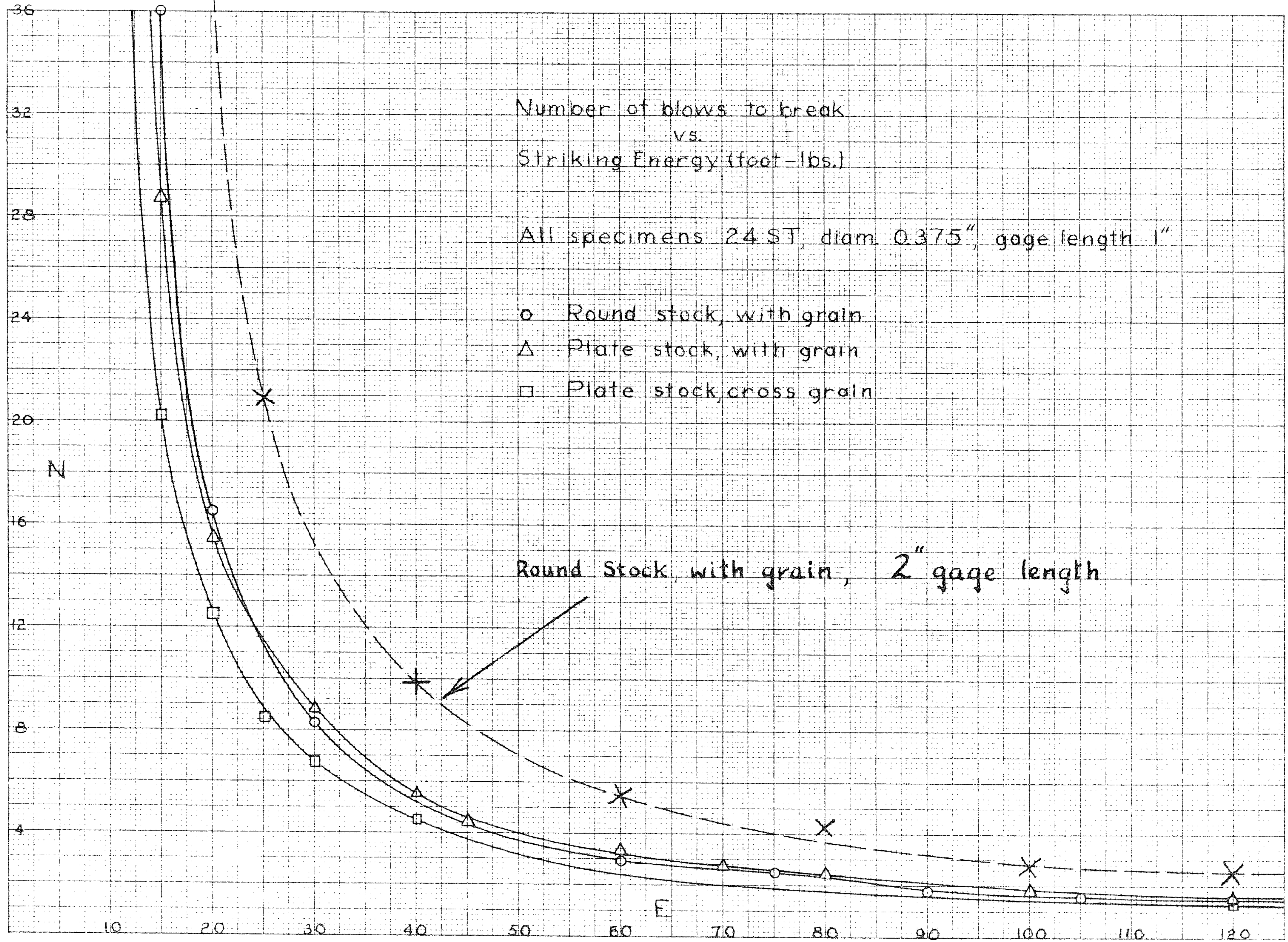
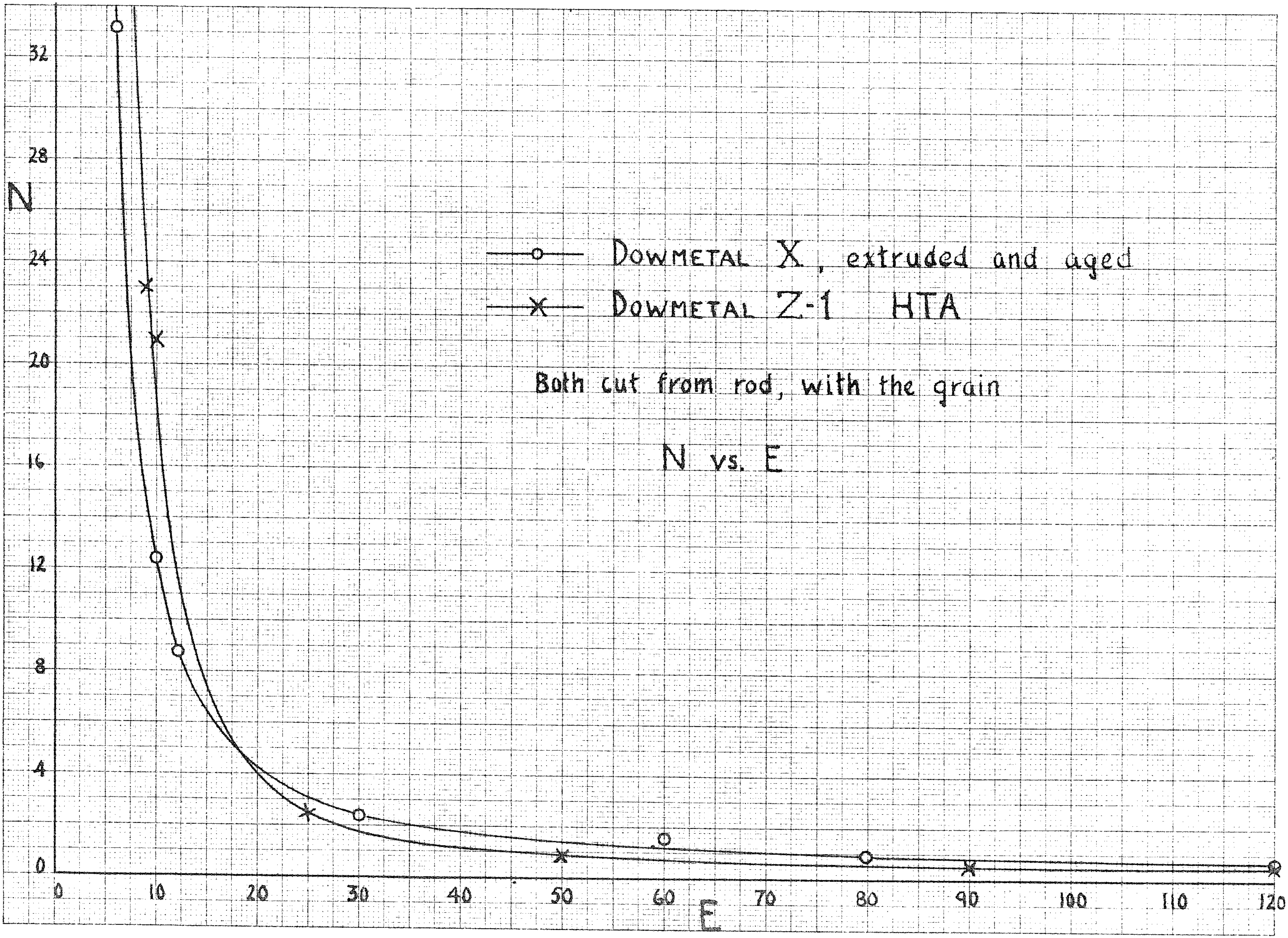


Fig. 8



Number of blows to break
vs.
Striking Energy (foot-lbs.)
All specimens 24 ST, diam. 0.375", gage length 1"
o Round stock, with grain
△ Plate stock, with grain
□ Plate stock, cross grain
Round Stock, with grain, 2" gage length
N
E
36
32
28
24
20
16
12
8
4
10
20
30
40
50
60
70
80
90
100
110
120


Fig. 9



N
32
28
24
20
16
12
8
4
0
DOWMETAL X, extruded and aged
DOWMETAL Z-1 HTA
Both cut from rod, with the grain
N vs. E
0
10
20
30
40
50
60
70
80
90
100
110
120
E


