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April 1944

THE MEASUREMENT OF FORCES WHICH RESIST PENETRATION OF STS ARMOR, MILD STEEL, AND 24 ST ALUMINUM

By Gilbert D. Kinzer, A.V.H. Masket and J. R. Streeter, Ens.W-V(S)

Report O-2276

NAVY DEPARTMENT
OFFICE OF NAVAL RESEARCH
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NAVY DEPARTMENT

Report on

The Measurement of Forces Which Resist Penetration of STS Armor, Mild Steel, and 24 ST Aluminum

NAVAL RESEARCH LABORATORY
ANACOSTIA STATION
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ABSTRACT

The initial investigation of the forces which resist the penetration of armor by solid steel bullets have been continued in order to find the effects of the three variables, the hardness and thickness of the armor and the height of the ogive of the bullet. Complications due to brittle-type deformation were avoided by using mild steel having a hardness of 99 BH and STS having a hardness of 266 BH as armor samples.

Two noteworthy characteristics of the resisting forces were revealed by superimposing curves found for different thicknesses of armor. The first of these was the failure of the thickness of the armor and of the striking velocity (limit) to influence appreciably the forces which exist during the initial part of penetration. This seemed to be true throughout the thickness range covered by experiments, from 3/16-inch armor to 1/2-inch armor. The second characteristic consists of a similar agreement of the forces in any two different thicknesses of armor when the bullet emerges from the back of the armor. The distance of bullet travel along which the forces are equal in this second characteristic is dependent upon the ogival height of the nose of the bullet and upon the thickness of the thinner plate. When a bullet becomes fully embedded in the thinner plate, that is, when its bourrelet reaches the front face, then the force acting upon it becomes equal to and remains equal to the force acting upon a bullet penetrating any thicker plate for a corresponding amount of remaining penetration.

The interesting fact pointed out in an earlier report that the effect of hardness is to multiply the force by a constant factor is confirmed by the results in this report.

No sudden changes were found in the slopes of the force-penetration curves which could be interpreted to mean that the motion of a bullet is irregular in ductile type penetrations because of the cracks which occur with the formation of petals.

The shape of the nose of a bullet was found to control the amount of energy absorbed to a certain extent. A bullet having an ogival height of 1.5 calibers encountered a greater force, except just at the peak, and required more energy during the penetration of 1/4-inch STS armor than a bullet did whose ogival height was 1.78 calibers.

In the analysis of photographic traces, the influence of bullet vibration upon the motion of the base of the bullet was observed, and the period of vibration (longitudinal) was found to be about 8.4×10^{-6} seconds. Using a theorem developed in a theoretical study of bullet vibration, it was possible to evaluate the deceleration of the center of mass of the bullet and thereby determine the true force acting on the nose of the bullet.

[redacted]

Measurements of the areas under the force-displacement curves were plotted against thickness of armor expressed in calibers, and the points followed a straight line of the form

$$E = a + b\ e/d$$

where E is the area under the curve (energy absorbed), e/d is the thickness in calibers and a and b are two constants. The values of a and b depend upon the hardness of the armor but their ratio seems to be constant for the two materials, mild steel and STS.

INTRODUCTION

A. Authorization

1. This investigation was authorized by the letter of reference (a) which is listed below together with other references in the report.

(a) BuOrd ltr. S13-1(4/173)(Q8) of 13 December 1934.
(b) NRL Report No. O-1591 of 6 February 1940.
(c) "Trend Analysis of Statistics," Sasuly, 49, (1934).
(d) NRL Report No. O-2275 of 13 April 1944.
(e) "Attempt of a Theory of Armor Penetration", H. A. Bethe, Frankford Arsenal Report, of 23 May 1941.
(f) NPG Report No. 1-43 of 9 April 1943.

2. The purpose of this investigation was to continue the work described in reference (b) of measuring the force which resists the penetration of armor by nondeforming bullets, and information has been obtained which shows the effects of three variables upon the force, the first and second being the hardness and thickness of the armor and the third being the height of the ogive of the bullet.

3. It is hoped that the effects of other variables upon the force, such as: the density of the armor, the weight of the bullet and the striking velocity of the bullet, can be found in future investigations, and the measurement of force vs. penetration for 0.281-inch 24 ST Aluminum included in this report begins a study of the effect of density. Since no measurements have been made yet using steel armor of the same hardness and thickness as the 24 ST Aluminum, it is not possible at the present time to give a quantitative discussion of the effect of density.

EXPERIMENTAL METHOD

4. The apparatus giving the results in the first NRL report of force-penetration measurements, reference (b), has been changed in order to increase the accuracy of the experiment and in order to decrease the work of analysing the data. It was estimated in the first report that there could be 6 percent error in measurements of the deceleration of the base of the bullet near the maximum values. The error of similar measurements in this report using the modified apparatus should not exceed 4 percent, and the probable error compounded from all conceivable sources should not be more than 2-1/2 percent. These percentages of error in the deceleration measurements apply to values obtained from smoothing processes, and it is correct only to say that the probable error in the deceleration averaged over a distance of bullet travel of roughly 0.03-inches should not be more than 2-1/2 percent.

5. The modification of the apparatus which increased the accuracy was a construction which gave larger traces on photographic film without an

increase in the width of the slit. A diagram on Plate 1 illustrates the formation of a trace, and it can be seen that by narrowing the slit or, giving the same effect, by enlarging the shadowgraph without increasing the slit width, the trace or edge made by the base of the bullet becomes sharper. (An enlargement of an actual trace is shown on Plate 2.) This allows a more certain measurement of the trace. The decrease in the amount of effort necessary to analyse a trace arises from the fact that it is now possible to measure the velocity of the bullet as a function of time by finding the slope of a straight edge set tangent to the trace at positions of successive equal intervals of time, and only one differentiation is required to evaluate the deceleration of the bullet. Previously, when smaller shadowgraphs were used, slope measurements were so uncertain that it was necessary to make a double differentiation of displacement as a function of time before the deceleration could be found.

6. In order to get larger photographic traces, the diameter of the aluminum alloy drum which holds the photographic film was changed from 1 inch to 4 inches, and the height of the drum was increased to accommodate 35 mm motion picture film. This was accompanied by a change in the optical reduction factor of the objective lens system from 0.3 to 0.8, and it made necessary the use of lenses of larger apertures. The photographs on Plates 3 and 4 show the new drum and the revised apparatus. The essential elements of the apparatus are shown on Plate 5 by a line drawing. A driving torque producing drum speeds up to 800 revolutions per second is provided by directing air through nozzles at turbine vanes machined on the shaft of the drum. When the drum is supported by ball bearings of the magneto type, air pressures of 100 pounds per square inch or less are needed to provide sufficient drum speeds. Two small steel plugs set in the bottom of the drum produce two similar variations in the reluctance of a magnetic circuit in each revolution. This causes a periodically varying emf to control the vertical deflection of a cathode-ray oscilloscope whose sweep is operated by an interpolation audio frequency oscillator. The rps of the drum is numerically equal to the frequency of the oscillator when a stationary pattern showing two peaks appears on the screen of the oscilloscope. The air flow to the drum can be held constant to give a desired drum speed while a photographic trace is being made. There have been no changes in the procedure described in the earlier report, reference (b), for obtaining traces.

