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

Thesis

by

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In particular, they wish to thank Dr. Th. von Karman, Director of the Laboratory, for his cheerful cooperation and Dr. E. E. Sechler under whose direction the research was carried out.

SUMMARY

The Impact Endurance Limit is evaluated for several materials used in aircraft construction. The Impact Endurance Limit is defined as the energy per blow in tension impact below which the specimen will withstand an indefinitely large number of blows without fracture.

The effect of grain orientation on the Impact Endurance Limit is shown.

Evidence is presented that the Impact Endurance Limit may be a function of the ultimate tensile strength but not of the elongation or the yield point.

The effect of service stresses on the Impact Endurance Limit is discussed.

INTRODUCTION

During the course of its useful service life, any assembled structure, such as an airplane, is subjected to stresses varying greatly in their magnitude and nature. Of all the types of single and combined stresses that determine the duration of service life, fatigue is probably the most important single factor under routine service conditions.

With this in mind, this research was undertaken in order to broaden the scope of the work carried out by Beardsley and Coates (see Ref 1); to check their results; to extend the investigation to a very large number of repeated impacts; and to attempt to correlate the Impact Endurance Limit with the physical properties of the materials tested.

TENSION IMPACT TESTING

Single Impact

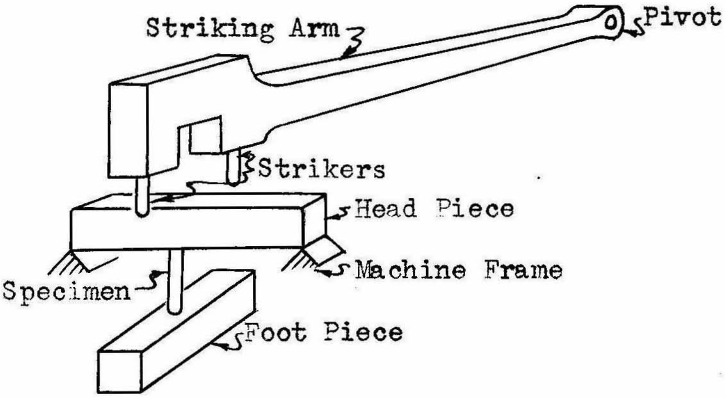
The work carried on in impact testing of metals has been, until recently, concerned primarily with the determination of the dynamic energy necessary to rupture a specimen in tension or cantilever bending with one blow. Various machines and countless specimen shapes and sizes have been used (see Ref 2). The Proceedings of the Annual Meeting of the American Society for Testing Materials (see Ref 3) contains the more important results of the above tests, and H. C. Mann (see Ref 4) has made several interesting reports upon this type of testing.

The wide divergence of results obtained by using different types of specimens indicates that a standardized specimen should be used. The failure of investigators to show consistent correlation between physical, static, and dynamic characteristics indicates that tension impact results must be compared with each other as one of the bases for selection of a material of construction. The fact that metals in practical applications have sudden dynamic loads applied repeatedly indicates the desirability of having relative data available in order to select the most efficient material.

Repeated Impact

In 1938, repeated impact testing was started at the California Institute of Technology (see Ref 1). A standard Tinius-Olsen Izod impact machine was modified to hold the specimens so that the pendulum could impart its energy to the specimen in tension. Consistent results were obtained with this machine; the only difficulties encountered were the inaccuracies of the machine at energies lower than about six foot-pounds per blow and the fact that the resetting and release of the pendulum had to be done by hand.

In order to increase the rapidity of testing and to obtain low energy values per blow a Matsumura Type, Impact Endurance Testing Machine, loaned by the Hughes Tool Company, Houston, Texas, was modified (see Fig 1) by the authors so that it would impart a tension impact to the specimen as indicated schematically below:



Adjustable strikers were secured to the striking arm so that they struck the foot piece on both sides of the specimen simultaneously. The specimen was secured by threads at the top to a head piece and held the foot piece at the other end. Thus, the blow was imparted to the foot piece, was carried through the specimen to the head piece, and thence to the frame of the machine. The machine was further modified so that a pad would catch the striking arm and hold it off the specimen between blows. This was necessary because the elasticity of the metal being tested caused the striking head to rebound and impart several minor blows for each major impact.

The machine used imparted about 70 blows per minute to the specimen. At this rate, a satisfactory curve of energy per blow against the number of blows to fracture, up to 500 blows, could be obtained with approximately ten specimens in about three hours. A counter facilitated recording the blows, and an arc marked off in tenths of degrees in conjunction with a pointer on the striking head gave a direct indication of energy per blow. A device to trip a clutch on the driving motor when the specimen breaks eliminated the necessity for constant attention.

Another type of repeated tension impact testing machine, designed by Beardsley and Coates (see Ref 1), was built and assembled at the California Institute of Technology (see Fig 2). This machine is ready for operation except for a few minor adjustments and calibration. 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 being screwed into the base of the carriage, and on to the lower end of the specimen is screwed a block of any desired mass. When the carriage is released it drops, striking the anvil; however, the specimen and its attached mass pass into the vertical opening in the anvil. 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. By controlling the mass of the attached blocks and the height of drop, the striking velocity and striking energy can be made independent variables.

Specimens

In (Ref 1) it was found that there was no correlation between the energy absorbed per unit volume and the size of the specimen; therefore, it was arbitrarily decided to select a constant gage length of one inch and a diameter of 0.375 inch. The threaded portion was made the same at both ends. It was soon found that the original fillet radius was too small and that it had to be increased, as all of the specimens of magnesium alloys were breaking at the base of the fillet. The specimen finally chosen is shown in Fig 3. Increasing the fillet did not entirely eliminate the troubles with the Dowmetals, as machining marks tended to become surface cracks after impact. Experiments were made with ground, and ground and polished specimens and the results indicated the advantage of removing all machining marks. A light polishing operation after machining was found to be satisfactory. The finishing machine cut was found to be sufficient for the duralumin specimens.

Impact Velocity

The effect of velocity on the energy value obtained from the impact testing in this research has been neglected (see Ref 4). The maximum velocity obtainable from the Matsumura machine is of the order of ten feet per second. This value is well below the transition velocity of light alloys where normal material behavior may be expected. However, an investigation of high velocity tension impact for materials of aircraft construction under conditions involving high dynamic loadings would be of value to the designer.

TESTING PROCEDURE AND MATERIALS

Specimens of the various materials were fractured by repeated tension impact. A series of fractures were obtained for each type of material tested; each specimen being subjected to a constant striking energy per blow, E, until fracture resulted at a number of blows, N. The number of blows to break was plotted against the striking energy per blow or N vs E. A curve was faired through these points and, from this curve, values were selected and replotted as the number of blows divided by the striking energy per blow against the number of blows or N/E vs N (see Figs 6 to 16 inclusive). The inverse slope of this second curve, N/E vs N, is defined as the Impact Endurance Limit or E_L. A composite set of curves of N/E vs N was plotted for all the round stock materials tested to indicate a comparison of the respective slopes (see Fig 17). The computed values of the impact endurance limit, for the various materials, are also recorded in Table I.

The specimens were machined from round and rectangular bar stock except for the propeller blade specimens. The duralumin 17ST and 24ST stock was purchased in the open market in the form of 9/16" round and 3/4" x 3" rectangular rolled bars. The Dowmetals J-1HT, X-1HT, and Z-1HT were furnished by the Dow Chemical Company in the same dimensions as above. The propeller blade specimens of forged 25ST were machined from sections furnished by the Commanding Officer, Naval Air Station, San Diego, California. The sections of the propeller blades were from propellers of identical design and section. Propellers "A" and "B" had 738 and 129.7 hours in service respectively. Both blades were bent and damaged near the tip, resulting in their being scrapped, but the area immediately adjacent to the sections tested showed very little distortion.

GENERAL DISCUSSION

Table I shows the Impact Endurance Limit, E_L, for all the materials tested in comparison with the other physical characteristics of the materials. The results indicate a general correlation between the impact endurance limit and the ultimate tensile strength of various materials. The relative per cent elongations as determined by static test do not bear any apparent relation to the impact endurance limit. This is contrary to the generally accepted theory that brittle materials or materials with low elongation values are not adaptable to applications in which shock loadings are encountered.

A certain correlation was indicated between the types of fractures encountered and the ductility of the materials. All of the aluminum alloys evidenced a typical shear type of break while the Dowmetals indicated the typical tension type of fracture. All the Dowmetal specimens broke at the base of the fillet in the low energy per blow range. These specimens were extremely sensitive to stress concentration such as machining marks and "V" bottom type threads. Special care was taken to remove machinining marks by polishing the specimens without any apparent increase in breaking energy. It was found necessary in the Z-1HT specimens to cut a round bottomed thread instead of the standard 60° thread, as the latter broke between the lock nuts and the anvils at the lower striking energies. The round bottomed threads were continued for the J-1HT specimens.

The curves of E vs N for the Dowmetals are, in general, slightly different from those of the duralumins. The latter have an abrupt curvature and the general slope of the curve in the lower energy per blow range is almost parallel to the N axis. On the other hand, the Dowmetal curves are much less abrupt and curvature is present until a large number of blows have been imparted to the specimen. This may be explained by the fact that cold working is taking place and that the material is constantly being changed in character and properties. This theory would make the resultant curve the average of several curves each representing a different state of the metal encountered on the testing regime.

The above theory is strengthened by the behavior of the Dowmetal specimens when rupturing. In the high energy per blow range one or more of the specimens in each group evidenced a shear type of fracture, while those specimens in the low energy per blow range were all of the tension type of fracture at the base of the fillet (see Fig 4).

The grain structure of the 24ST specimens was in evidence on the surface of the ruptured specimens (see Fig 5). The 24ST round specimens indicated that the grains were stretched, especially, in the "necking down" region. In the 24ST rectangular bar with specimens cut with the grain, flow lines appeared the entire gage length of the specimen. These lines were very definite and could be seen after the first few blows. The 24ST rectangular bar specimens cut across the grain have a mottled appearance on the surface. This phenomenon is difficult to explain since it is impossible to have such large grain size.