Fig. 10

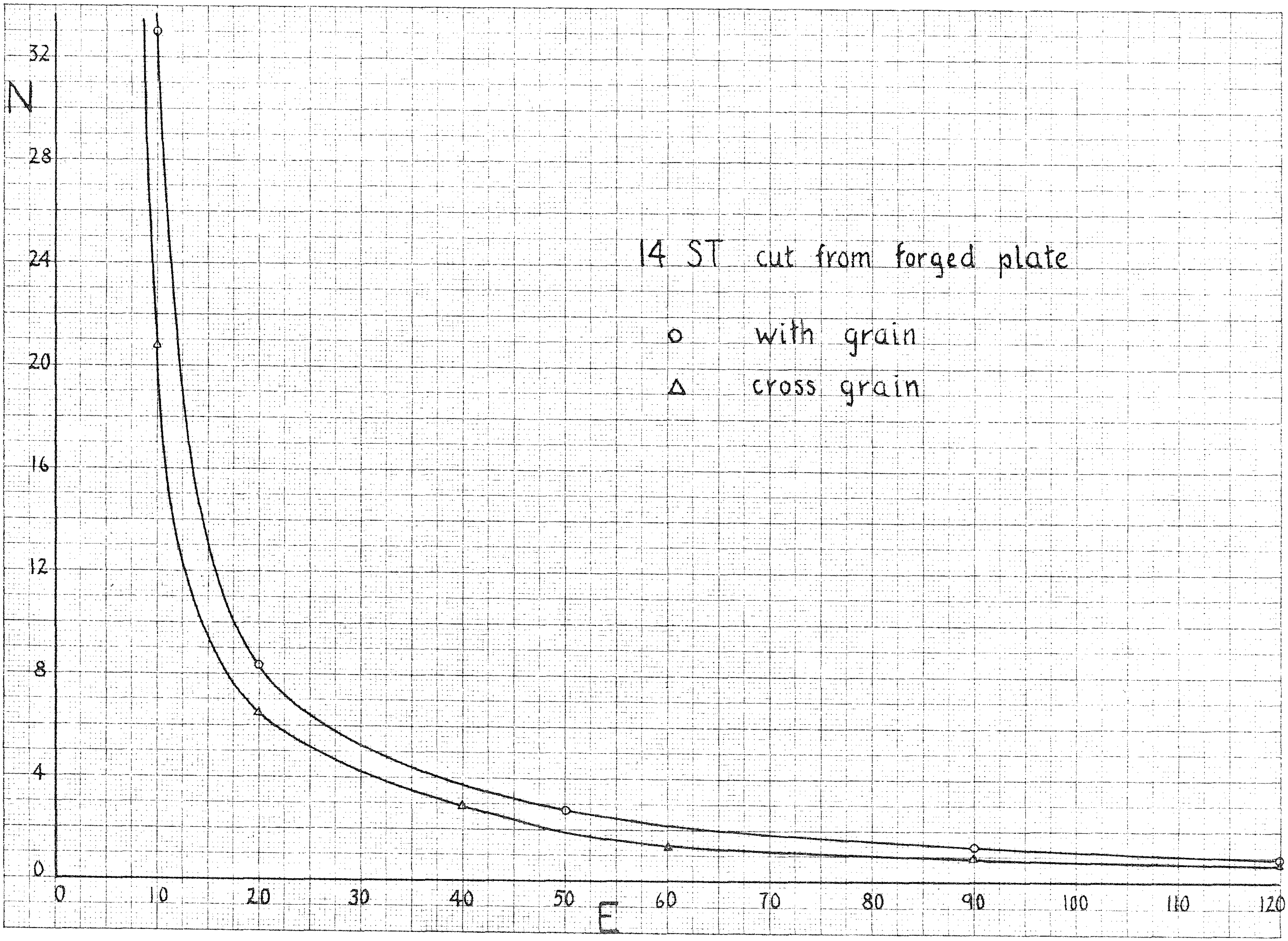
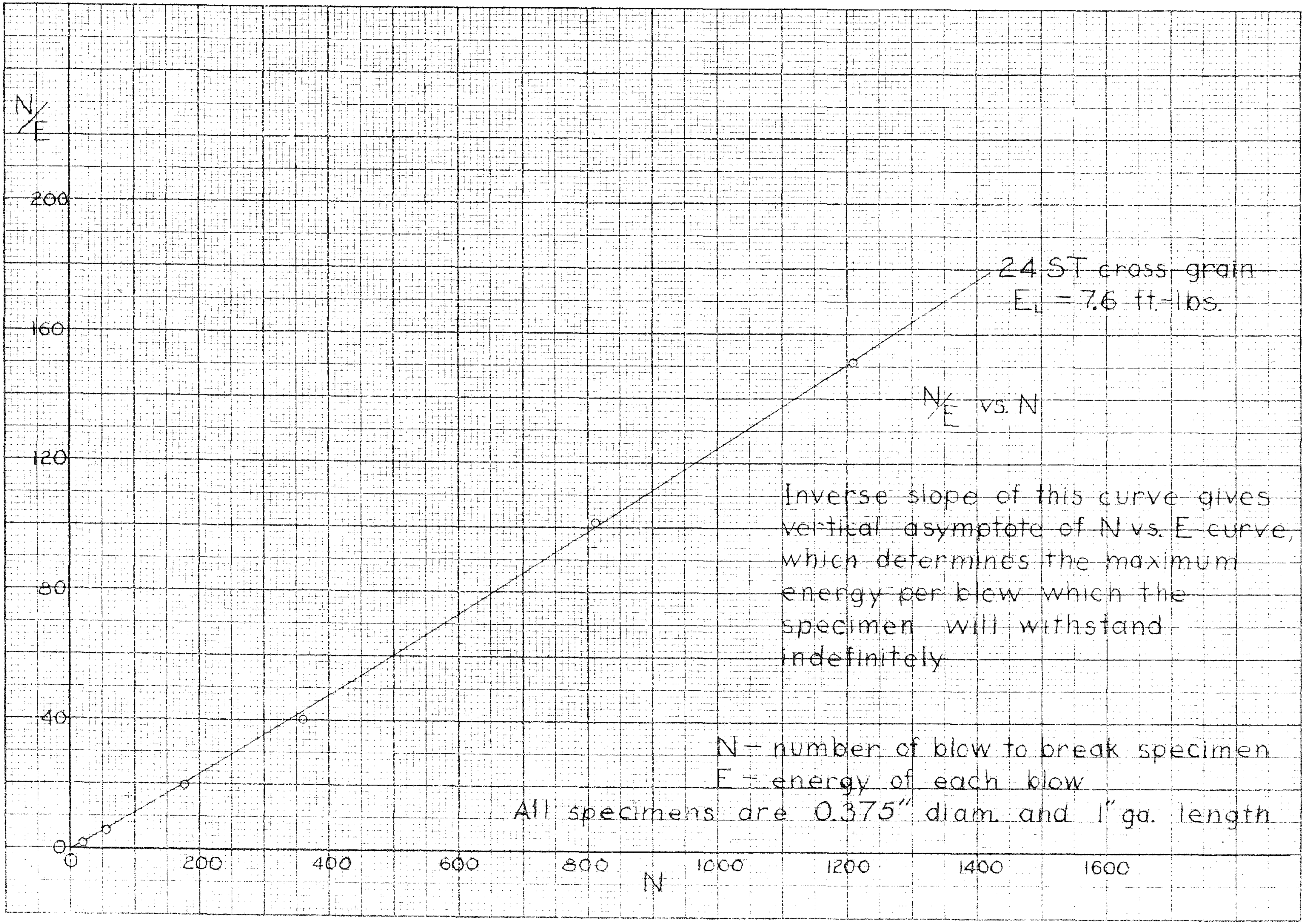

14 ST cut from forged plate
o with grain
Δ cross grain
N
32
28
24
20
16
12
8
4
0
10
20
30
40
50
60
70
80
90
100
110
120
E

Fig. 11



N/E
200
160
120
80
40
0
0
200
400
600
800
1000
1200
1400
1600
N
24 ST cross grain
E_L = 7.6 ft-lbs.
N/E vs. N
Inverse slope of this curve gives
vertical asymptote of N vs. E curve,
which determines the maximum
energy per blow which the
specimen will withstand
indefinitely
N - number of blow to break specimen
E - energy of each blow
All specimens are 0.375" diam. and 1" ga. length