METHODS OF ANALYSIS

7. The analysis of the photograph required the measurement of:

(a) Plate mass
(b) Bullet mass
(c) Bullet langth
(d) Distance from a reference wire to the specimen
(e) Drum speed

A reference wire was stretched between the upper and lower brackets of the specimen holder in the direct path of the bullet as shown on Plates 1 and 5. The distance from the wire to the specimen remained constant at 0.254 inches, the thickness of the brackets. The drum speed was measured directly by a cathode ray oscilloscope in connection with an interpolation oscillator.

8. In addition to measuring the above quantities the optical Reduction Factor (referred to hereinafter as R.F.) had to be determined. The R.F. is the ratio of lengths of images on a film to the actual lengths of corresponding objects. Adjustments in the optical system made it necessary to redetermine the R.F. from time to time.

9. Since the velocity of the base of the projectile at any instant of time is proportional to the slope of the edge of the photographic trace at that instant, the velocities may be obtained directly by measuring the angles between the direction of the film motion and a cross-hair placed tangent to the trace at points along the curve. The direct reading of velocities is shown to be justified by the fact that if all velocities up to a given time are added, the sum differs from the displacement read directly by an amount that is no greater than the error incurred in reading the displacement. The measurements were made on a coordinate comparator having a specially constructed eyepiece with cross-hairs that can be rotated through known angles. After each slope reading, the comparator microscope was given a horizontal displacement corresponding to the time unit arbitrarily chosen as a distance of 0.01 cm (0.015 cm in the case of long penetrations.) The vertical displacements necessary to keep the cross-hair tangent at each new "time" represented the travel of the base of the bullet between corresponding times.

10. As the bullet strikes the specimen it imparts motion to the plate. The velocities measured are the resultant of the bullet velocity and plate velocity and must be corrected to give the velocity of the bullet relative to the plate. If M_B and M_P are the masses of the bullet and plate respectively, $V_B(t)$ and $V_P(t)$ their respective velocities at time t, and if $V_B(o)$ and $V_{B,P}(t)$ are respectively the velocity of the bullet at $t = o$ and the velocity of the bullet with respect to the plate at time t, then

$$M_P V_P(t) = M_B \left[V_B(o) - V_B(t) \right]$$

since the momentum lost by the bullet during the interval of time from $t = o$ (impact) to t is transferred to the plate, or

$$(1) \qquad V_P(t) = \frac{M_B}{M_P} \left[V_B(o) - V_B(t) \right]$$

But $\quad V_{B,P}(t) = V_B(t) - V_P(t)$

Substituting from (1)

$$V_{B,P}(t) = \left(1 + \frac{M_B}{M_P} \right) V_B(t) - \frac{M_B}{M_P} V_B(o)$$

[redacted]

The quantities in the right hand side of the equation are all measured and $V_{B,P}(t)$ can be computed.

11. It is necessary to determine the position at impact when $t = o$. This may be expressed by the following:

$$D - 2.54 \; (\ell - 0.254) \; R.F.$$

where D is the vertical displacement reading at the trace of the reference wire, ℓ is the length of the bullet and 0.254 is the distance from the reference wire to the specimen in inches. The result is expressed as a reading on the comparator. In order to obtain the actual depth of penetration of the projectile into the plate at time t , the difference between the position at t and the position at impact $(t = o)$ is divided by the R.F. and expressed in inches. These penetration values were corrected for plate motion.

12. The time unit in seconds is given by:

$$\frac{0.01 \; (0.015)}{31.83 \times r.p.s.} \quad \text{secs.}$$

where 0.01 (or 0.015) is the length in centimeters of an interval on the film, 31.83 is the length of the film in centimeters and r.p.s. is the revolutions per second of the drum. To facilitate handling of the data, readings were taken at 0.1 mm spacings on the comparator. Usually impact fell at some point within an interval, for example, 0.7 of the distance between one reading and the next. The time in seconds at the first interval past impact would then be 0.3 of the time interval in seconds. The time after impact at the n^{th} interval would then be:

$$t_n = 0.3 \; \frac{0.01 \; (\text{or } 0.015)}{31.83 \; r.p.s.} + (n-1) \; \frac{0.01 \; (\text{or } 0.015)}{31.83 \; r.p.s.}$$

$$= (n-0.7) \; \frac{0.01 \; (\text{or } 0.015)}{31.83 \; r.p.s.}$$

13. With the measurements described above completed, it was possible to proceed with an analysis of the data to obtain the force-displacement and force-time curves.

14. The decelerations are proportional to the forces and must be determined as a first step in analysing the data. They were obtained from the velocities. Here one advantage in reading the velocities directly is seen in the smoothing which the eye automatically accomplishes in fitting the cross-hair tangent to the curve. No further smoothing of the slopes was necessary before proceeding to a computation of the decelerations. The first method tried for determining the decelerations is described in reference (c). Briefly, it consists in fitting the velocities as a function of time, in successive groups of seven, to a parabola by the method of least squares and

[redacted]

taking the slope at the midpoint as the deceleration at that time. The results of this manipulation are represented by the curves on Plate 6. These curves of deceleration plotted against time show a series of secondary maxima and minima occurring at fairly regular intervals, and it was concluded that these were a consequence of longitudinal vibrations set up in the bullet when it struck the plate.

15. The period of the bullet vibration was determined from a careful study of the secondary minima in curves such as those on Plate 6. In Table 1 there is listed for a number of penetrations the times after impact at which the minima occur in the deceleration curves of the base of the bullet. The last row in this table gives the average times after impact for the occurrence of successive minima. These averages were fitted to a straight line by the method of least squares and gave a value of 8.4×10^{-6} seconds for the period of vibration. The curves shown on Plate 6 are intersected by vertical lines drawn at times corresponding to 1-1/2, 2-1/2, 3-1/2 and 4-1/2 periods after impact, and there is good agreement between the times of minima and these lines. Failure of the traces to have any curvature for a short time after impact confirms the fact that elastic bullet deformation is observed because, until a time equal to 1/2 of the fundamental period has elapsed following impact, the base of the bullet can show no deceleration.

16. The behavior of the center of mass of the bullet was considered instead of the behavior of the base in order to eliminate the secondary maxima and minima caused by the vibration in the bullet and thereby obtain a (smooth) curve which gives a clear picture of the force resisting penetration. This is explained fully in reference (d). In this reference it is proved that the acceleration of the center of mass of the bullet for any time t' at the midpoint of a fundamental period of vibration of the bullet is equal to the average acceleration of the base for that period. This can be expressed succinctly by the equation:

$$A_{CM}(t') = \frac{c}{2\ell}\left[V_B(t' + \frac{\ell}{c}) - V\,(t' - \frac{\ell}{c})\right].$$

where $\frac{2\ell}{c}$ is the period of vibration of the bullet,

$V_B(t' - \frac{\ell}{c})$ is the velocity of the base of the bullet at a time half a period before t' and

$V_B(t' + \frac{\ell}{c})$ the velocity of the base of the bullet at a time half a period after t'.