None of the above effects could be observed on the Dowmetal specimens. Circumferential surface cracks were frequent, but these could be traced to machining marks. On the cross grain specimens, the direction of the grain was clearly visible after rupture.

In attempting to correlate the Impact Endurance Limit, E_L, with the physical properties several methods were tried and the results tabulated in Table I. The E_L value for each material was divided by its density in pounds per cubic inch and these values were recorded in Table I. The result of a comparison of these values indicates that when the weight of the material is considered Dowmetal Z-1HT is superior in impact to 24ST.

Further, in Table I, a ratio of ultimate tensile strength multiplied by the impact endurance limit of the material to the ultimate tensile strength multiplied by the impact endurance limit of 24ST, the latter being used as a standard, is recorded as K. This comparison indicates that all of the materials are inferior to 24ST when the density of the material is not considered. When the value of K is further weighted by the density, δ , a different result is obtained. In this case, the value K_δ for Dowmetal Z-1HT is superior by four per cent.

Thus there are several factors to influence the designer in his selection of a material to withstand tension impact. These factors are, namely, the impact endurance limit, the ultimate tensile strength, and the density of the material.

In making the above comparisons, no consideration is given to the fact that Z-1HT is very susceptible to stress concentrations. Also corrosion difficulties and prevention of corrosion have not been considered.

The value of E_L was plotted against the corresponding ultimate tensile strength (see Fig 18). While this plot does not indicate a close correlation between the two properties, it does show a tendency for E_L to increase with the ultimate tensile strength.

The comparison of two different propeller blades to determine the effect of service stresses on the impact endurance limit was suggested from N.A.C.A. Technical Report No. 659 (see Ref 5). The results of the respective values for E_L for the two blade sections were not inversely proportional to the operating time as might be expected (see Fig 19), but were directly proportional to their ultimate tensile strengths as actually determined from a stress strain analysis. This variation may be due to manufacturing technique or to the amount of damage suffered by the blades; however, the service history, including the amount of damage, of each of the blades is identical, except for total service operating hours. All of the specimens had a shear type fracture of elliptical cross section, probably caused by the unequal directional strength induced by forging.

A more extensive investigation to determine the effect of service stresses on the impact endurance limit would be an important factor in the determination of the useful service life of airplane structures.

REFERENCES

(1) Beardsley, G. F., and Coates, L. D.: Repeated Tension Impact Loadings. Research paper for Degree of Master of Science in Aeronautical Engineering at California Institute of Technology, 1939.

(2) Mann, H. C.: A Fundamental Study of the Design of Impact Test Specimens: Proceedings, A.S.T.M., Vol. 37, Part II, 1937.

(3) Symposium on Impact Testing: Proceedings, A.S.T.M., Vol. 38, Part II, 1938.

(4) Mann, H. C.: High Velocity Tension Impact Tests: Proceedings, A.S.T.M., Vol. 36, Part II, 1936.

(5) Kies, J. A., and Quick, G. W.: Effect of Service Stresses on Impact Resistance: N.A.C.A. Technical Report No. 659, 1939.

TABLE I

	Material	Specimens	E_L	E_L/δ	K	K_δ	Quoted Values Yield	Quoted Values Ult.	Quoted Values Elong.	δ
DOWMETAL	X-1HT	Round Stock	5.22	80.3	0.330	0.508	30,000	41,000	10%	0.065
	J-1HT	Round Stock	5.97	92.0	0.396	0.609	30,000	43,000	12%	0.065
	J-1HT	Rect. Stock with grain	5.10	78.5	0.338	0.520	30,000	43,000	12%	0.065
	J-1HT	Rect. Stock cross grain	5.48	84.2	0.364	0.560	30,000	43,000	12%	0.065
	Z-1HT	Round Stock	7.55	116.0	0.675	1.040	42,000	58,000	8%	0.065
DURALUMIN	17ST	Round Stock	7.75	77.5	0.670	0.670	30,000	55,000	18%	0.100
	24ST	Round Stock	10.47	104.7	1.000	1.000	40,000	62,000	14%	0.100
	24ST	Rect. Stock with grain	10.00	100.0	0.955	0.955	40,000	62,000	16%	0.100
	24ST	Rect. Stock cross grain	9.90	99.0	0.945	0.945	40,000	62,000	16%	0.100
	25ST	Prop. Blade "A"	6.72	66.5	0.606	0.600	38,300*	58,500*	---	0.101
	25ST	Prop. Blade "B"	5.84	57.8	0.527	0.521	30,200*	49,500*	---	0.101

E_L = Impact Endurance Limit (foot pounds)

δ = Density (pounds per cubic inch)

$$K = \frac{(\text{U.T.S. x } E_L)_{\text{Mat.}}}{(\text{U.T.S. x } E_L)_{24ST}}$$

$$K_\delta = K \frac{\delta_{\ 24ST}}{\delta_{\ \text{Mat.}}}$$

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* Actual Test Values.

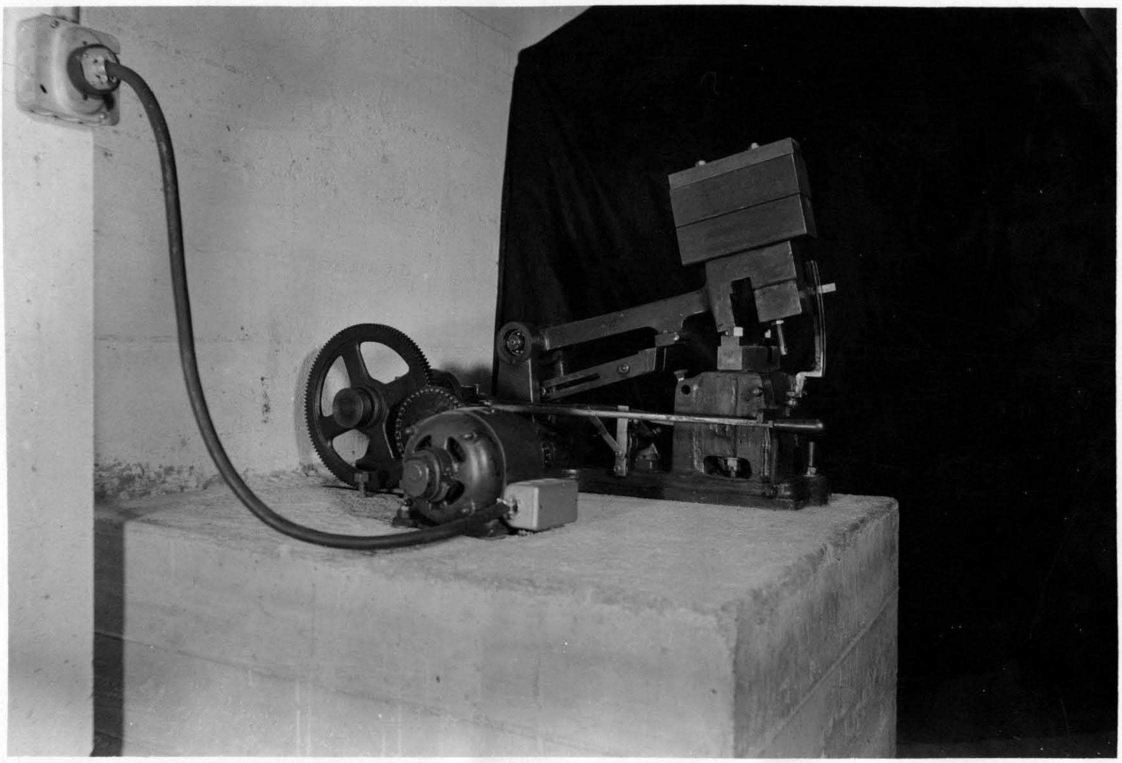
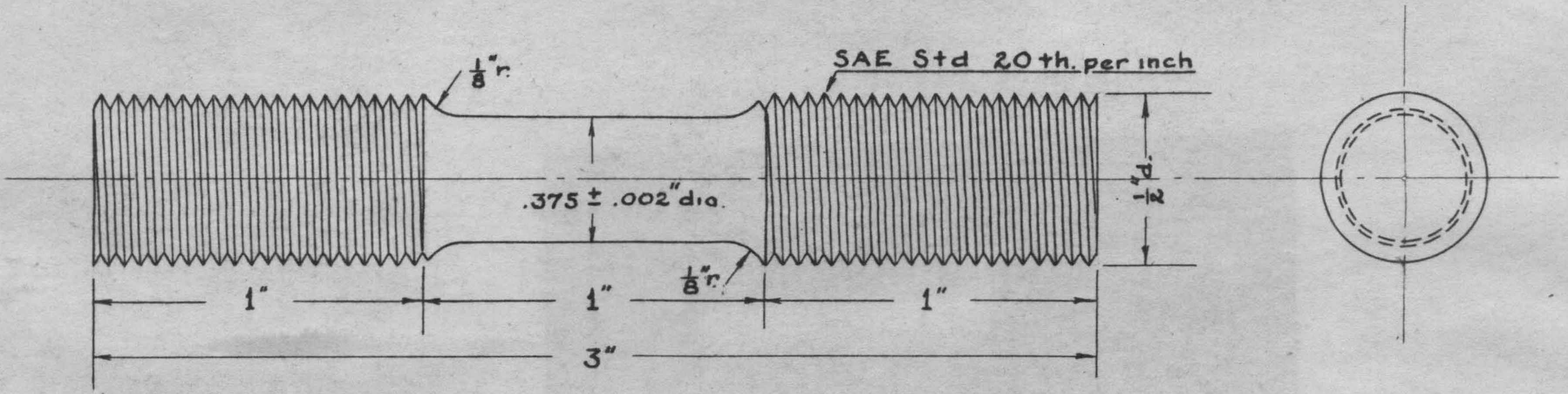


Fig. 1

Fig. 2



SCALE
2 inch = 1 inch

			Gantner		Sechler		TOLERANCES ± .010 OR $\frac{1}{64}$ UNLESS OTHERWISE NOTED
MATERIAL	FINISH	HEAT TREAT	DRAFTSMAN	CHECKED	APPROVED	ENGINEER	
GUGGENHEIM AERONAUTICAL LABORATORY CALIFORNIA INSTITUTE OF TECHNOLOGY			TENSION IMPACT SPECIMAN				1-244-21
			NAME				DRAWING NO.