Fig. 12

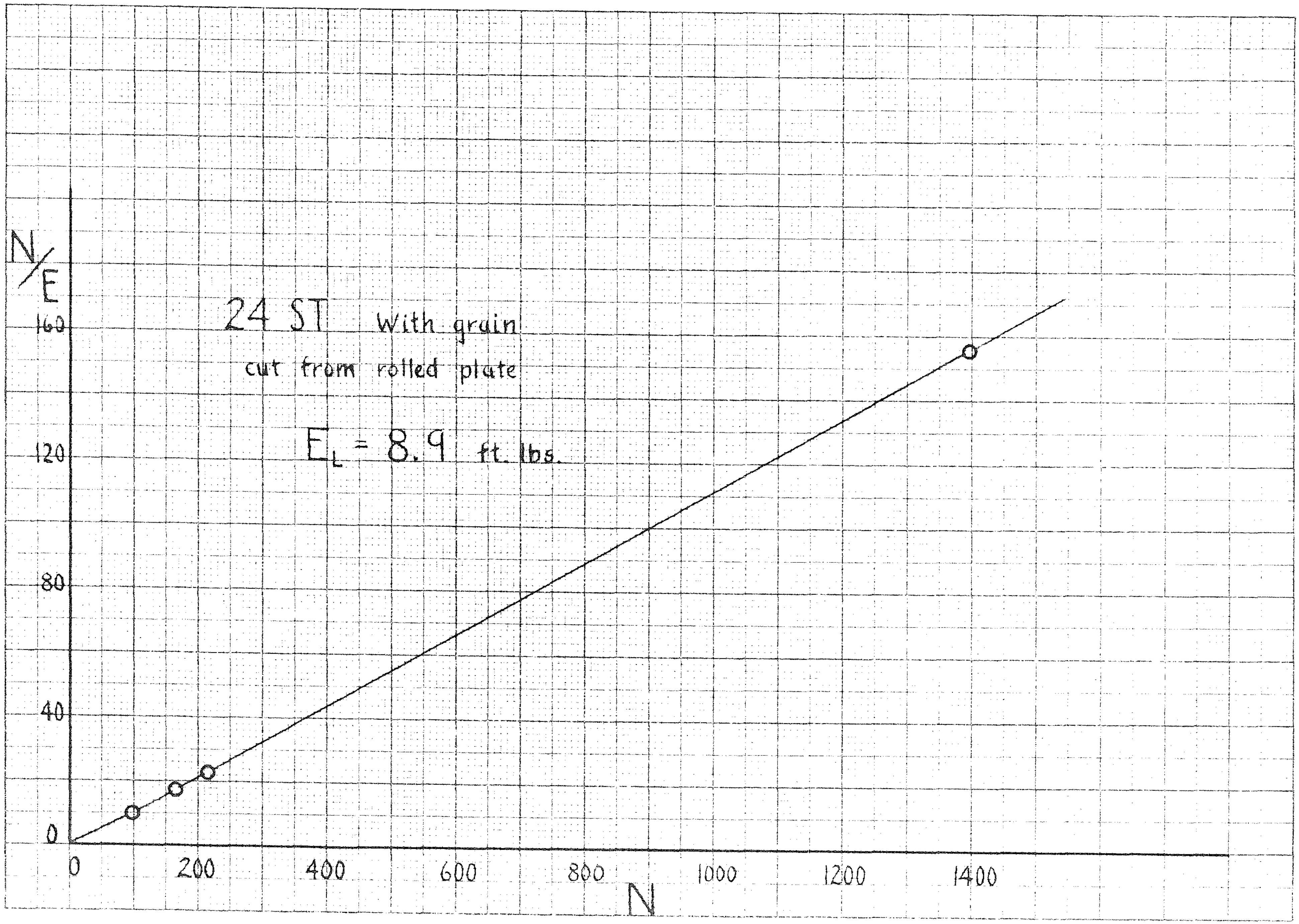

N/E
160
120
80
40
0
24 ST With grain
cut from rolled plate
E_L = 8.9 ft. lbs.
0
200
400
600
800
1000
1200
1400
N