After values proportional to the acceleration of the center of mass were found for every point on the curve by taking the difference of the velocity half a period before and half a period after the point under consideration,

[redacted]

they were converted to forces in pounds by multiplying by a constant equal to

$$\frac{1.044}{8.4 \times 10^{-6}} \cdot \frac{\text{r.p.s.} \times M_B}{7000 \times 32.18 \text{ R.F.}}$$

where, in addition to the quantities defined above,

1.004 is the length of the film in feet,

7000 is the number of grains in a pound, and

32.18 is g .

RESULTS

17. The experiments have been limited to three groups. In the first group, measurements have been made of the force resisting penetration of 0.1875, 0.250, 0.3560, and 0.500-inch thick samples of STS armor having a hardness of 266 BH. The force penetration curves derived from these measurements are shown on Plate 7. In the second group, force-penetration curves shown on Plate 8 were obtained for penetrations of 0.1875, 0.250, 0.350, and 0.500-inch thick samples of mild steel having a hardness of 99 BH. These samples were prepared by splitting one large piece each of 3/4-inch mild steel and STS into specimens having the desired thicknesses. Hardness surveys of both materials had shown a high degree of homogeneity, consequently there is a reasonable certainty that the penetrations have been made in materials of unvarying physical properties. All available data concerning the physical properties are listed in Table 2. Lastly, a force-penetration curve for 24 ST Aluminum Alloy 0.281-inches thick was obtained, and it is shown on Plate 9. The same Cal .27 solid steel bullet was used throughout this group of experiments and a diagram showing its dimensions is on Plate 10. All force-penetration curves are for limit velocity shots.

DISCUSSION OF RESULTS AND CONCLUSIONS

A. Force-Displacement Curves

18. The group of four curves shown on Plate 7 and relating to STS have been superimposed one on another on Plate 11 in such a way that the depths of penetration have the same ordinate scale. A similar arrangement of the curves on Plate 8, relating to mild steel are shown on Plate 12.

19. An interesting feature demonstrated by these arrangements is that the initial rise of the force follows a curve which is more or less common for all thicknesses of a given armor. It is also to be noted that the force for a particular thickness begins to fall below this common curve before the tip of the bullet manages to reach the plane of the back surface, and it is surmised that this is probably associated with the beginning of a bulge on the back. It is suspected, therefore, that the movement of the material backward when petals begin to form limits the magnitude of the force to a value which is considerably less than it would be if the plate material were

all thrust laterally aside. From Plates 15 and 16 which show respectively photographs of cross-sections of perforations in STS armor and sketches of lines appearing on the cross-sections when etched, it is evident that a major portion of deformation in thin armor is associated with petalling, but for thick armor a considerable amount of material must move sideways from the bullet.

20. For limit velocity shots, it cannot be ascertained from the curves on Plates 10 and 12 whether or not the rising force of thin armor would be less than the rising force of thick armor. Certainly, there must be some added inertial resistance in the case of thicker armor because there will be a higher striking velocity. Such velocity effects are too small to be observed with the present inaccuracies in the force measurements.

21. When the curves on Plates 7 and 8 are rearranged so that there is coincidence of the ordinates of the forces existing at the instant the tip of the bullet reaches the back of the armor, the arrangements on Plates 13 and 14 are obtained. This reveals another feature of penetration. Examine for a moment the curve of the 3/16-inch STS armor. It will be seen that the force at and beyond a distance to the right of impact equal to the ogival height of the bullet (0.405 inches) lies on the curves of all thicker armor. This same remark holds true also for the 1/4-inch and 0.360-inch thicknesses. What this means is that when the bourrelet of a bullet reaches a position in a thick piece of armor where the remaining distance to be travelled before complete penetration is equal to the remaining distance to be travelled by a bullet embedded up to its bourrelet in a thinner piece of armor then the forces on the two bullets become approximately equal to each other and remain equal until penetration is completed.

22. Another feature of the force-penetration curves which has been mentioned previously, reference (b), is that a change in hardness from 99 BH to 266 BH does not change the shape of the curves except to multiply the forces by a constant amount, In other words, so long as the deformation is of a ductile nature a change in hardness changes the amount of energy absorbed in a way shown by plots of the "P" coefficient against hardness but it does not introduce any changes otherwise in the more detailed picture of penetration given by the force-displacement curve.

23. When areas under the force-displacement curves were measured and then expressed as foot pounds of energy, they were found to vary linearly with the thicknesses in calibers in the manner shown on Plate 18. This plot is closely related to the method of plotting discussed by the Naval Proving Ground in reference (f), and obviously suggests that the absorbed energy, E , must be related to the thickness in calibers, e/d , by a relationship of the form

$$E = a + b\,(e/d)$$

Attempts to interpret this relationship in terms of the features observable in the force-displacement curves have not been entirely successful, and, at present, it is looked upon as being simply a fortuitous simplification over a limited range of the thickness variable <u>e</u> . Experiments both at Princeton University and at the Naval Research Laboratory support the belief that for use over a more extensive range of thicknesses a more appropriate empirical formula may be of the form

$$E = A(e/d)^n$$

where A and n are constants determined by the physical properties of the armor and by the shape of the bullet.

24. The ratio of the constants in the first formula above, namely a/b, was the same for both mild steel and STS, and the constant b shows the effect of the difference in hardness. Both constants probably depend upon the shape of the bullet.

25. The effect of the shape of the projectile on the force curve is shown on Plate 17. The curves representing penetration of 1/4-inch mild steel and STS by a bullet with ogival height of 1.78 calibers were taken from the Sixth Partial Report. The forces on this bullet rise more slowly, come to a sharper peak and start falling more rapidly than those on the blunter projectile used in the present series of experiments. The energy loss as represented by the area under the curve seems to be the same for both bullets for mild steel but for STS the loss is greater in the case of the blunter bullet

B. Extent of Agreement With Constant Pressure Theory

26. The results of this investigation into the forces resisting the penetration of homogeneous armor present data with which any detailed theory must have reasonable agreement if it proposes to give a point to point description of the penetration process. The most important considerations are bullet shape, plate thickness, yield stress, and a criterion for plastic deformation. Secondary influences are strain-rate, work hardening, and friction during the main part of the penetration. (These latter effects, however, are still beyond experimental determination.)

27. A rough agreement with respect to shape of force-displacement curves exists between observed values and those computed on the basis of constant-pressure theory. According to the latter theory the total force at any instant of penetration should be proportional to the projected area of contact at that instant. On account of the high velocity with which the projectile passes through the armor and the consequent considerable lateral impulse imparted by the ogive, it is to be expected that the constant pressure theory can only serve as a rough guide to what may be expected in the penetration of homogeneous armor. For non-homogeneous armor, the constant pressure theory is clearly inapplicable. As an example of the theory it should be noted that the effect of the shape of the nose of the bullet on the rising force shown by the curves on Plate 16 is just what would be expected. The projected area of the sharper bullet would increase more slowly and consequently the forces necessary to maintain a constant pressure would not build up as fast.