Round Stock

Z1-HT SPECIMEN

Rectangular Stock
With Grain

Round Stock

Rectangular Stock
Cross Grain

24ST SPECIMENS

Fig. 5

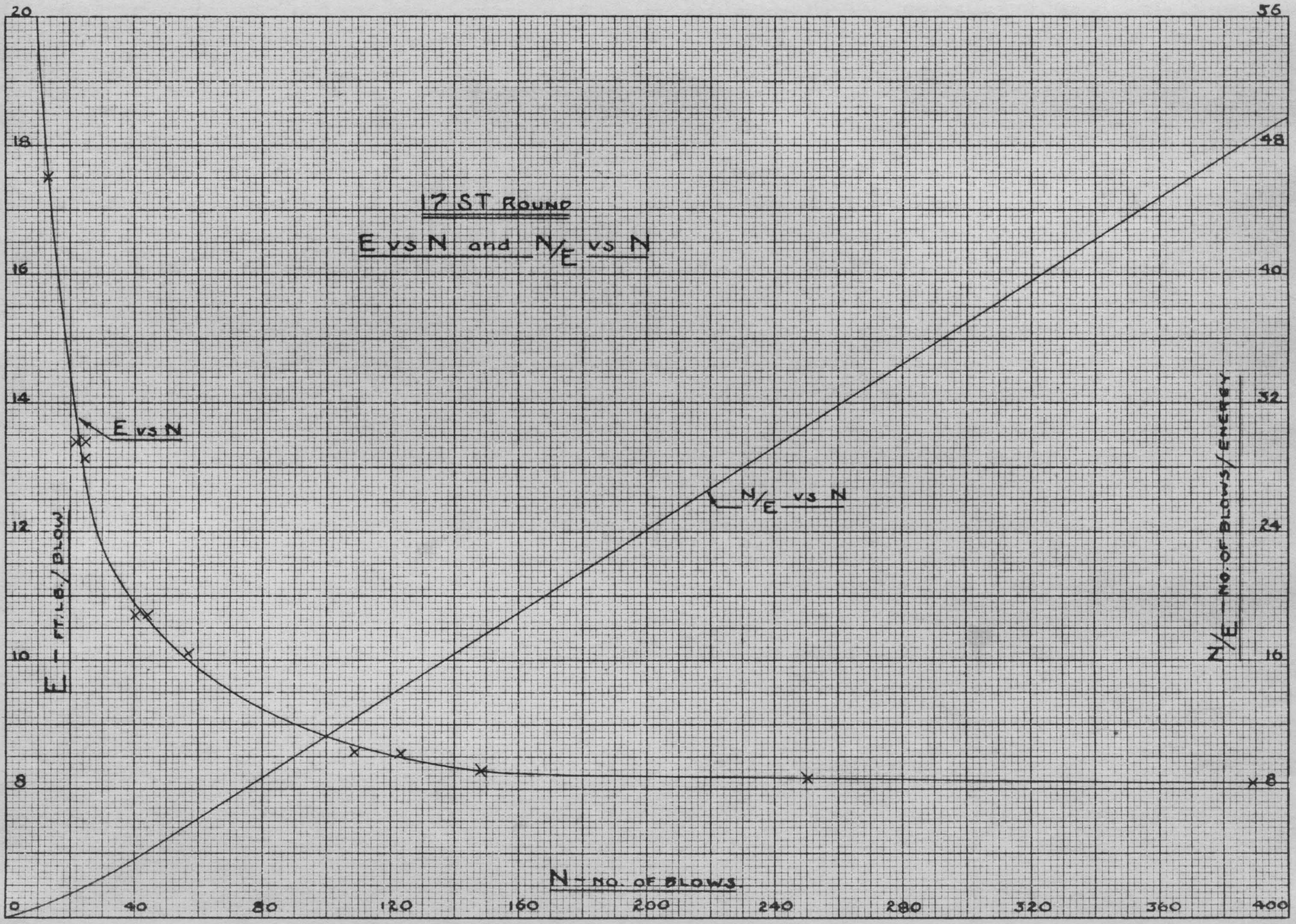

17 ST ROUND
E vs N and N/E vs N
E vs N
N/E vs N
E – FT. LB. / BLOW
N/E – NO. OF BLOWS / ENERGY
N – NO. OF BLOWS
20
18
16
14
12
10
8
56
48
40
32
24
16
8
0
40
80
120
160
200
240
280
320
360
400

Fig. 6

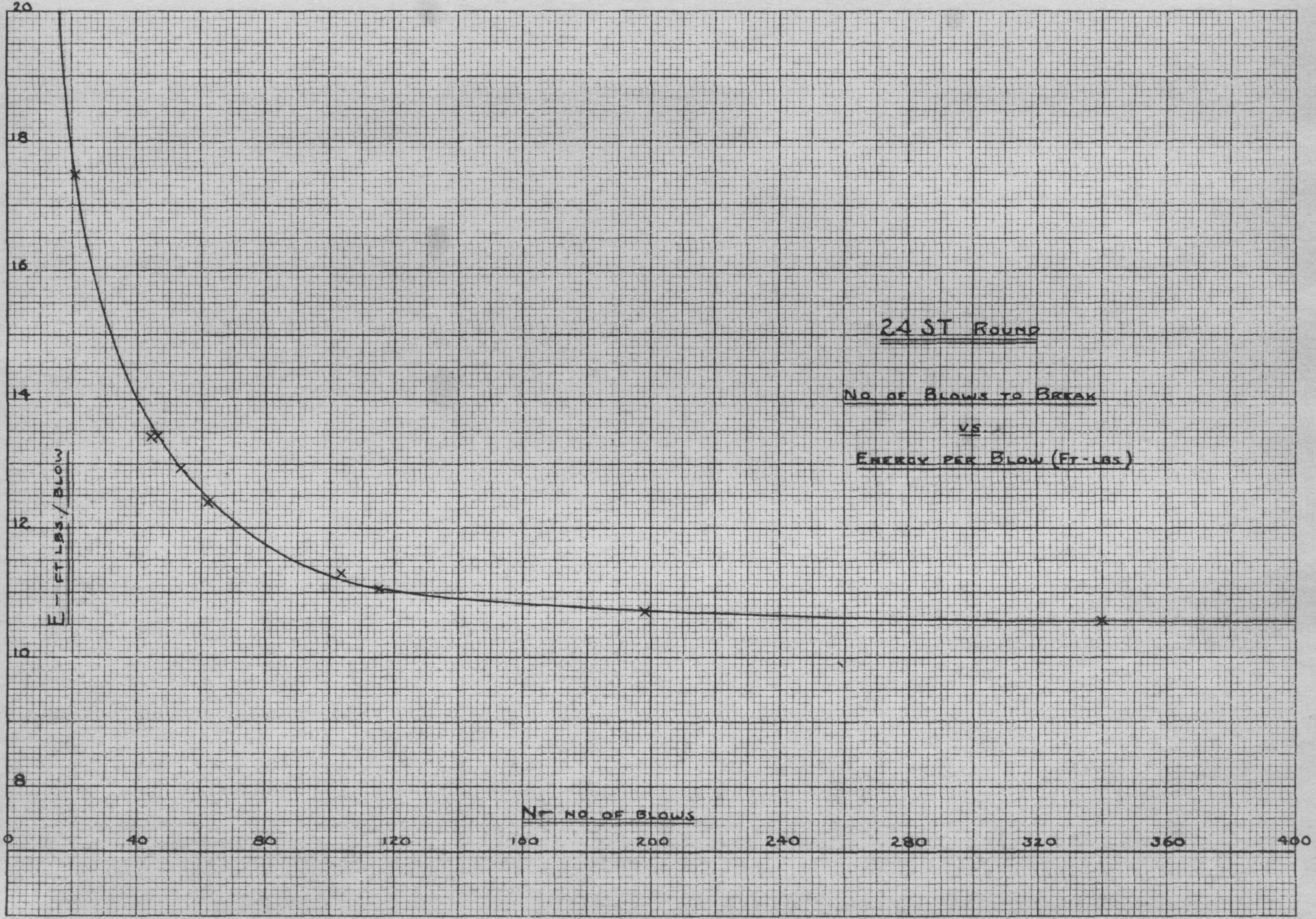

24 ST Round
No. of Blows to Break
vs.
Energy per Blow (Ft-lbs)
E - ft lbs./blow
20
18
16
14
12
10
8
N - no. of blows
0
40
80
120
160
200
240
280
320
360
400