Fig. 13

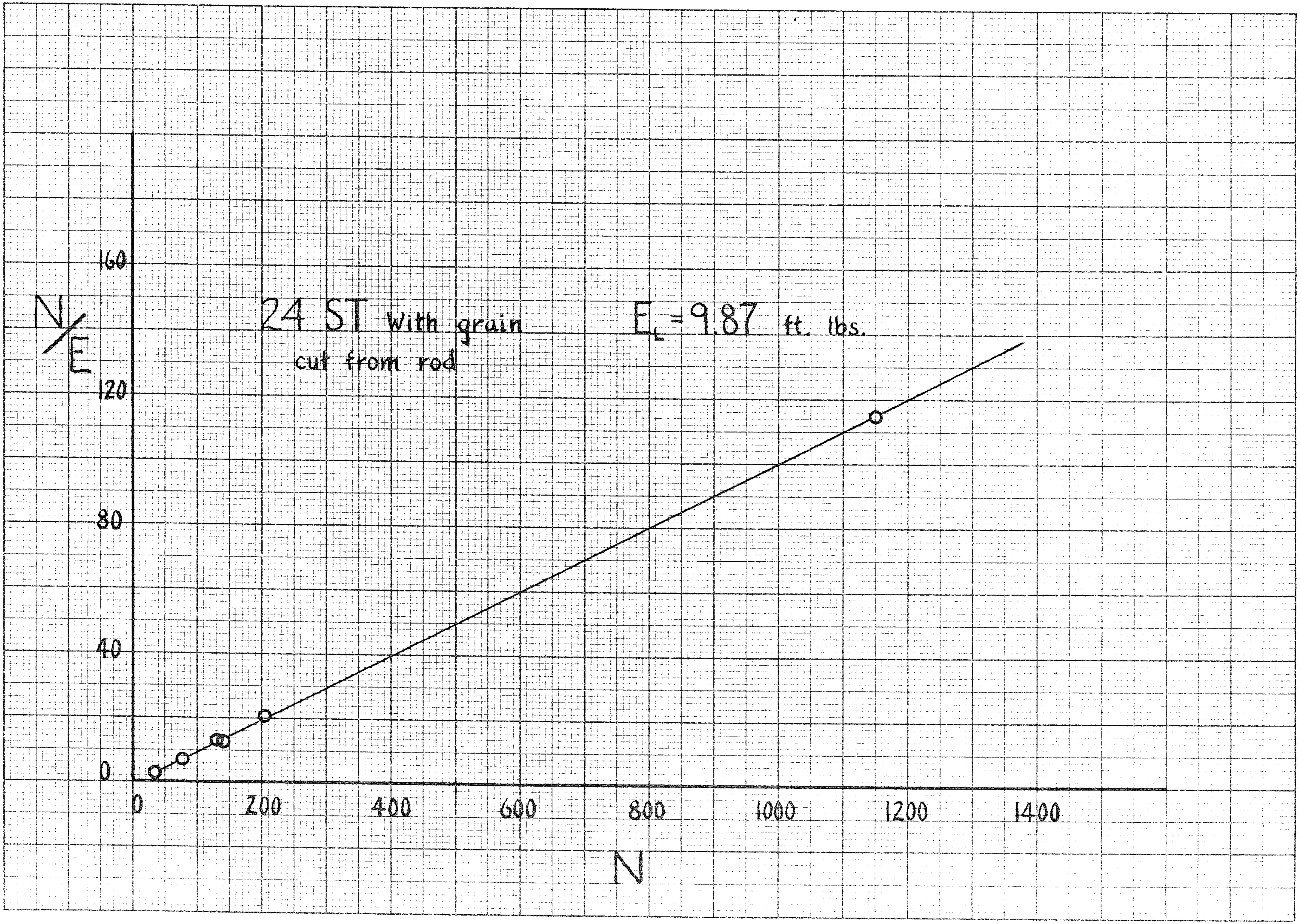

24 ST with grain
cut from rod
E_L = 9.87 ft. lbs.
N/E
160
120
80
40
0
0
200
400
600
800
1000
1200
1400
N

Fig. 14

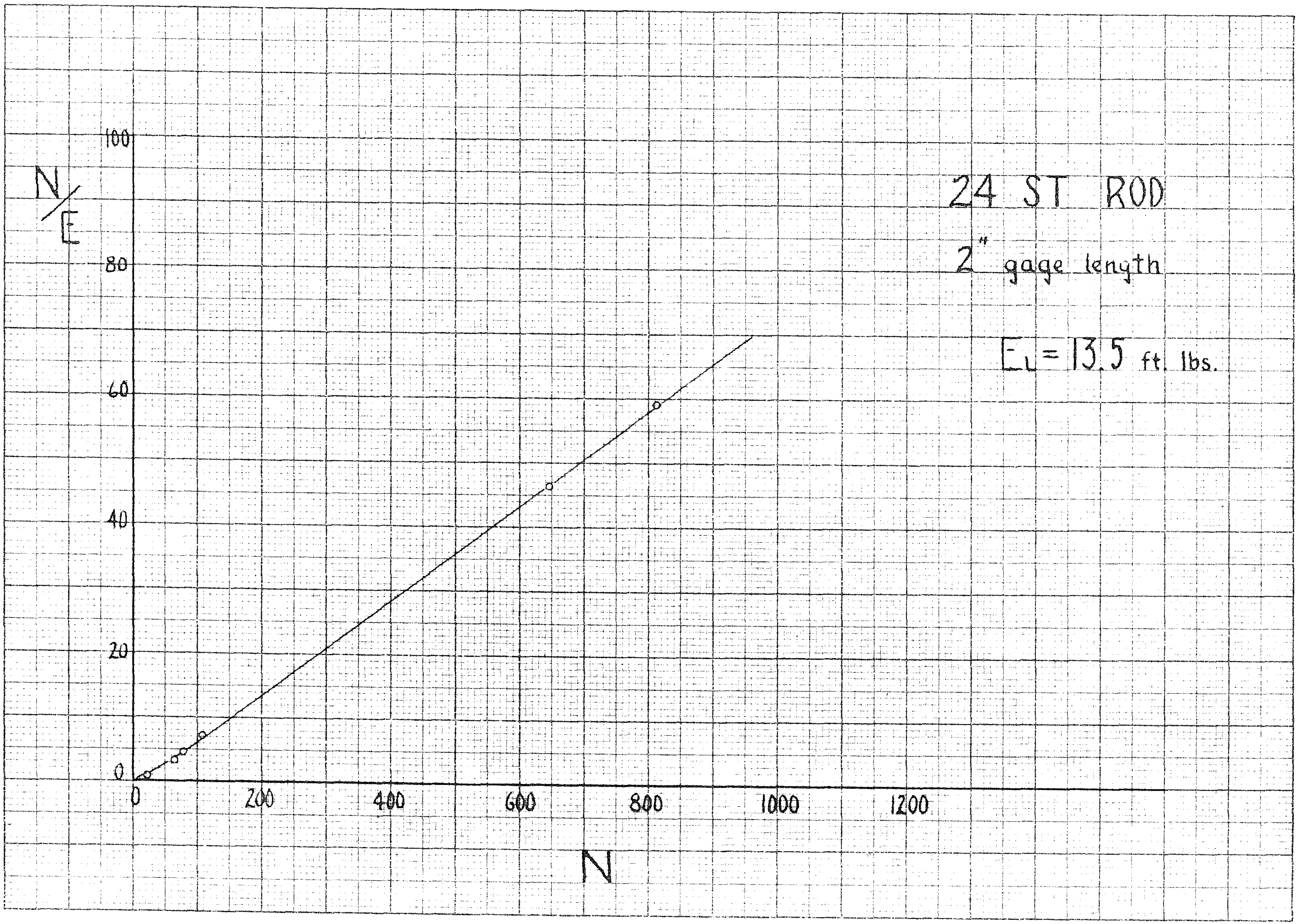

24 ST ROD
2" gage length
E = 13.5 ft. lbs.
N/E
100
80
60
40
20
0
200
400
600
800
1000
1200
N

Fig. 15

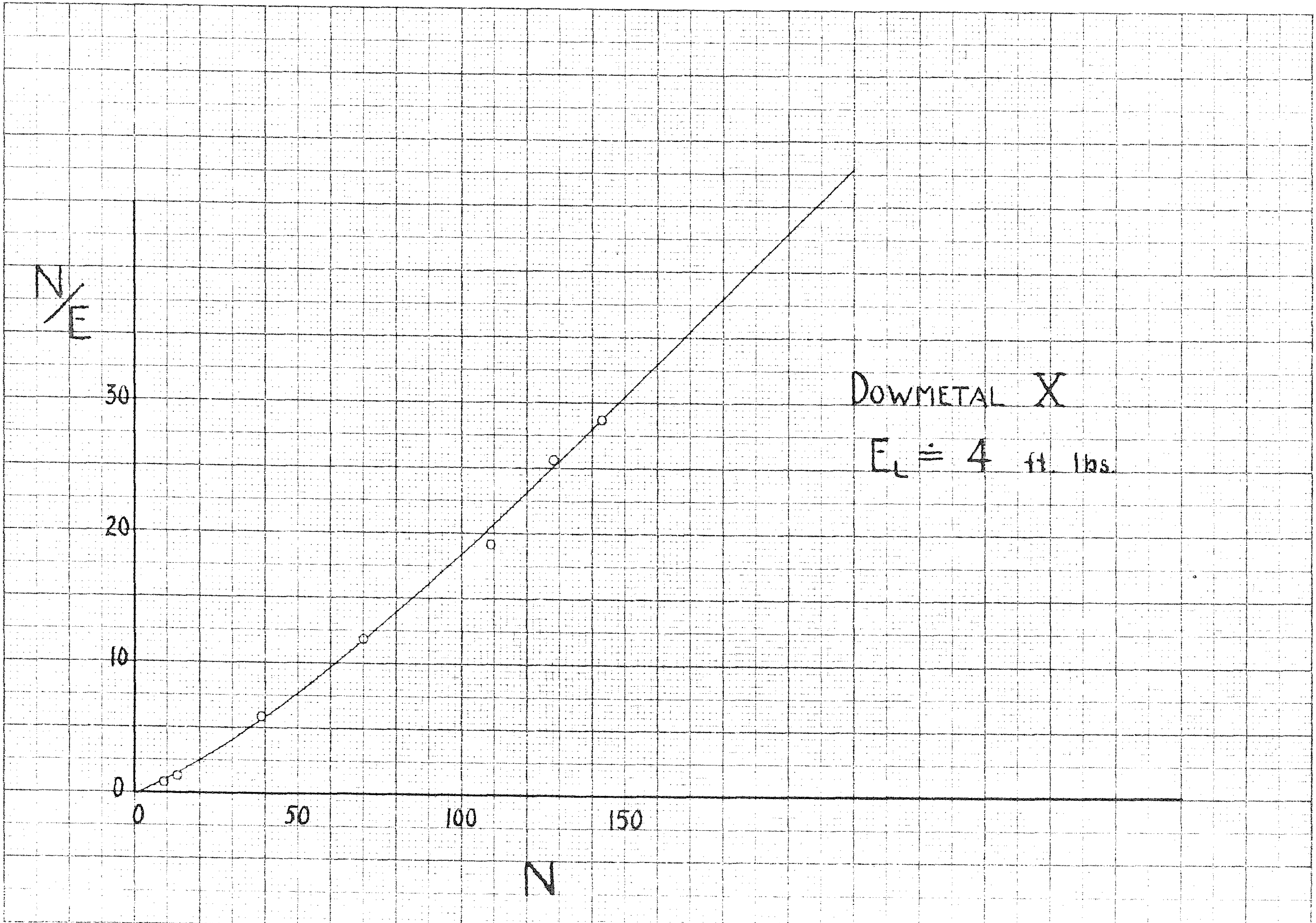



Fig. 16

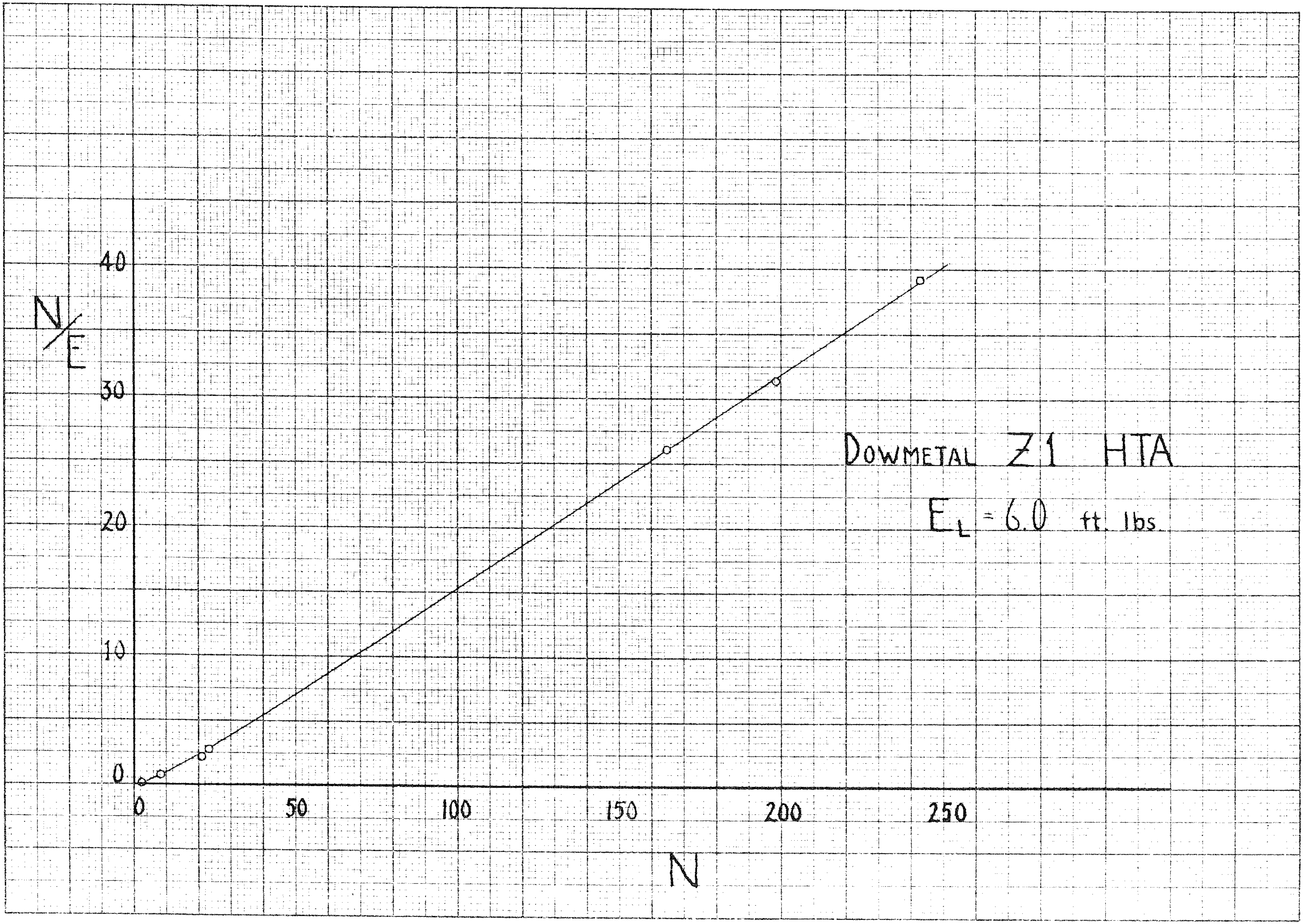
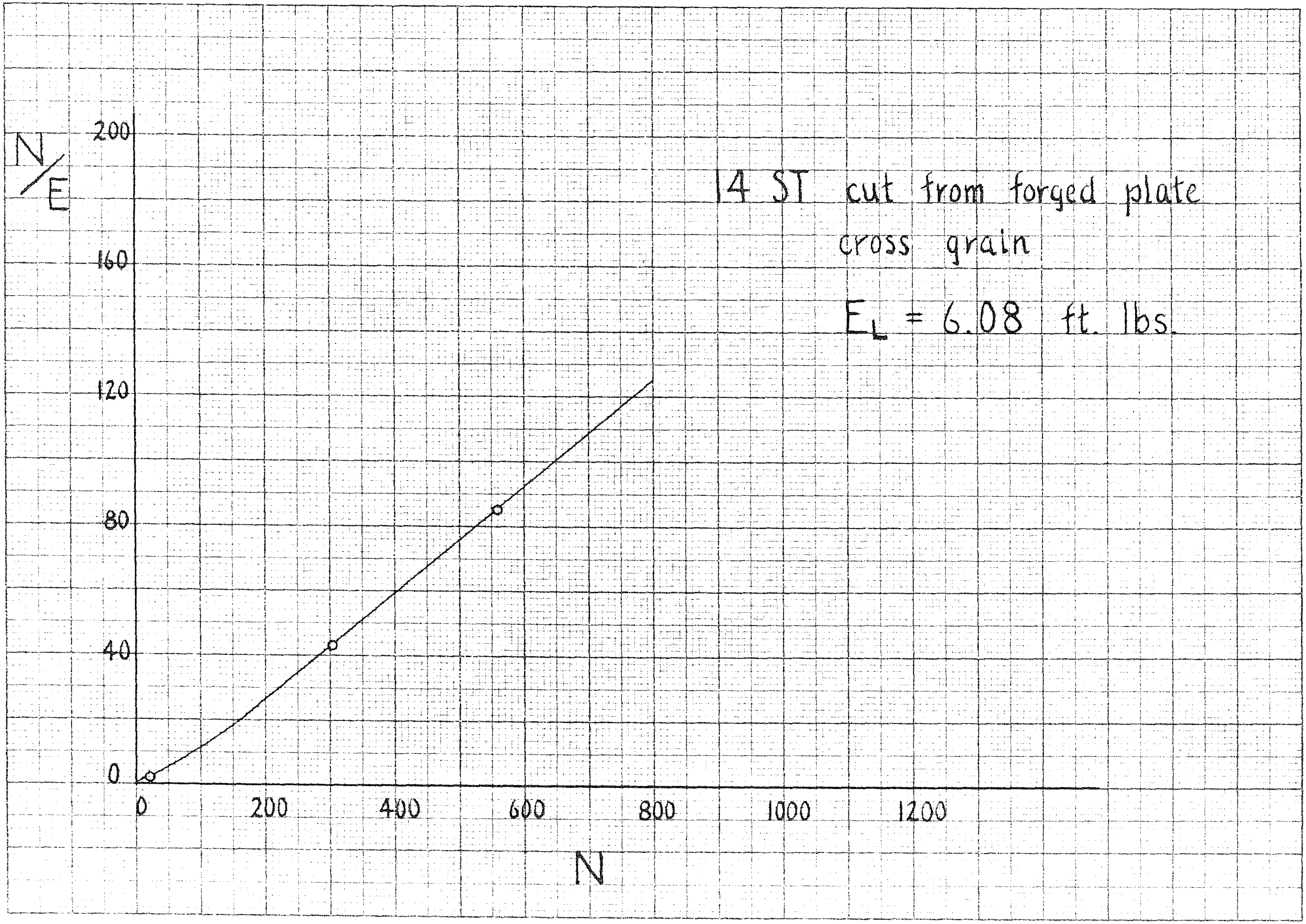