C. Evaluation of Other Theories

28. There exists no successful attempt to provide an adequate mathematical theory of the process by which a projectile pierces homogeneous armor based on a detailed application of the theories of elastic and plastic

[redacted]

deformation. The problem is one of great difficulty which arises from the fact that it is 3-dimensional, it involves a complex fusion of elastic and plastic theory, and it presents a situation which has no simple geometrical model. The recent attempt of Professor Bethe has received wide attention and it seems advisable to discuss Bethe's theory in connection with the results presented in this report.

29. The primary object of Bethe's analysis is to evaluate the energy required for a projectile of given caliber to pierce a plate of armor of given thickness and known yield stress. Bethe assumes that the complete penetration of a plate can be considered equivalent to the radial enlargement of a hole by some conceivable process and he assumes that in plastically deforming the armor the work done is independent of the process just so that the final deformation is achieved. This is open to objection because the work performed in plastic deformation must be a function of the "history" of the process. What may be expected from Bethe's analysis is an approximation that has greater validity in the case of thick rather than in thin plates. In the case of thick plates a larger percentage of the deformation can be considered as accomplished by sidewise thrust, whereas in thin plates dishing and petalling are at least as important deformations as sidewise displacement, in fact, they predominate in very thin plate penetration.

30. The Naval Proving Ground, reference (f), has extended the constant pressure theory by assuming that there exists, independent of the total armor thickness, a constant-depth back layer of the armor which is deformed during petalling by more of a bending type of deformation than the expanding hole deformation used by Bethe. For a given bullet the Proving Ground predicts the relationship given in paragraph 23 between the total energy absorbed at limit velocity and the armor thickness. The absorbed energies, carefully measured for homogeneous materials, that are plotted on Plate 18, agree quite well with this relationship. However, the forces measured near the end of penetration indicate that a more complicated connection than that assumed by the Proving Ground exists between the thickness of the armor and the energy absorbed during the formation of petals. Actually, it is doubtful that any clear distinction can be made between the formation of petals and the general deformation of the armor since etched cross-sections of perforations show that there is a gradual transition from regions where material is compressed laterally to regions where material is extended and bent sideways to form petals. On the other hand, it can be seen from the arrangements of force curves on Plates 13 and 14 that in any given series of armor thicknesses a certain constant-thickness of back layer could be assumed to be associated with a constant amount of energy of petalling. This thickness would not necessarily be the same for another series of thicknesses because it depends upon the thickness of the thinnest armor in the series and upon the ogival height of the nose of the bullet.

D. <u>Petalling Effect</u>

31. In addition to the fact that petalling at the back is responsible for a reduction in the force and a less effective type of energy absorption, it may be of interest to point out that there are no pronounced sudden changes in the force curves which might be ascribed to cracks forming with petalling.

[redacted]

In other words, the formation of a crack is of such a nature that the sudden force relief associated with the opening of a crack cannot be large in the type of deformation found in this investigation.

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Table 1

Occurrence of Secondary Minima in

Force-Time Curves

Impact No.	Time After Impact (Micro-seconds)			
	1st Minimum	2nd Minimum	3rd Minimum	4th Minimum
2	- -	22.6	- -	38.6
3	- -	19.4	- -	33.8
4	- -	22.0	- -	- -
5	- -	20.8	- -	- -
9	12.0	21.5	29.0	36.4
11	11.4	20.0	28.7	38.2
19	12.5	- -	29.0	37.3
20	10.0	19.7	- -	- -
22	- -	23.2	33.0	- -
23	- -	21.8	- -	- -
32	11.0	21.5	29.1	37.5
33	11.8	22.5	- -	39.7
34	12.1	21.1	29.1	- -
36	12.0	20.5	28.6	39.2
Average	11.60	21.28	29.50	37.60

[redacted]

Table 2

Physical Characteristics of Mild Steel and STS

Material	Composition	Heat Treatment	Tensile Strength Lb. per Sq. In.	Yield Point Lb.per Sq.In.	Brinell Hardness Kg.per Sq.mm.	Percent	
						Elongation	Reduction of Area
Mild Steel*	1010 (SAE) (Approx.)	Fully Annealed	80,000 (Approx)	- -	99	25 (Approx)	68 (Approx)
STS	C 0.31, M 0.24, P 0.012, S 0.022, Si 0.07, Ni 3.15, Cr 1.17	Green anneal at 675°C Quench at 788°C Draw at 612°C	125,300	107,300	266	23	68.2

* Physical Properties taken from Metal's Handbook (1939 Edition)

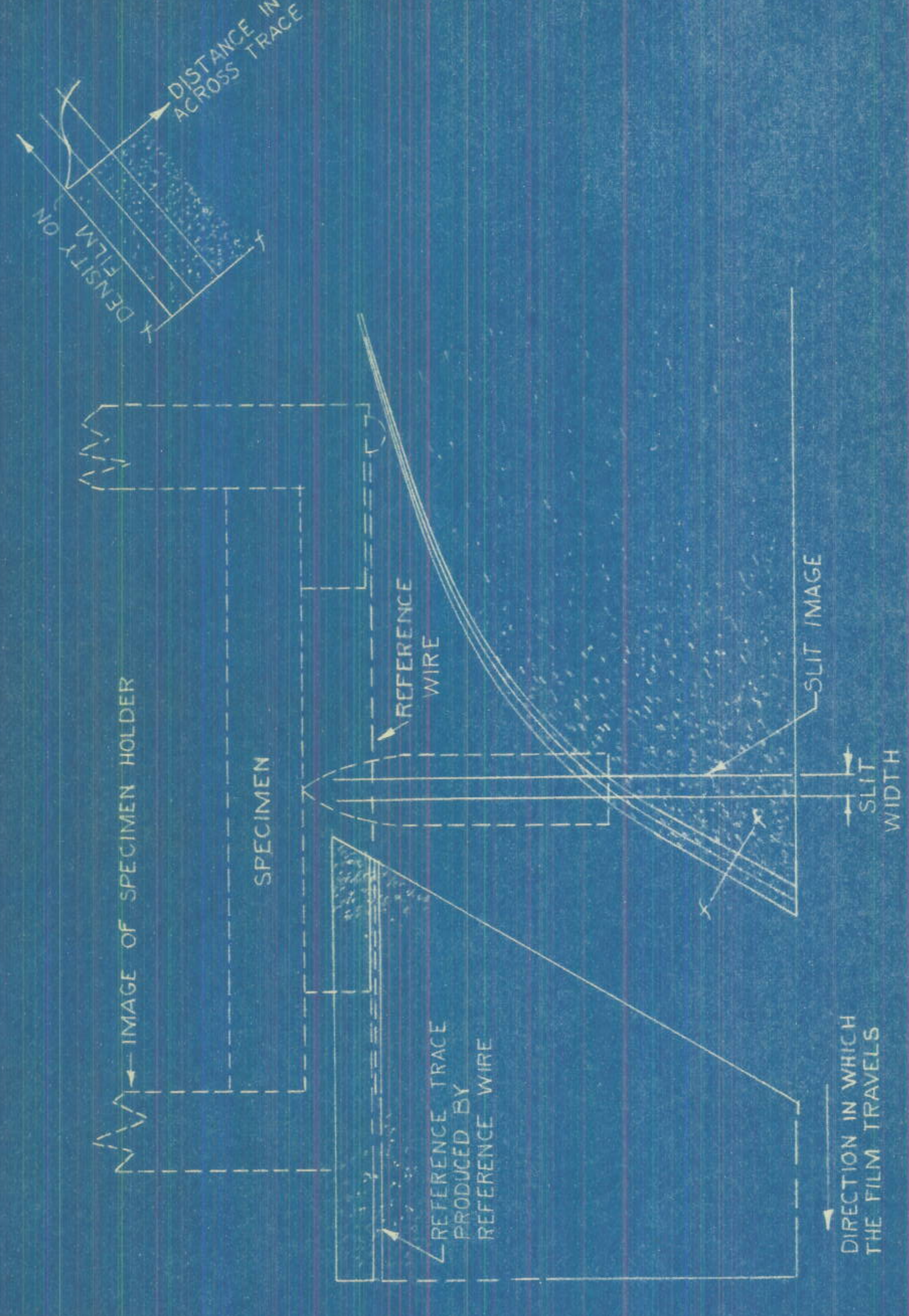
DISTANCE IN ACROSS TRACE
DENSITY ON FILM
IMAGE OF SPECIMEN HOLDER
SPECIMEN
REFERENCE WIRE
SLIT IMAGE
SLIT WIDTH
REFERENCE TRACE PRODUCED BY REFERENCE WIRE
DIRECTION IN WHICH THE FILM TRAVELS