Fig. 7

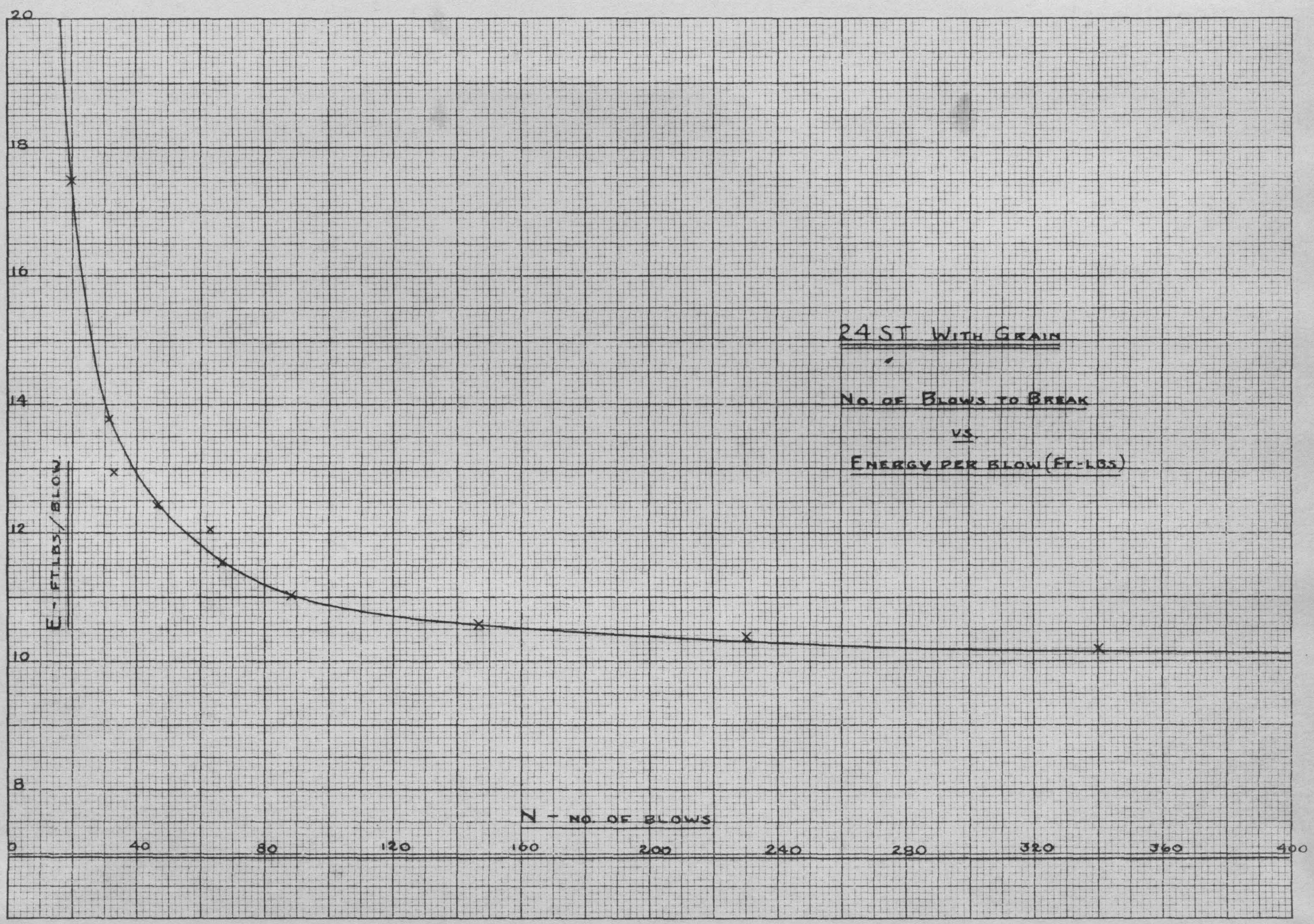

24 ST With Grain
No. of Blows to Break
vs.
Energy per Blow (Ft-Lbs)
E - Ft.Lbs/Blow
N - No. of Blows
20
18
16
14
12
10
8
0
40
80
120
160
200
240
280
320
360
400

Fig. 8

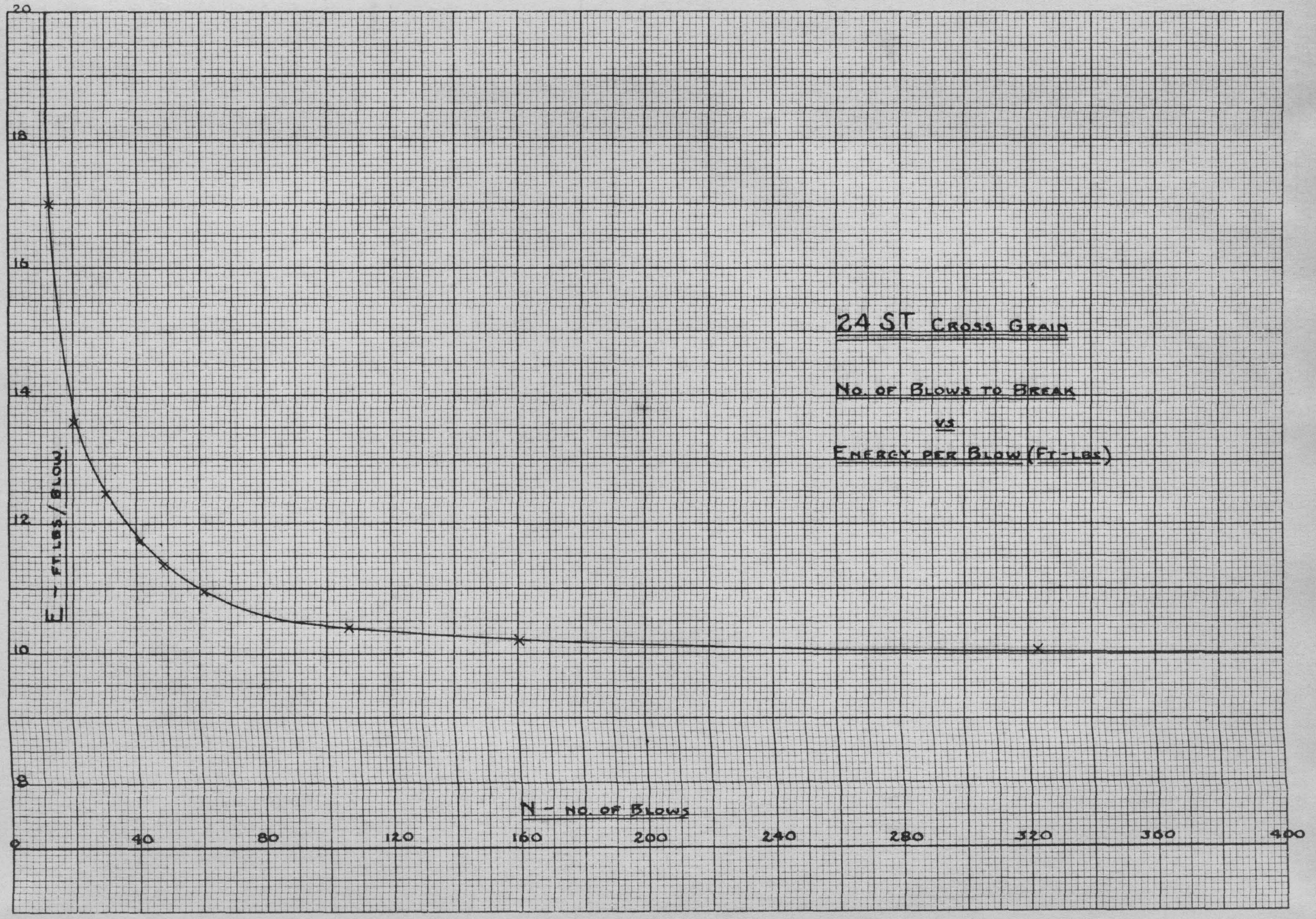

24 ST Cross Grain
No. of Blows to Break
vs
Energy per Blow (Ft-lbs)
E - ft. lbs/blow
N - no. of Blows
20
18
16
14
12
10
8
0
40
80
120
160
200
240
280
320
360
400

Fig. 9

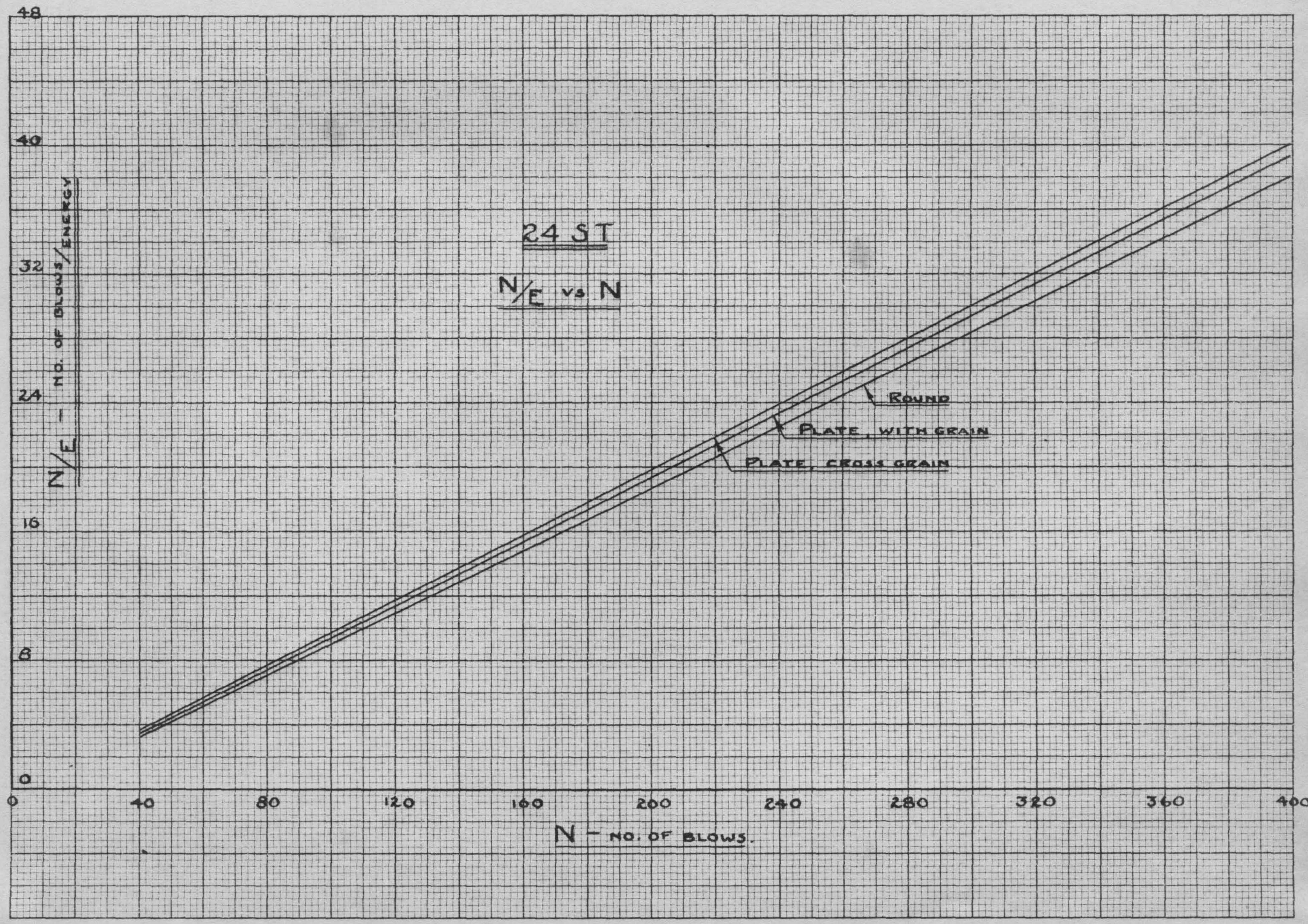

24 ST
N/E vs N
N/E — NO. OF BLOWS/ENERGY
N — NO. OF BLOWS.
ROUND
PLATE, WITH GRAIN
PLATE, CROSS GRAIN
0
8
16
24
32
40
48
0
40
80
120
160
200
240
280
320
360
400