Fig. 17



N/E
200
160
120
80
40
0
0
200
400
600
800
1000
1200
N
14 ST cut from forged plate
cross grain
E_L = 6.08 ft. lbs.


Fig. 19

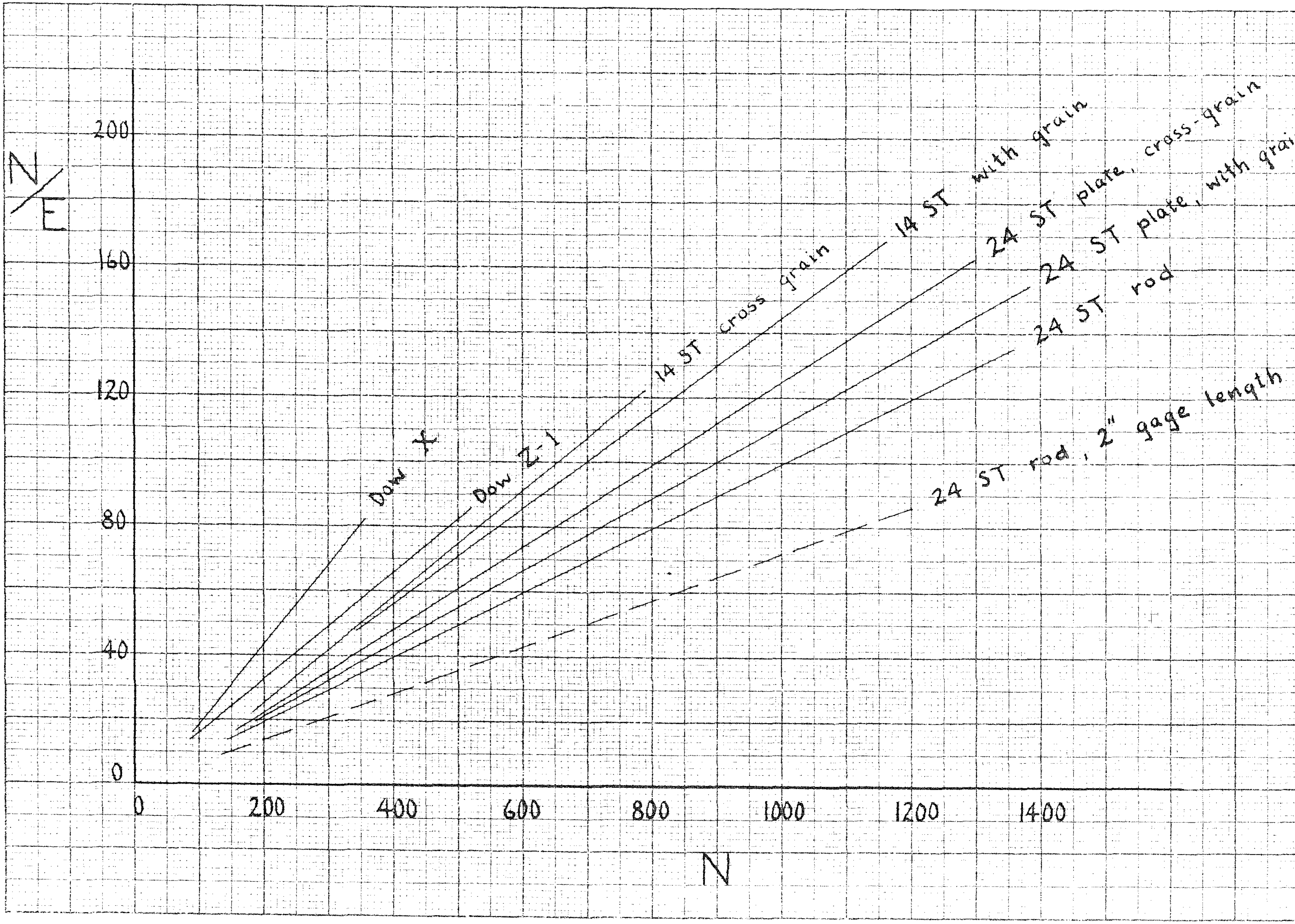
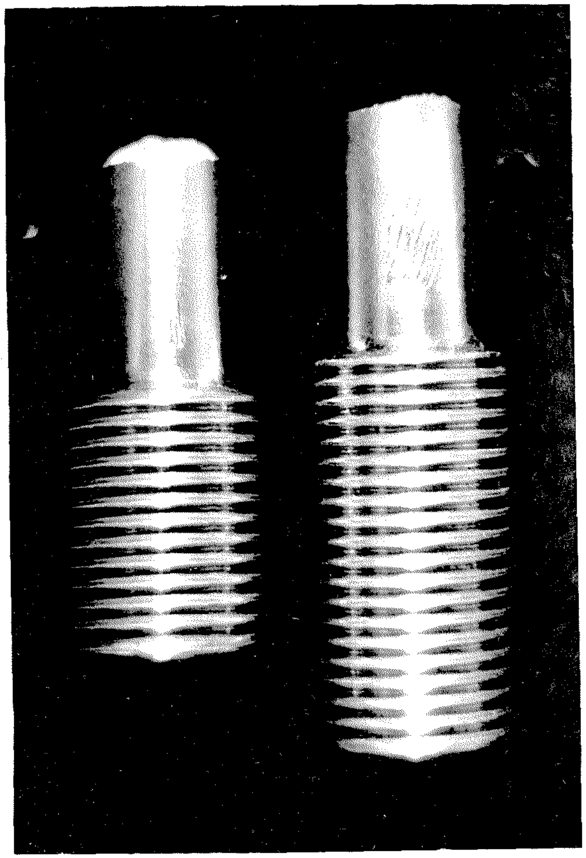
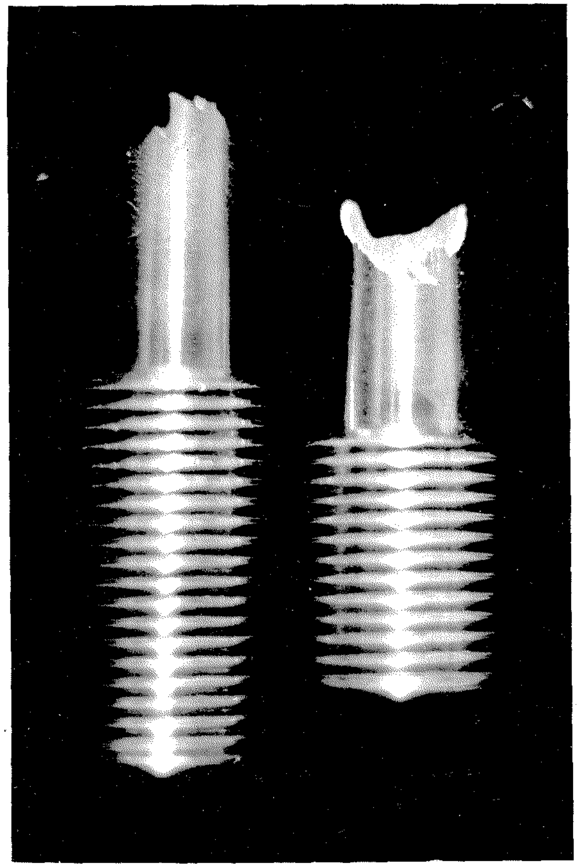