PLATE I

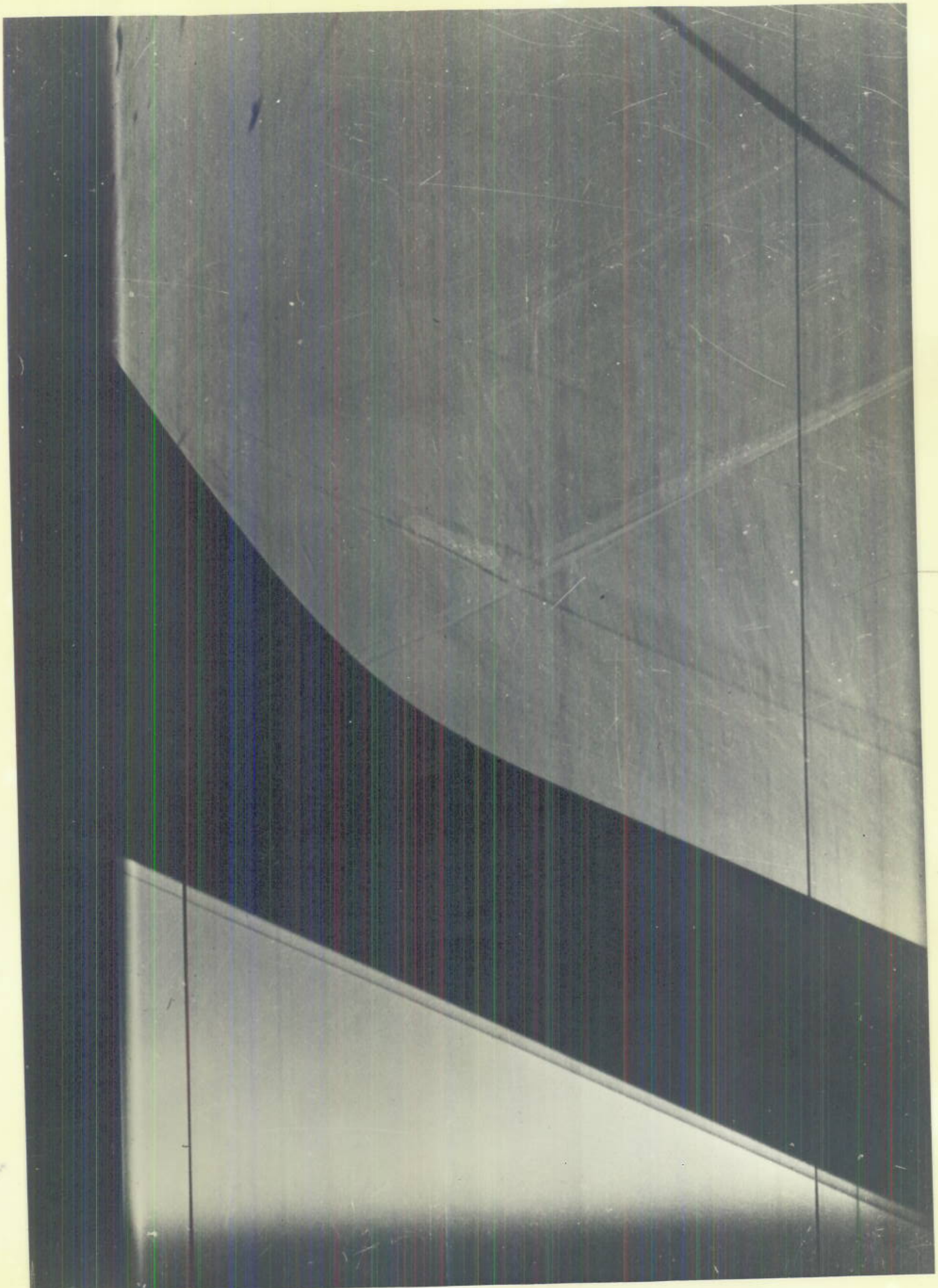

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PLATE 2

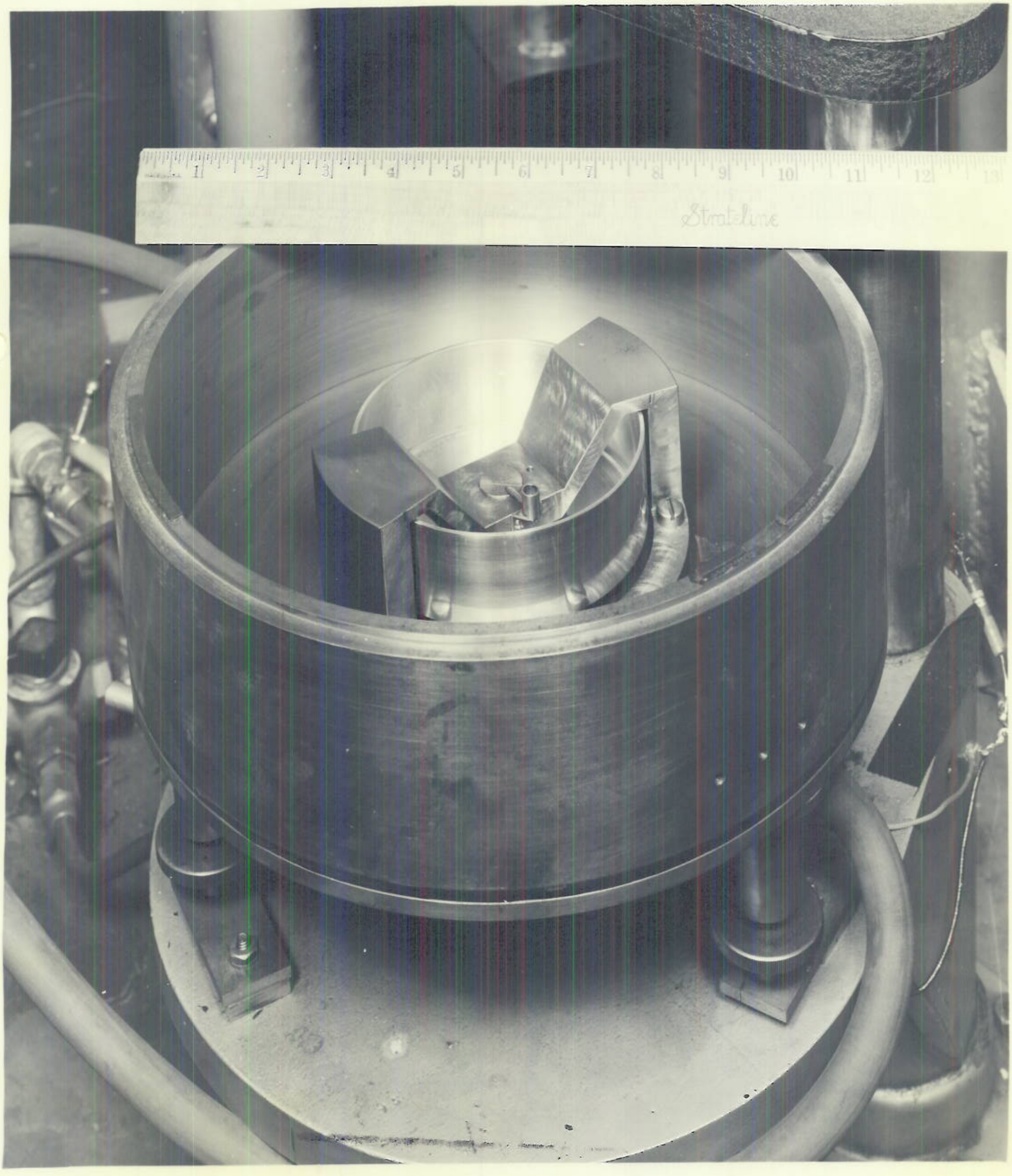