Fig. 10

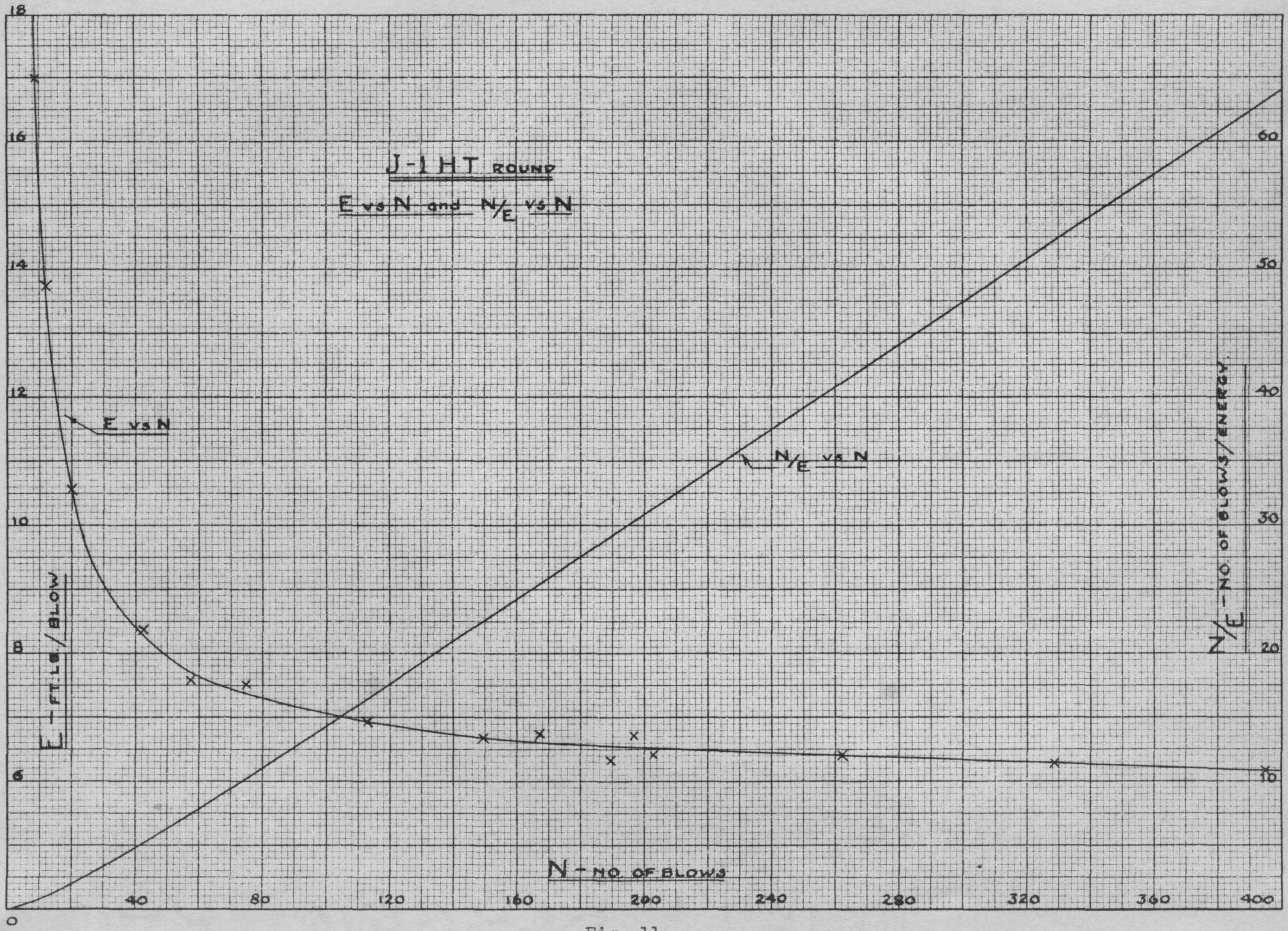

J-1 HT ROUND
E vs N and N/E vs N
E vs N
N/E vs N
E - FT.LB./BLOW
N/E - NO. OF BLOWS/ENERGY
N - NO. OF BLOWS
18
16
14
12
10
8
6
60
50
40
30
20
10
0
40
80
120
160
200
240
280
320
360
400

Fig. 11

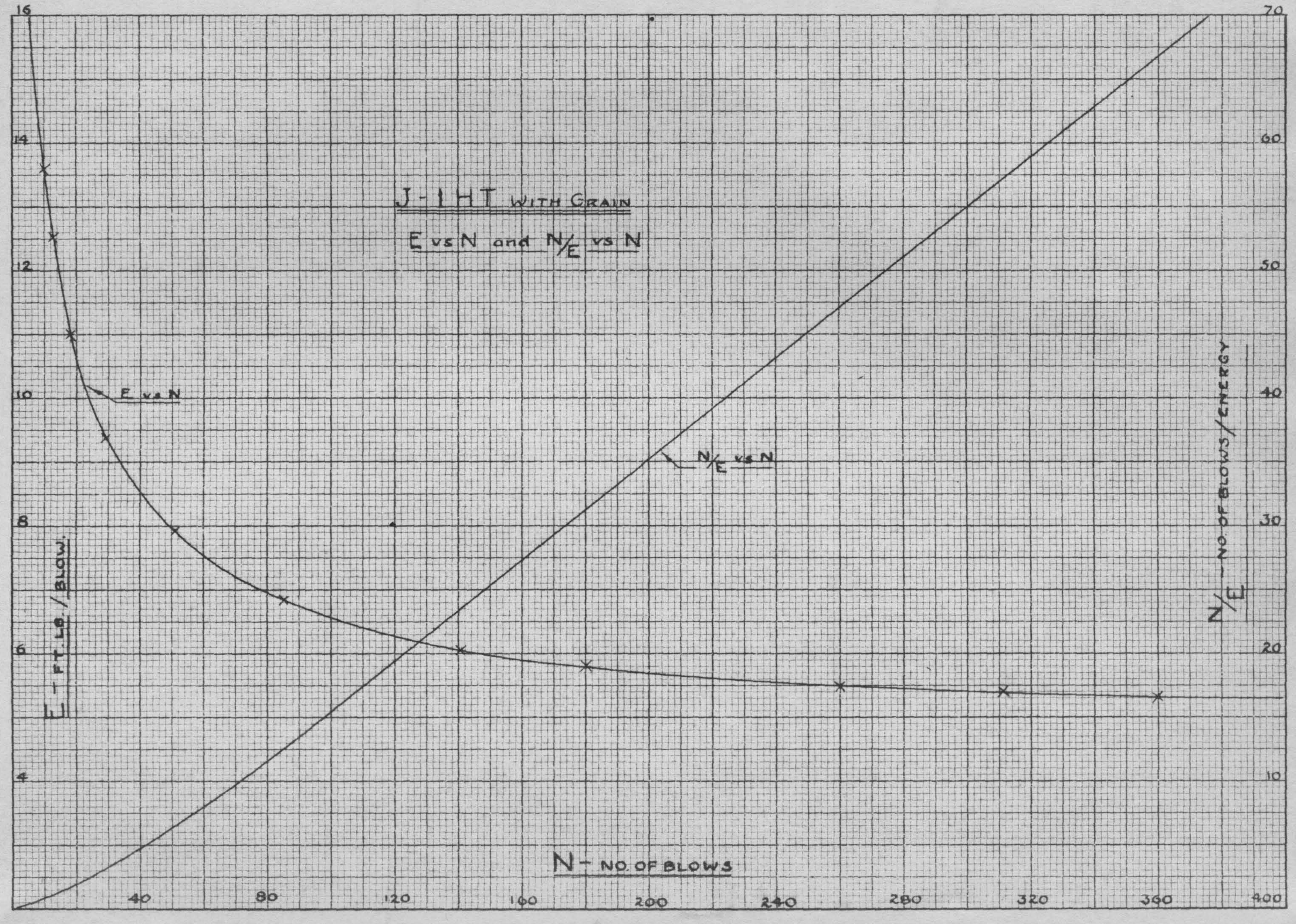

J-1HT WITH GRAIN
E vs N and N/E vs N
E vs N
N/E vs N
E – FT. LB. / BLOW.
N/E – NO. OF BLOWS / ENERGY
N – NO. OF BLOWS
16
14
12
10
8
6
4
70
60
50
40
30
20
10
40
80
120
160
200
240
280
320
360
400