N/E
200
160
120
80
40
0
0
200
400
600
800
1000
1200
1400
N
Dow X
Dow Z-1
14 ST cross grain
14 ST with grain
24 ST plate, cross-grain
24 ST plate, with grain
24 ST rod
24 ST rod, 2" gage length

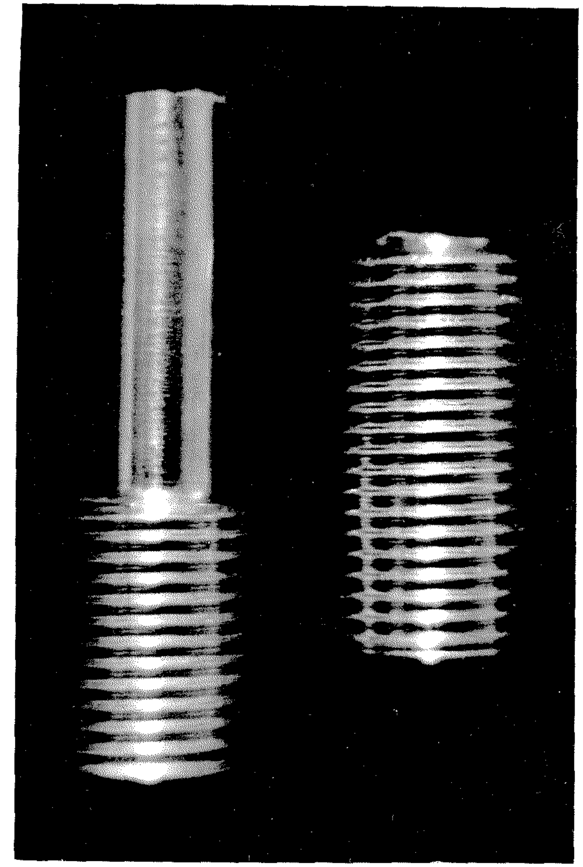
Fig. 20



24ST Rod



Dowmetal X



Dowmetal Z

Fig. 21

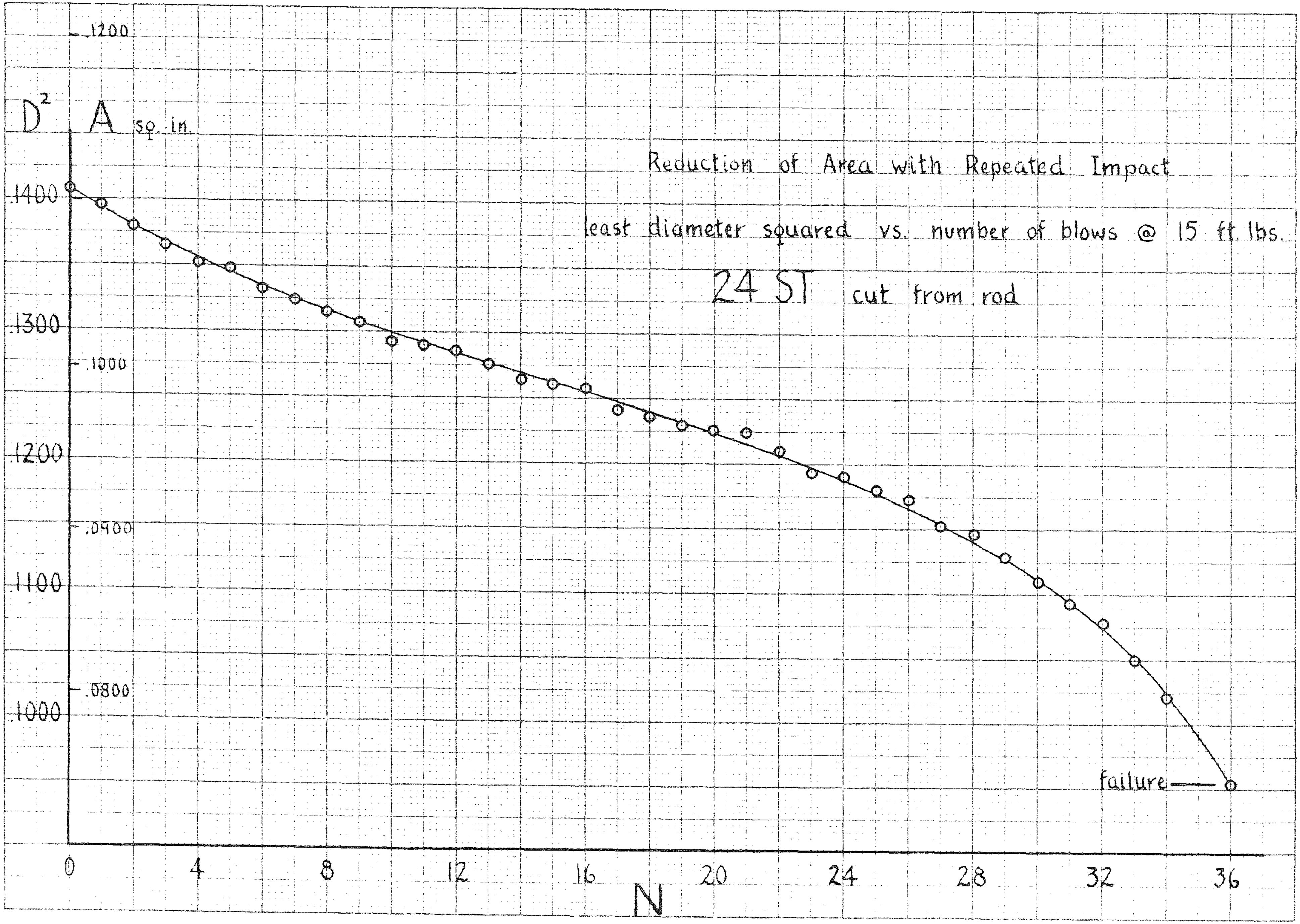

Reduction of Area with Repeated Impact
least diameter squared vs. number of blows @ 15 ft. lbs.
24 ST cut from rod
$D^2$
A sq. in.
.1200
.1000
.0900
.0800
.1400
.1300
.1200
.1100
.1000
0
4
8
12
16
20
24
28
32
36
N
failure