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PLATE 3

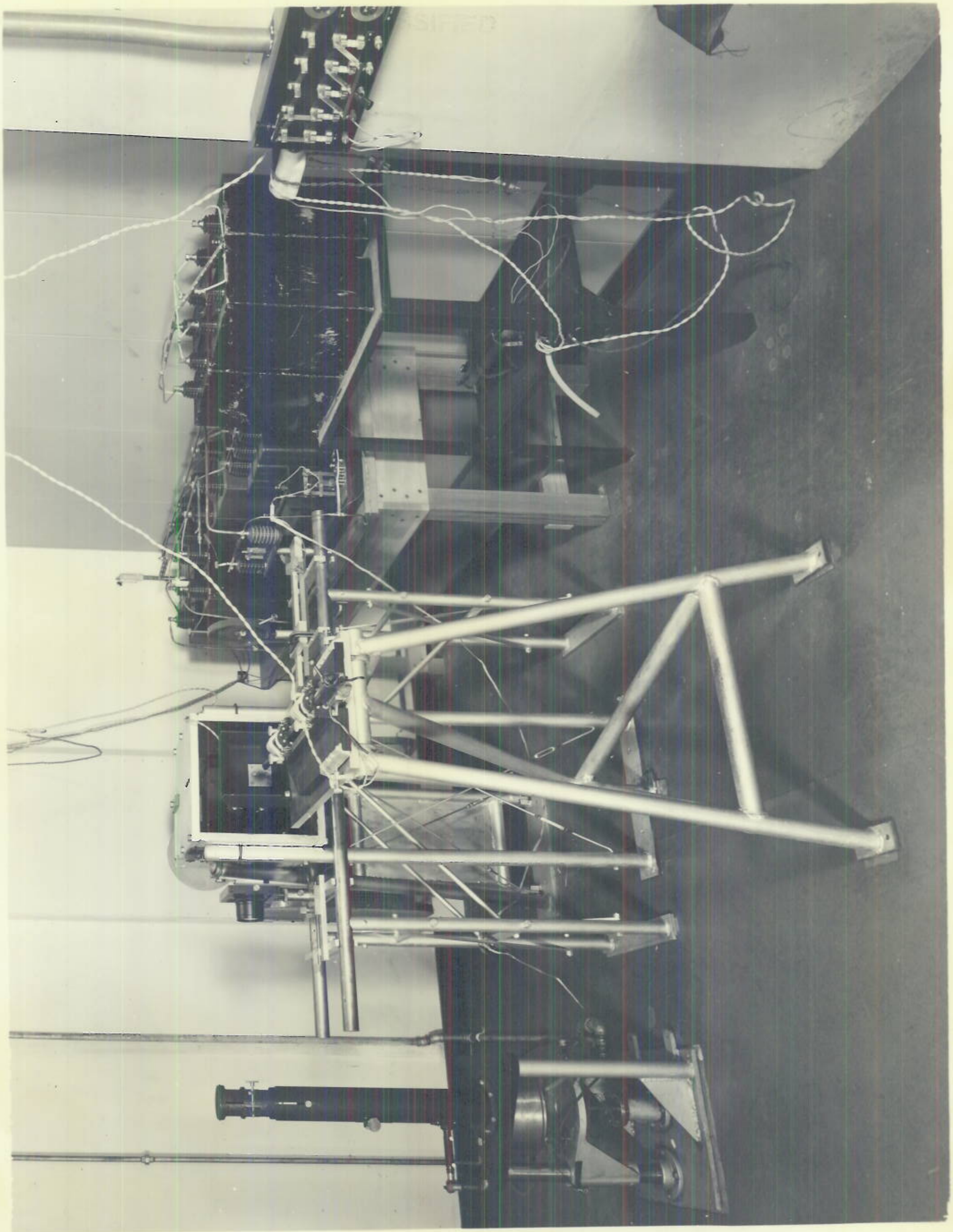

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