Fig. 12

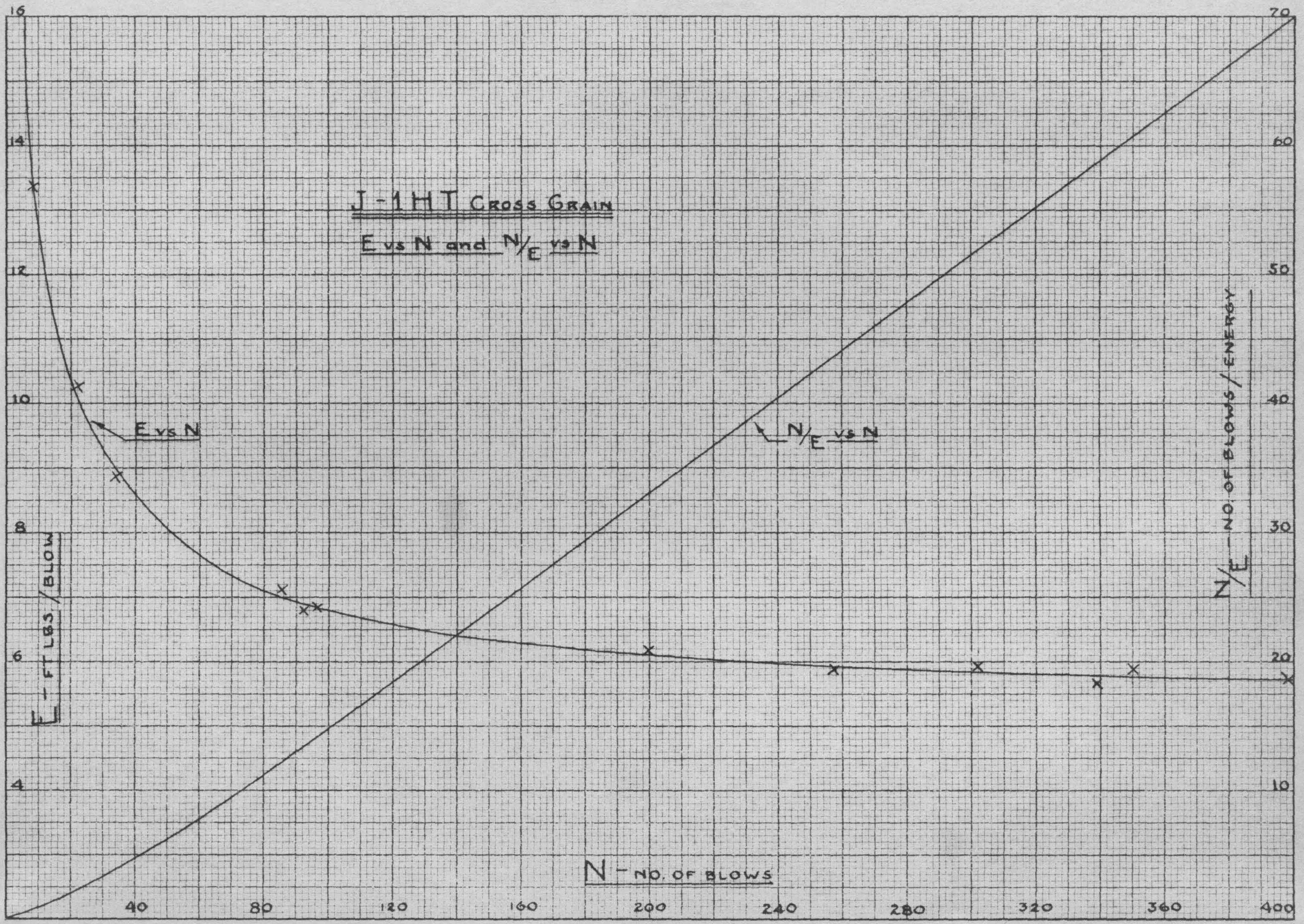

J-1HT Cross Grain
E vs N and N/E vs N
E vs N
N/E vs N
E - FT LBS / BLOW
N/E - NO. OF BLOWS / ENERGY
N - NO. OF BLOWS
16
14
12
10
8
6
4
70
60
50
40
30
20
10
40
80
120
160
200
240
280
320
360
400

Fig. 13

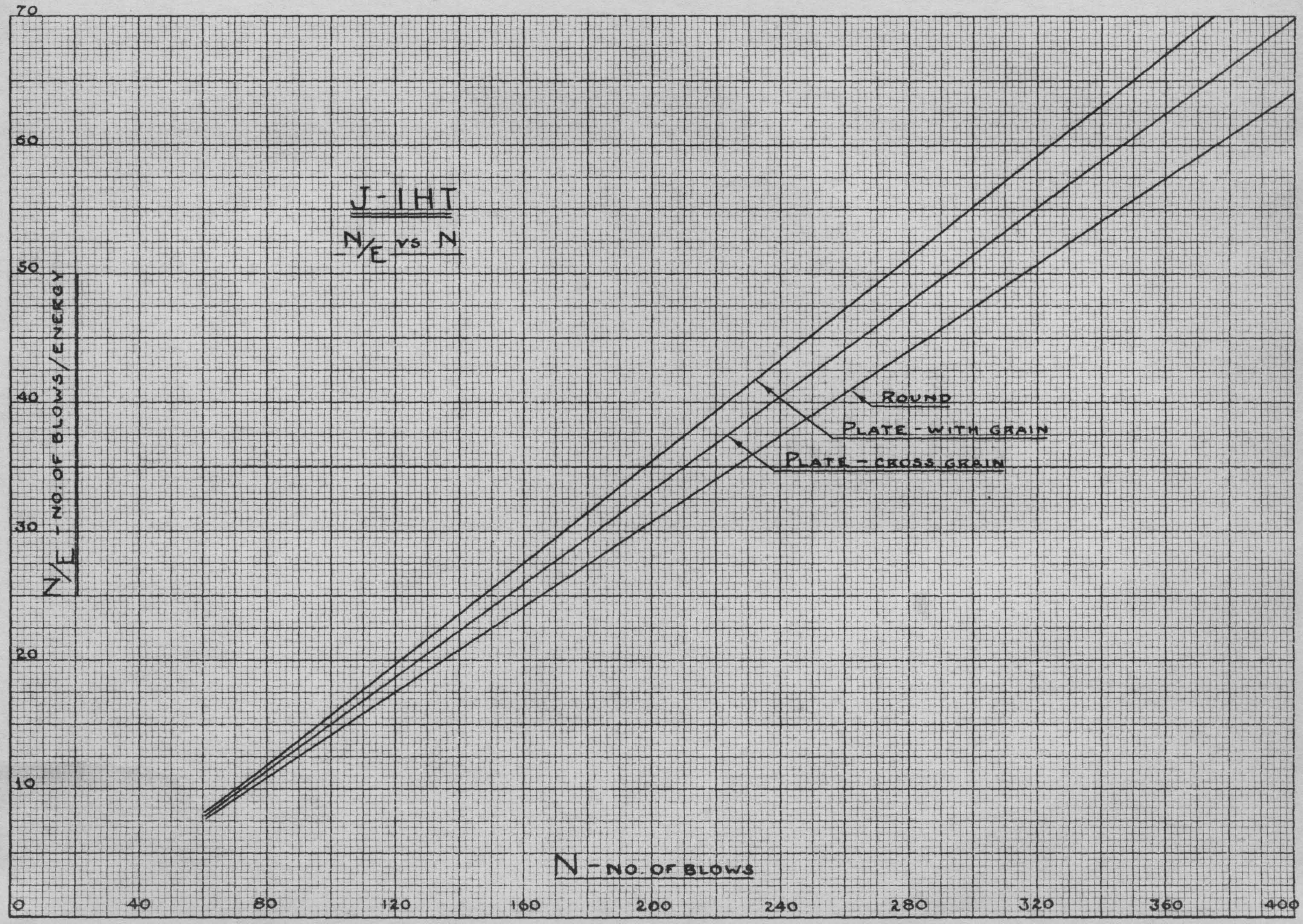

J-1HT
N/E vs N
N/E - NO. OF BLOWS/ENERGY
N - NO. OF BLOWS
ROUND
PLATE - WITH GRAIN
PLATE - CROSS GRAIN
70
60
50
40
30
20
10
0
40
80
120
160
200
240
280
320
360
400