Fig. 22

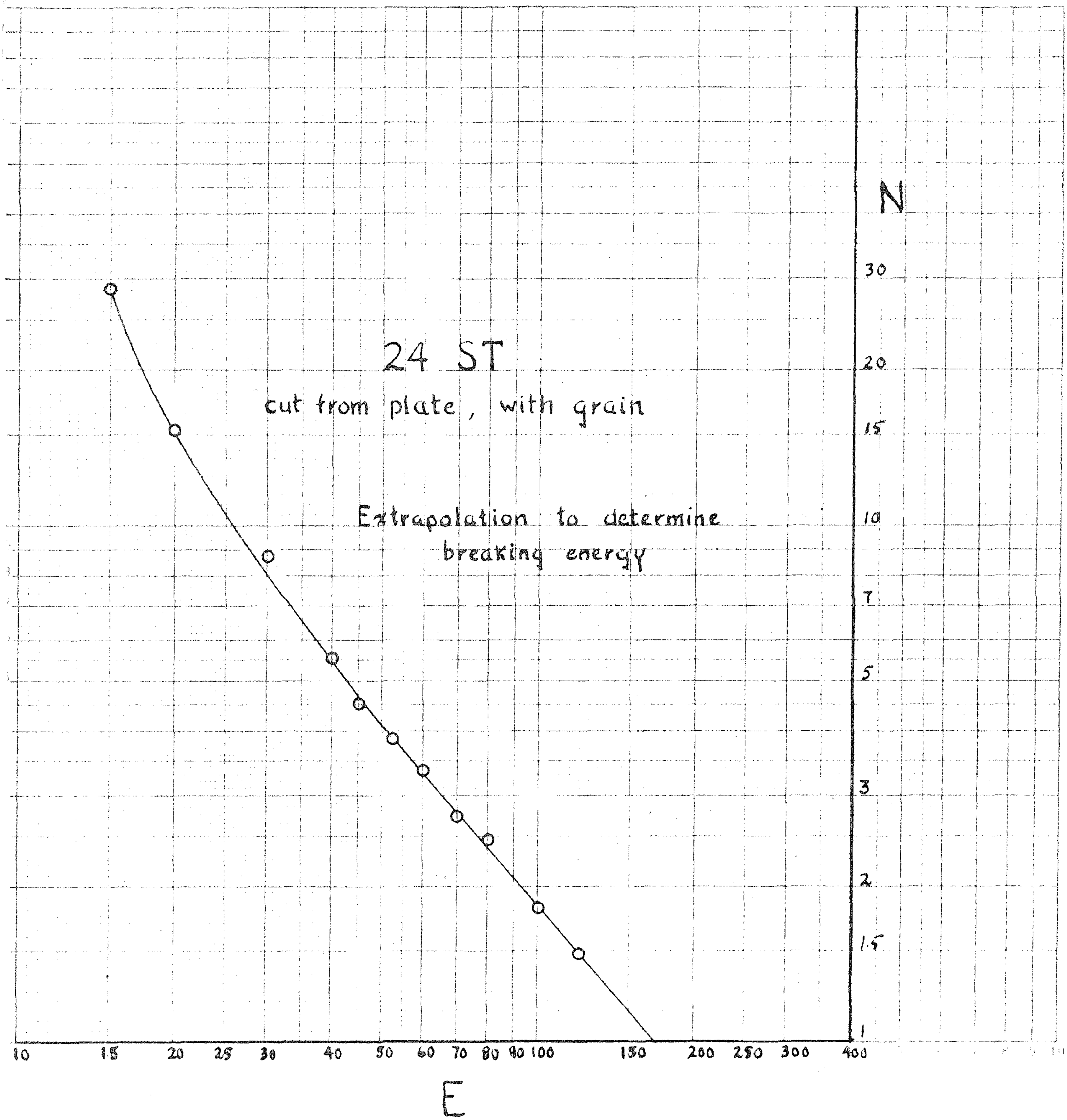
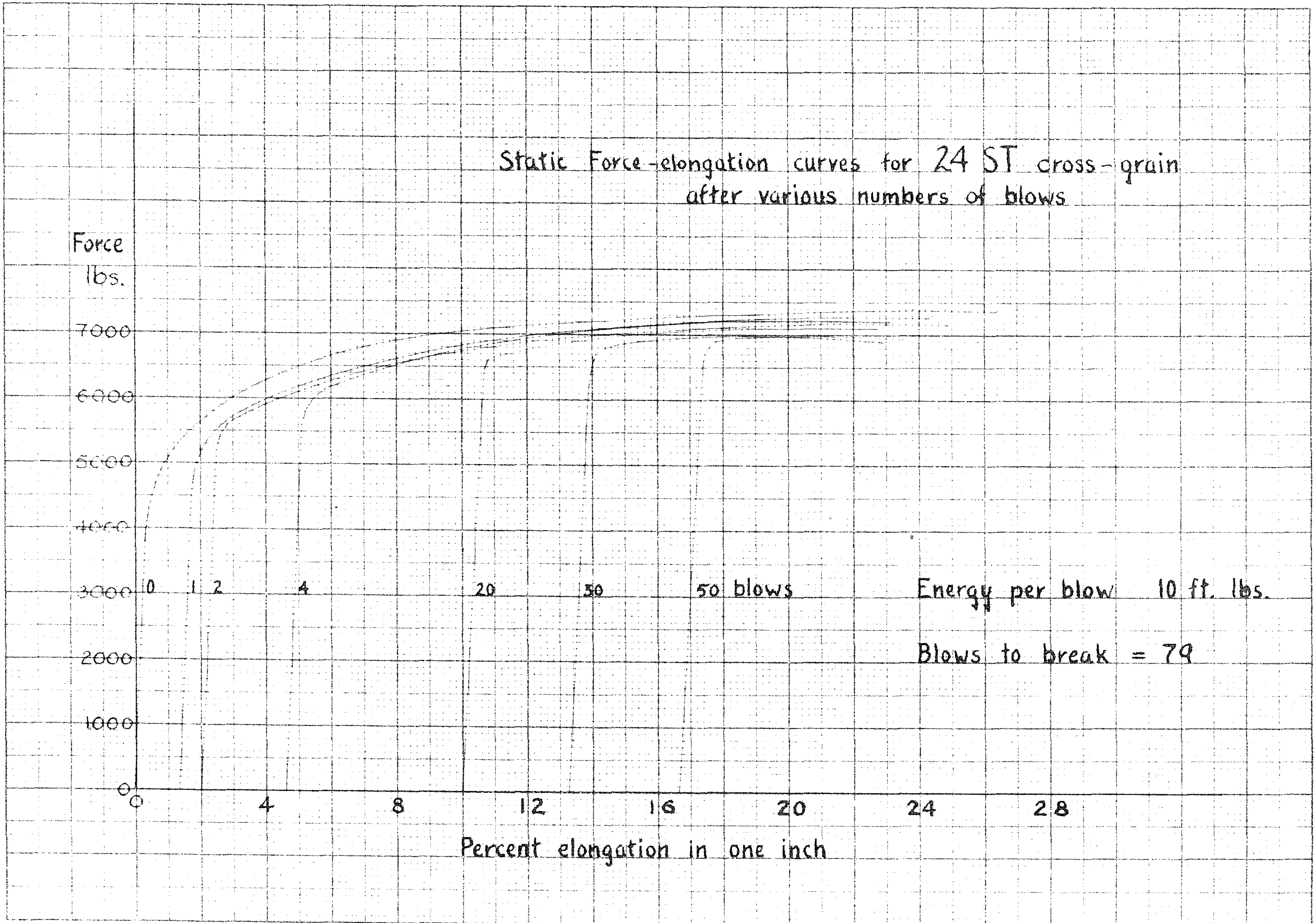

24 ST
cut from plate, with grain
Extrapolation to determine breaking energy
N
30
20
15
10
7
5
3
2
1.5
1
10
15
20
25
30
40
50
60
70
80
90
100
150
200
250
300
400
E

Fig. 23



Static Force-elongation curves for 24 ST cross-grain
after various numbers of blows
Force
lbs.
7000
6000
5000
4000
3000
2000
1000
0
0
1
2
4
20
30
50 blows
Energy per blow 10 ft. lbs.
Blows to break = 79
0
4
8
12
16
20
24
28
Percent elongation in one inch