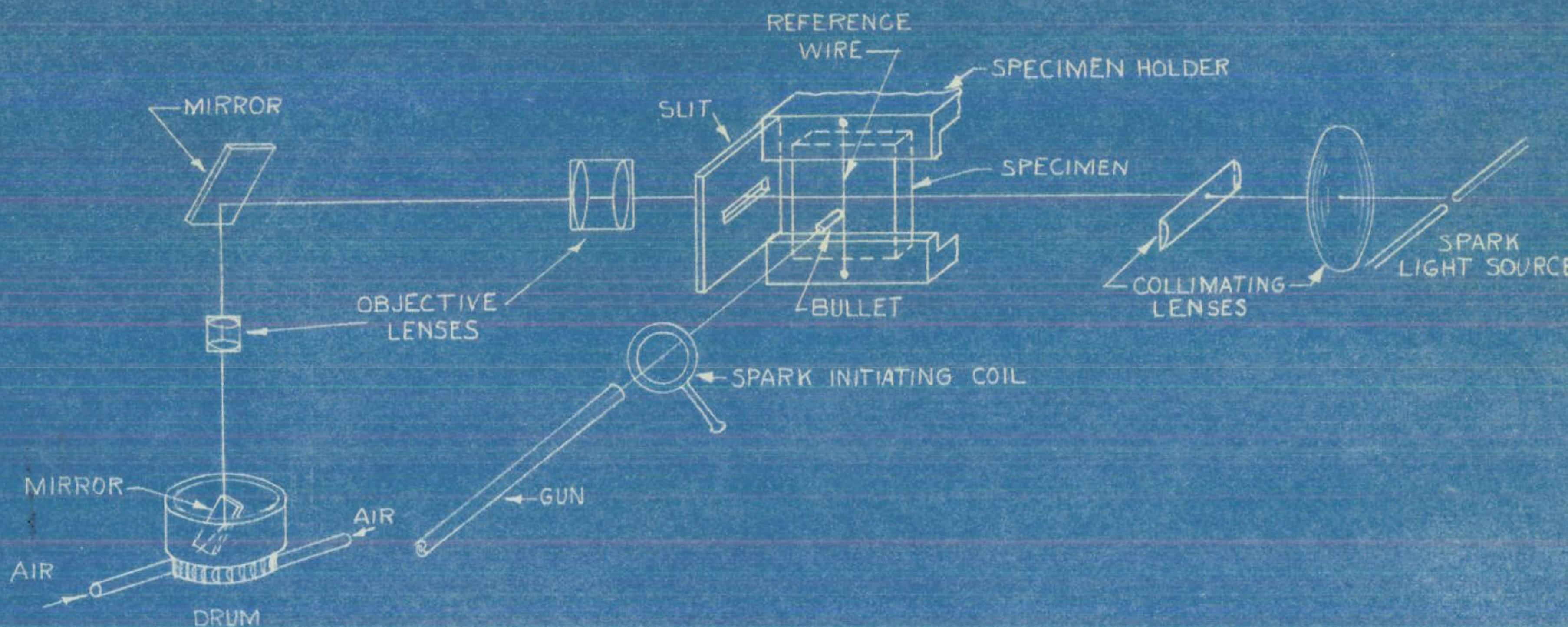
PLATE 4



[redacted]

PLATE 5

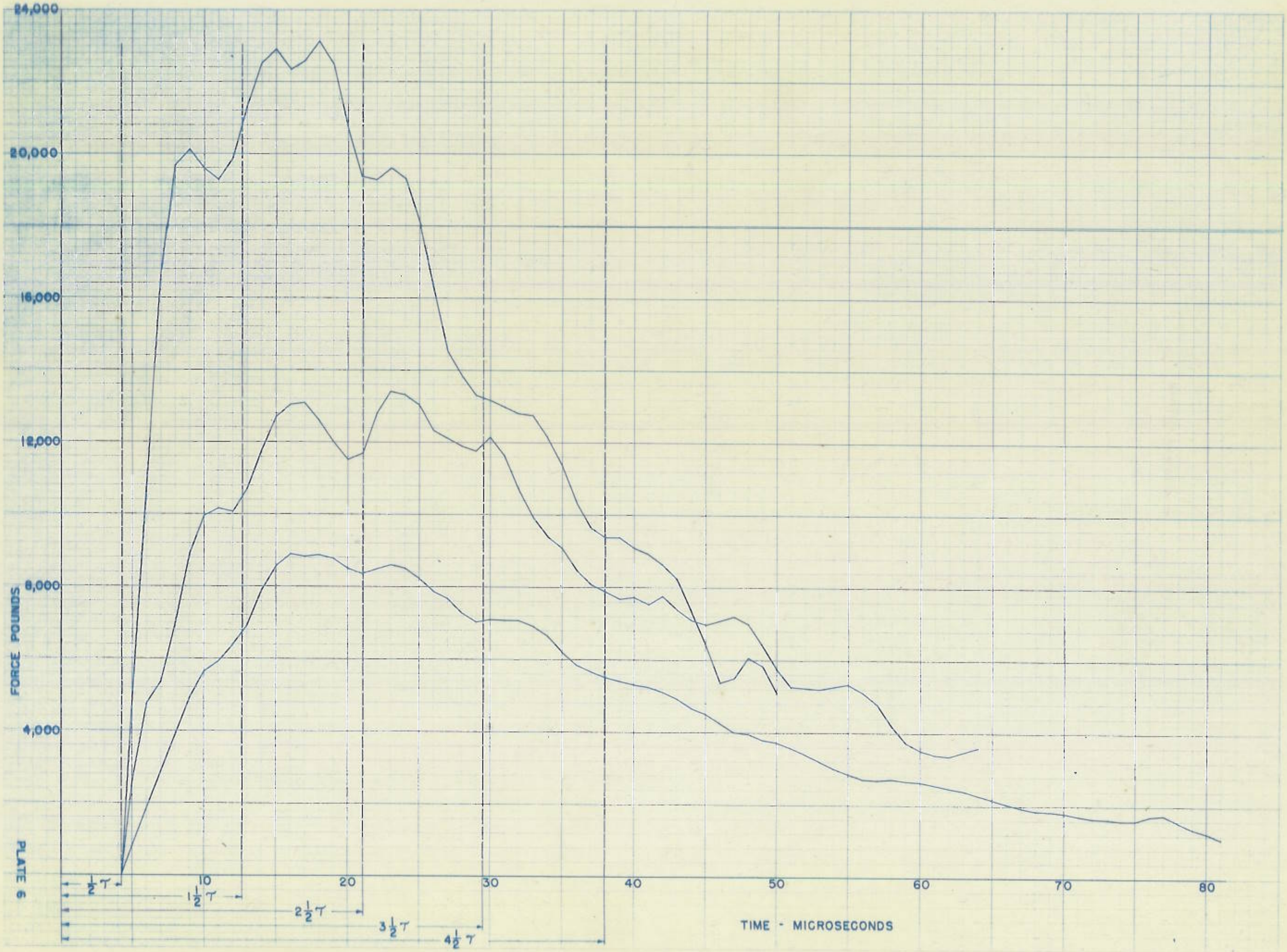


PLATE 6

[redacted]