Fig. 14

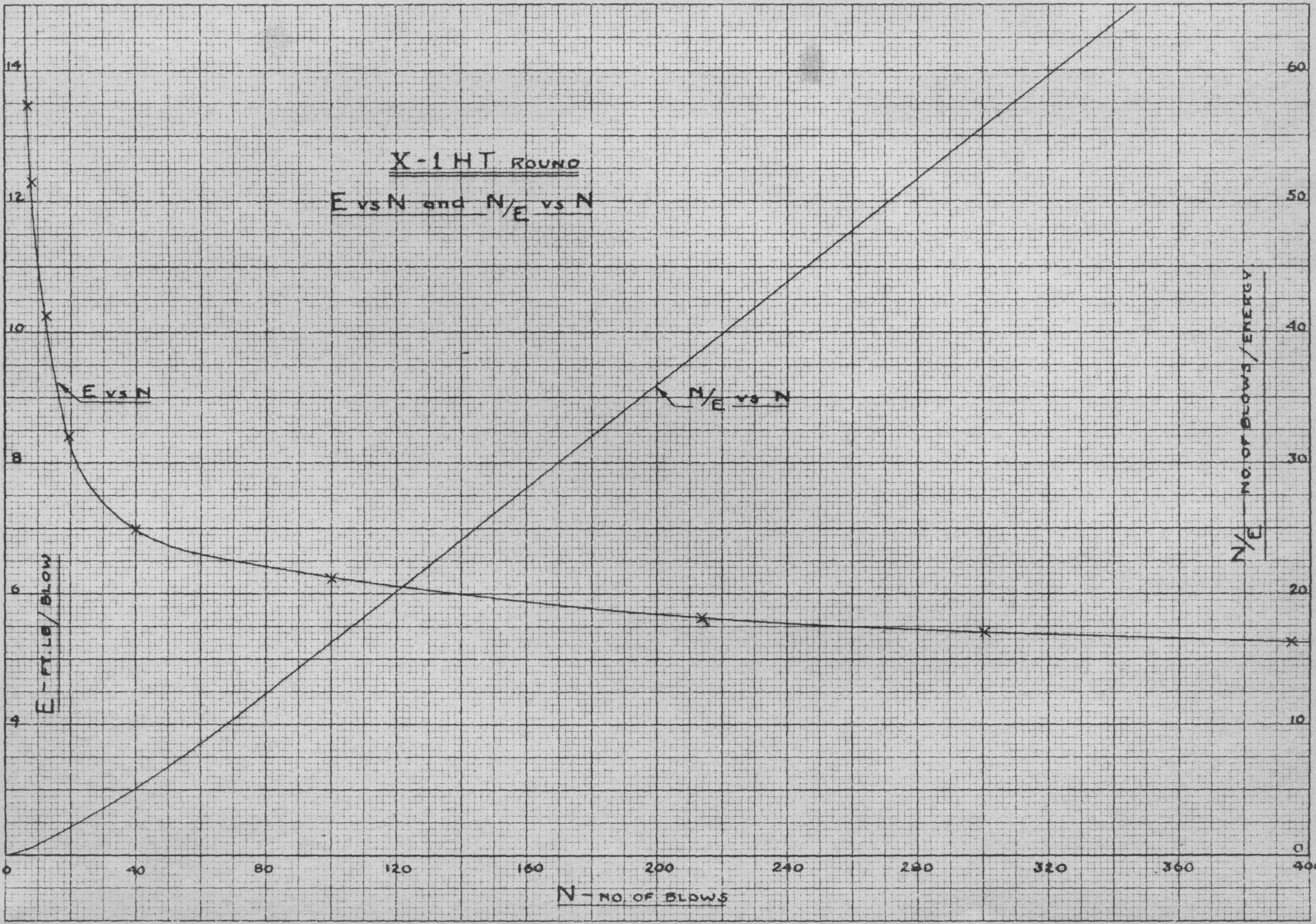

X-1 HT ROUND
E vs N and N/E vs N
E vs N
N/E vs N
E - FT.LB / BLOW
N/E - NO. OF BLOWS / ENERGY
N - NO. OF BLOWS
0
40
80
120
160
200
240
280
320
360
400
4
6
8
10
12
14
0
10
20
30
40
50
60

Fig. 15

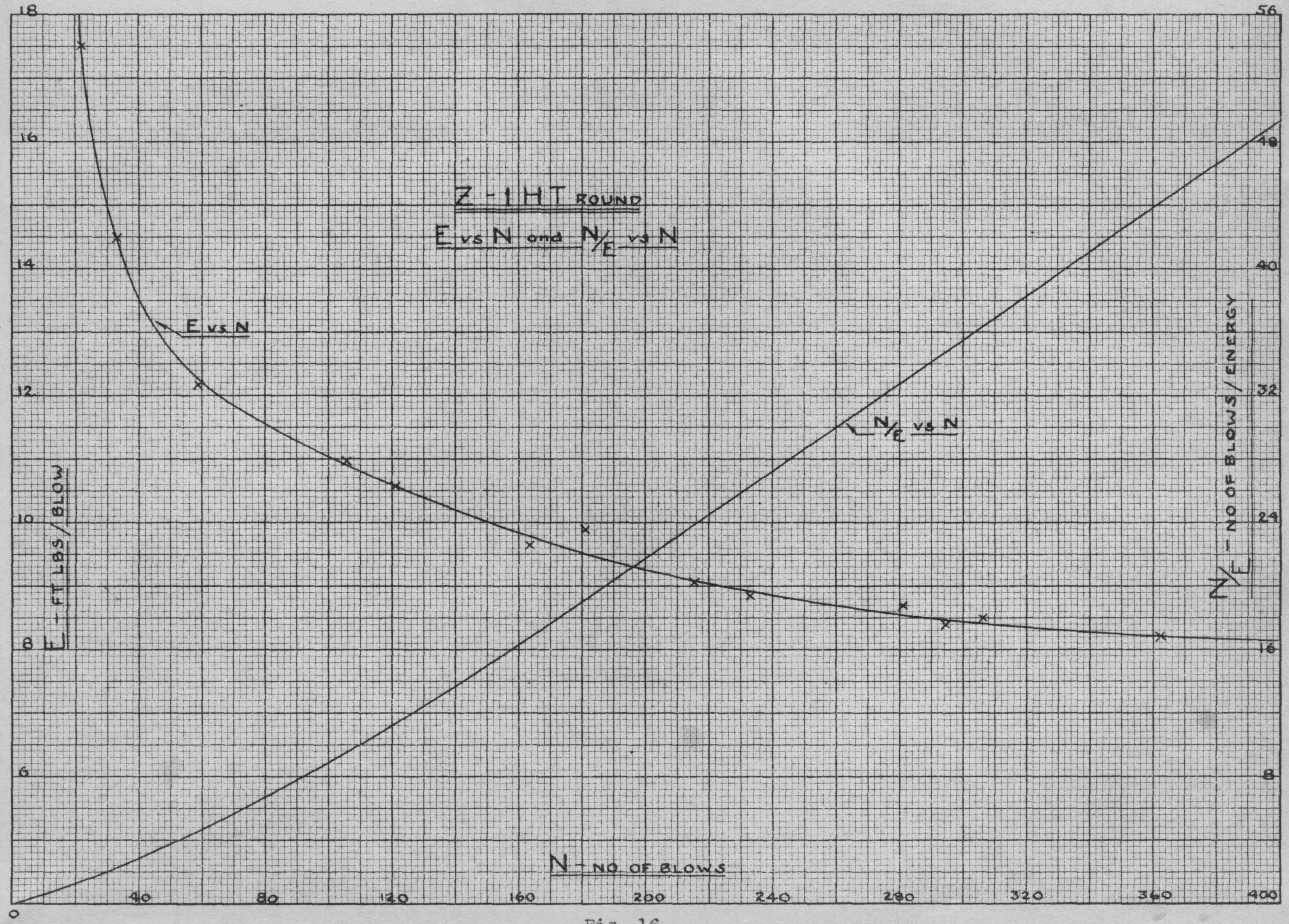

Z - 1 H T ROUND
E vs N and N/E vs N
E vs N
N/E vs N
E - FT LBS / BLOW
N/E - NO OF BLOWS / ENERGY
N - NO OF BLOWS
18
16
14
12
10
8
6
56
48
40
32
24
16
8
0
40
80
120
160
200
240
280
320
360
400

Fig. 16

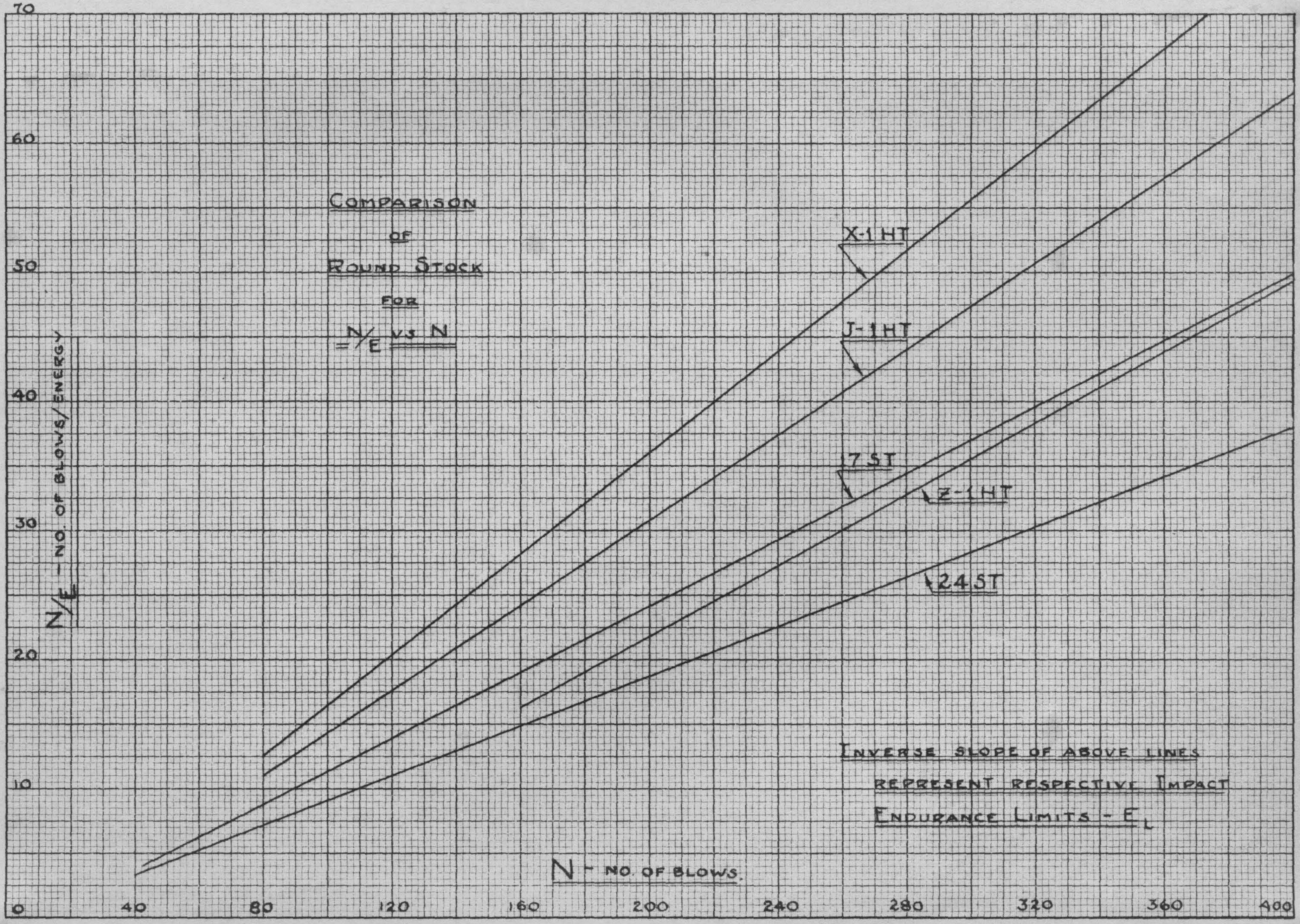

COMPARISON
OF
ROUND STOCK
FOR
N/E VS N
X-1 HT
J-1 HT
17 ST
Z-1 HT
24 ST
INVERSE SLOPE OF ABOVE LINES
REPRESENT RESPECTIVE IMPACT
ENDURANCE LIMITS - E_L
N/E - NO. OF BLOWS/ENERGY
N - NO. OF BLOWS.
0
10
20
30
40
50
60
70
40
80
120
160
200
240
280
320
360
400