Fig. 24

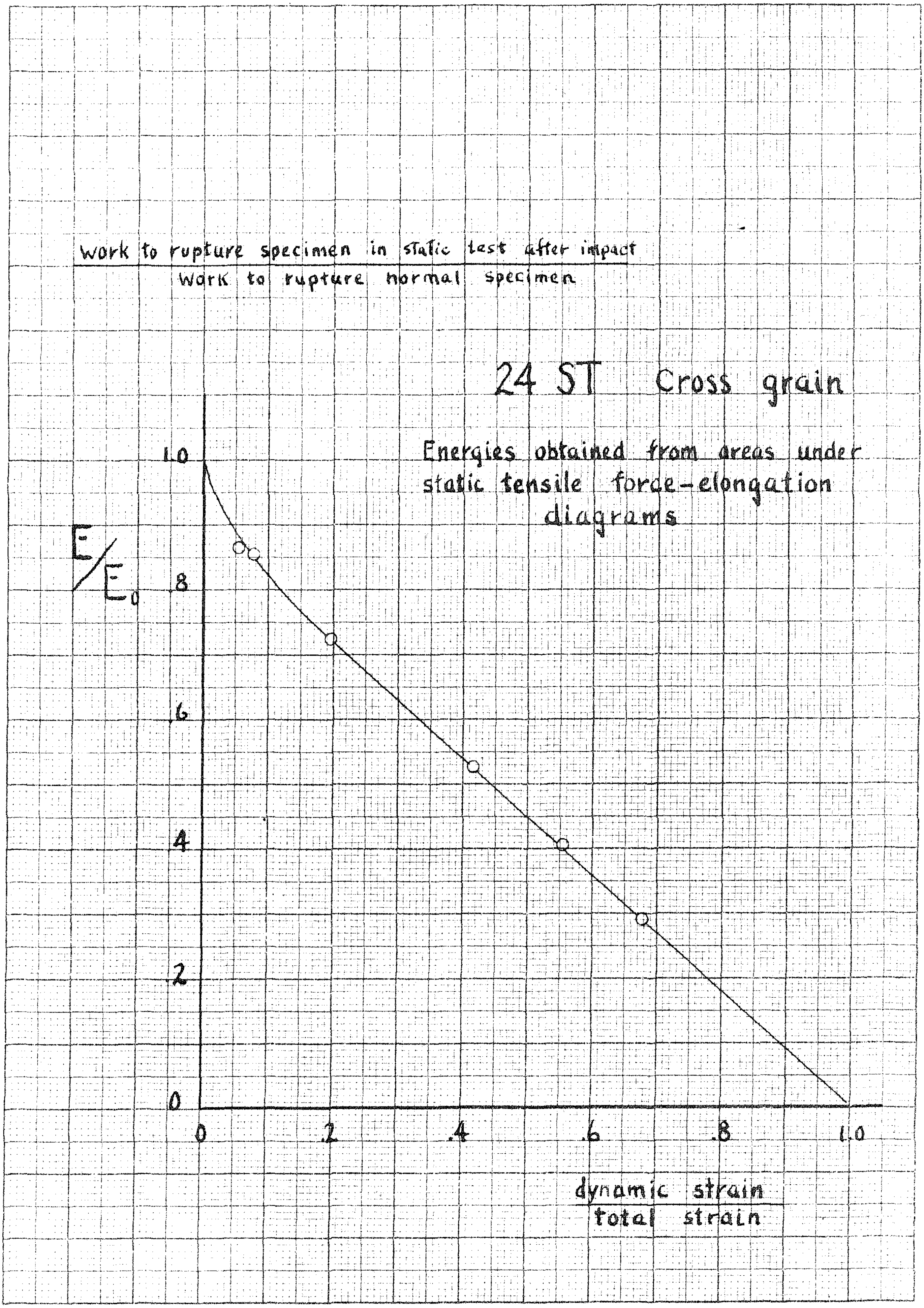

Work to rupture specimen in static test after impact
Work to rupture normal specimen
24 ST Cross grain
Energies obtained from areas under static tensile force-elongation diagrams
E/E0
1.0
.8
.6
.4
.2
0
0
.2
.4
.6
.8
1.0
dynamic strain
total strain

Fig. 25

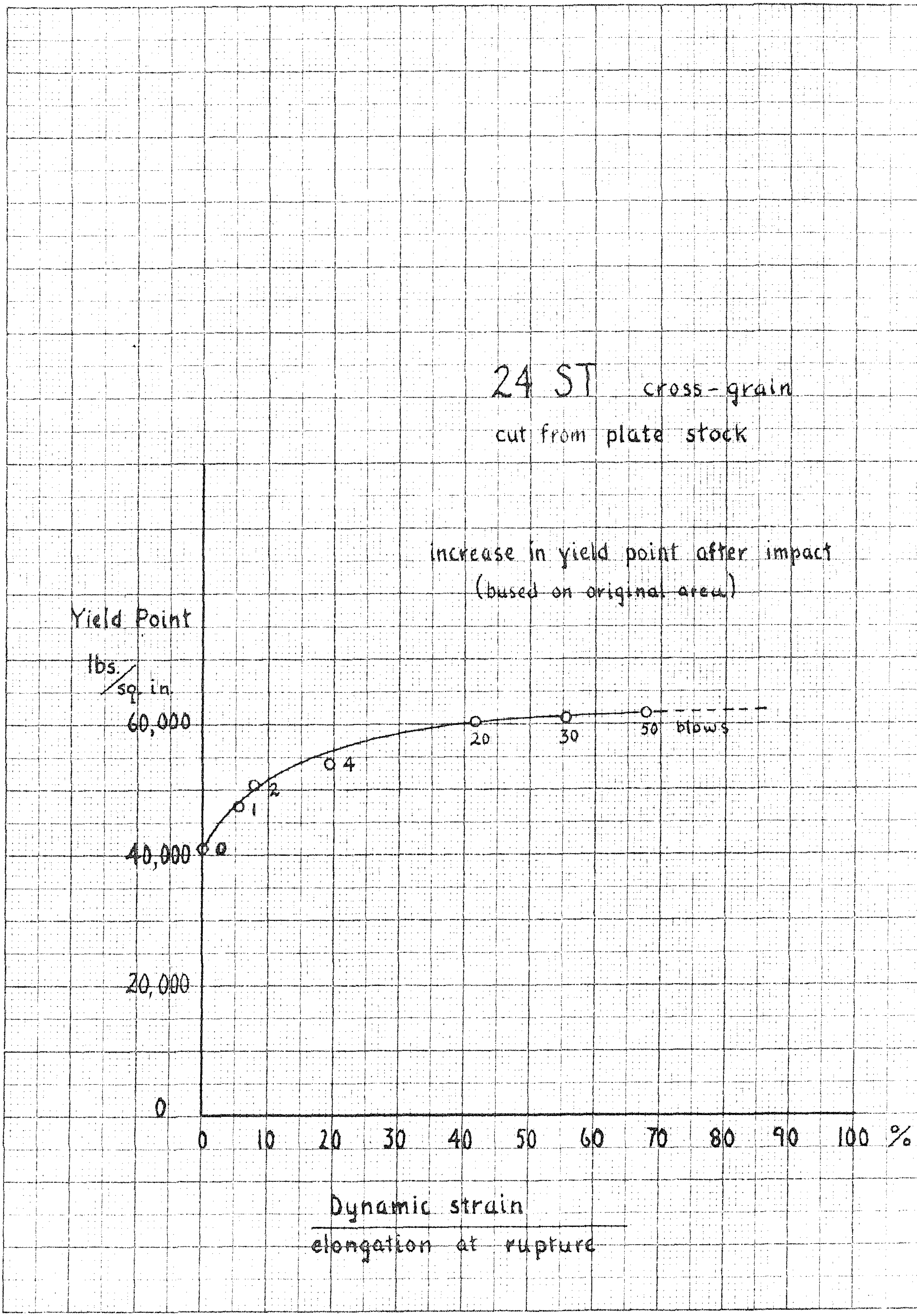

24 ST cross-grain
cut from plate stock
increase in yield point after impact
(based on original area)
Yield Point
lbs./sq. in.
60,000
40,000
20,000
0
0
1
2
4
20
30
50 blows
0
10
20
30
40
50
60
70
80
90
100 %
Dynamic strain
elongation at rupture

Fig. 26

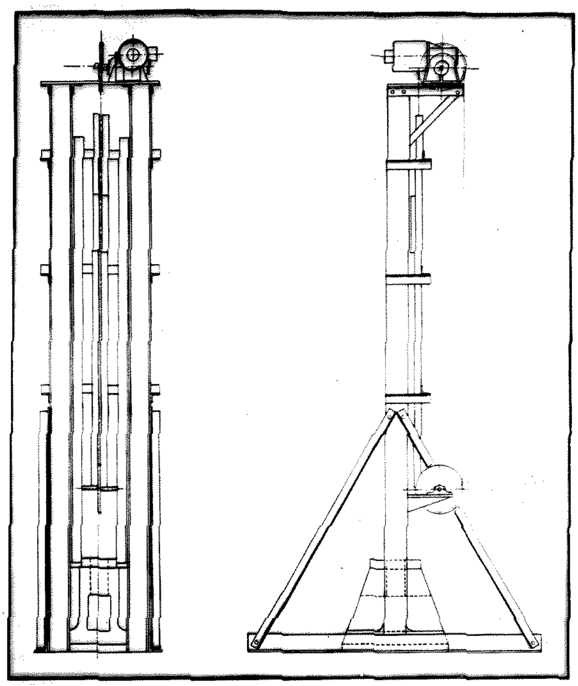


Fig. 27

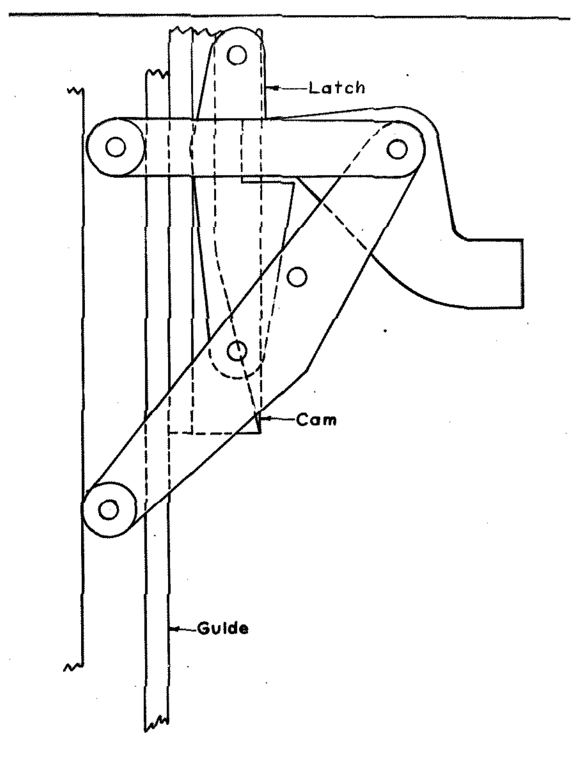



Fig. 28