Fig. 17

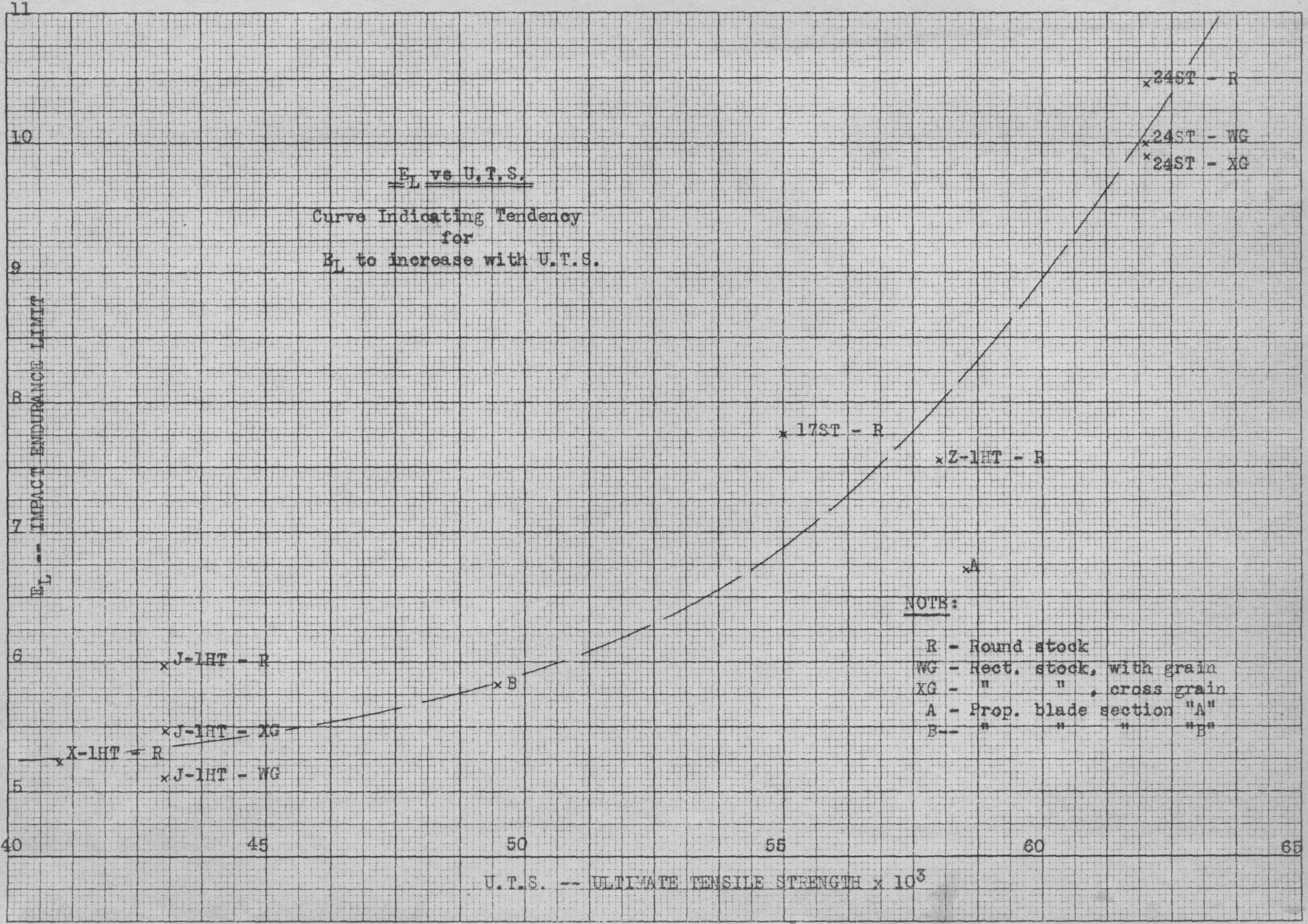

E_L vs U.T.S.
Curve Indicating Tendency
for
E_L to increase with U.T.S.
24ST - R
24ST - WG
24ST - XG
17ST - R
Z-1HT - R
A
B
J-1HT - R
J-1HT - XG
X-1HT - R
J-1HT - WG
NOTE:
R - Round stock
WG - Rect. stock, with grain
XG - " " , cross grain
A - Prop. blade section "A"
B-- " " " "B"
E_L -- IMPACT ENDURANCE LIMIT
11
10
9
8
7
6
5
40
45
50
55
60
65
U.T.S. -- ULTIMATE TENSILE STRENGTH x 10^3

Fig. 18

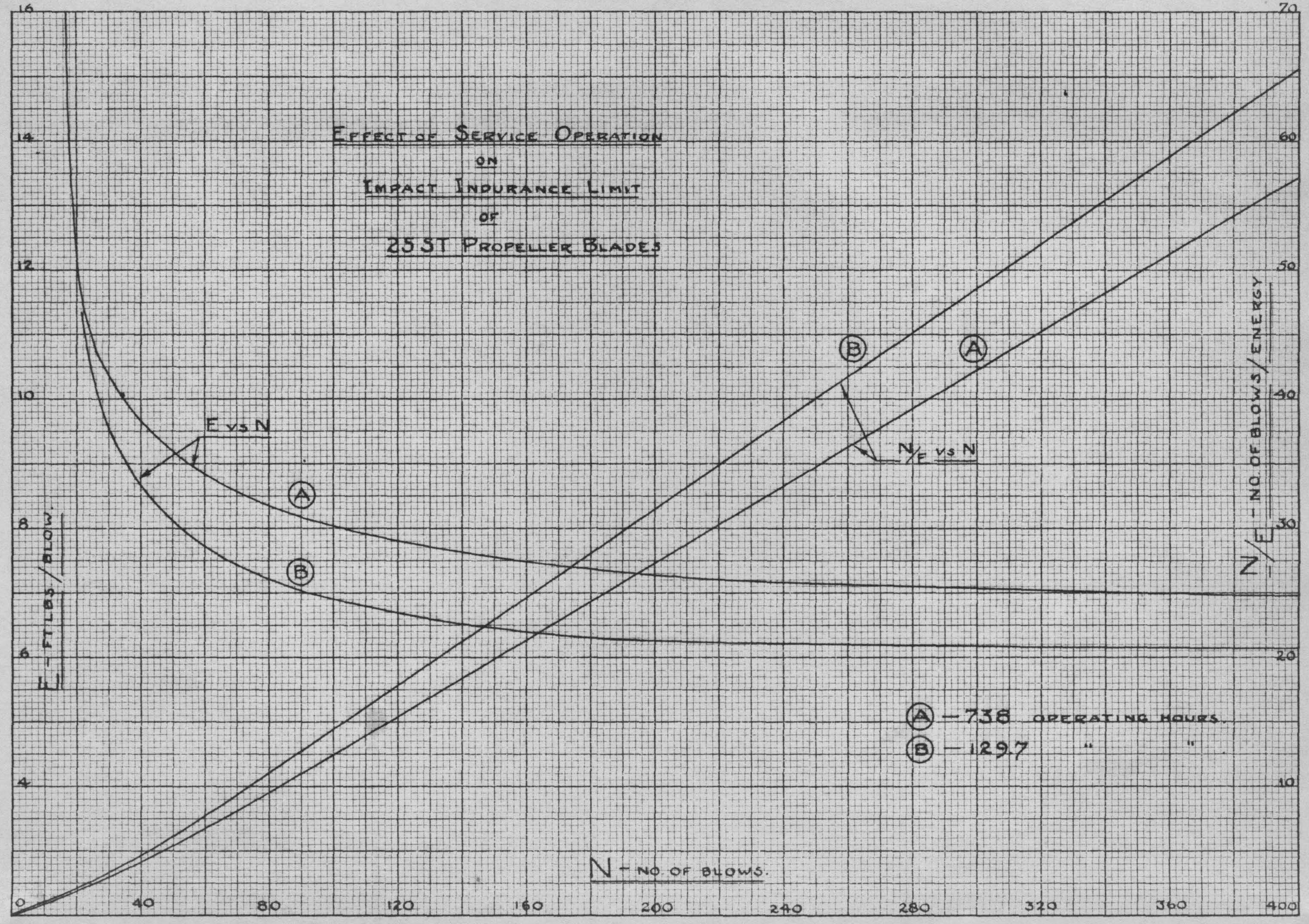

Effect of Service Operation
on
Impact Indurance Limit
of
25 ST Propeller Blades
E - FT LBS / BLOW.
N/E - NO. OF BLOWS / ENERGY
N - NO. OF BLOWS.
E vs N
N/E vs N
Ⓐ
Ⓑ
Ⓐ — 738 OPERATING HOURS.
Ⓑ — 129.7 " "
0
4
6
8
10
12
14
16
10
20
30
40
50
60
70
40
80
120
160
200
240
280
320
360
400

Fig. 19