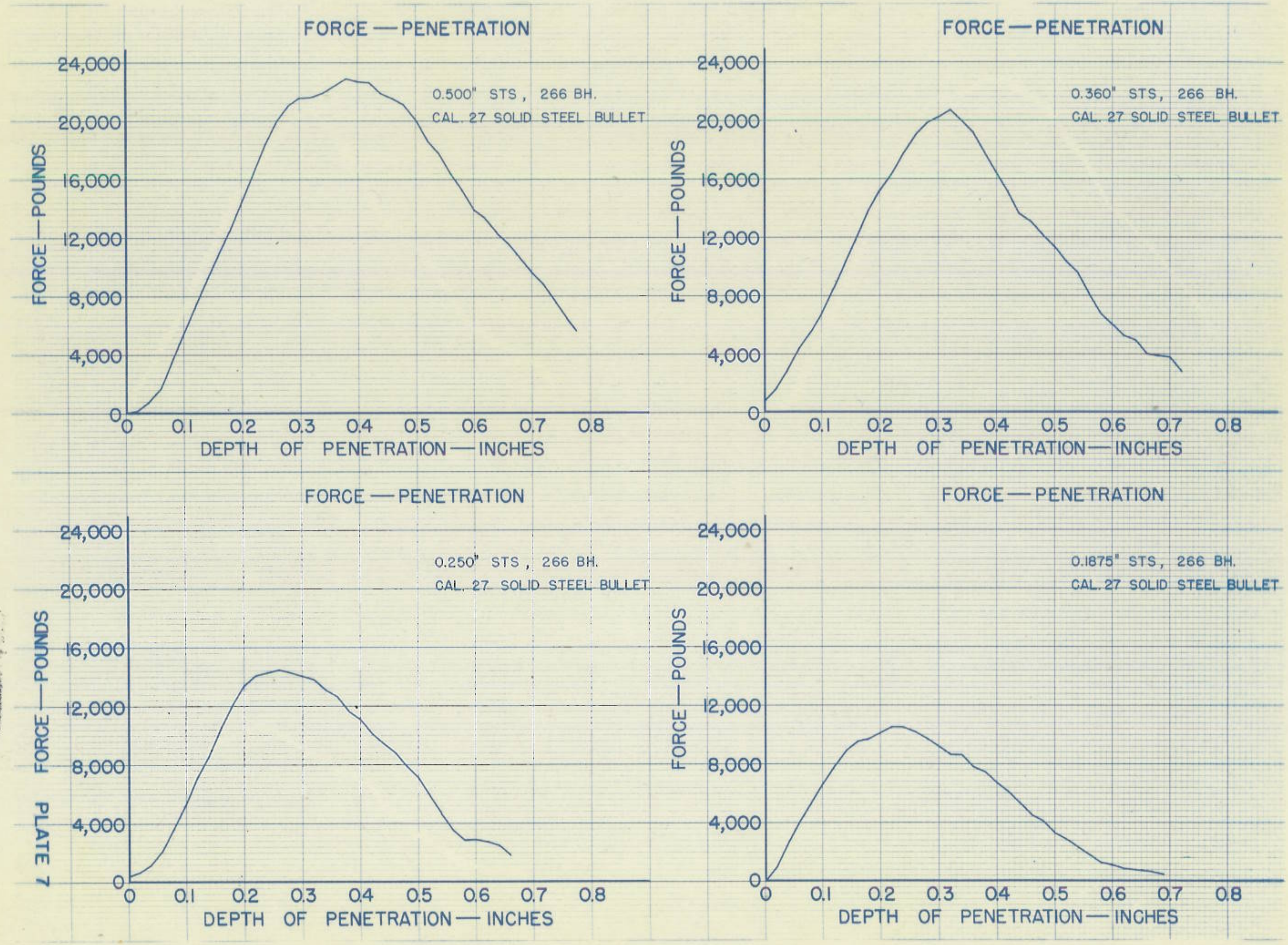


PLATE 7

[redacted]

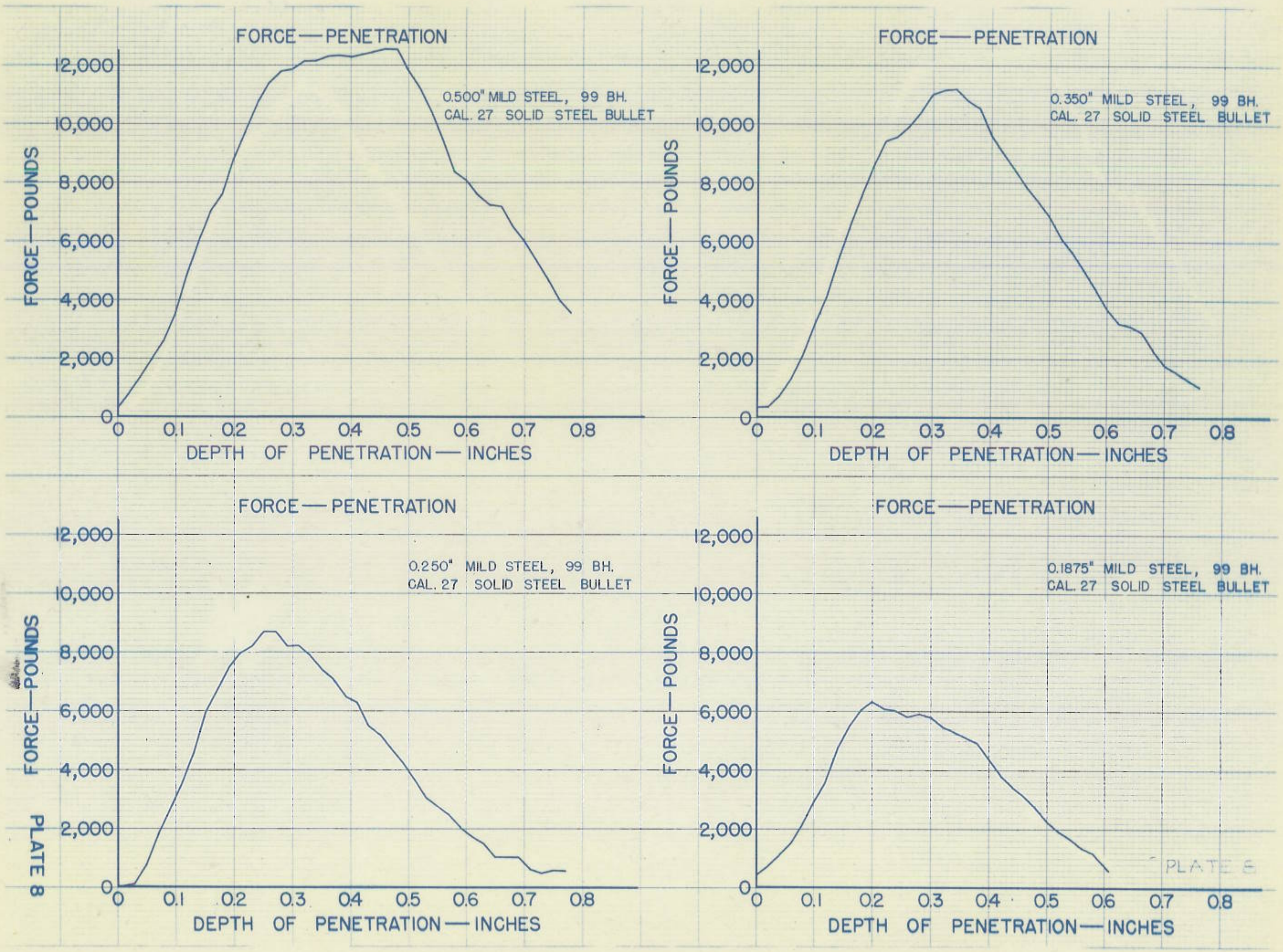


PLATE 8

[redacted]

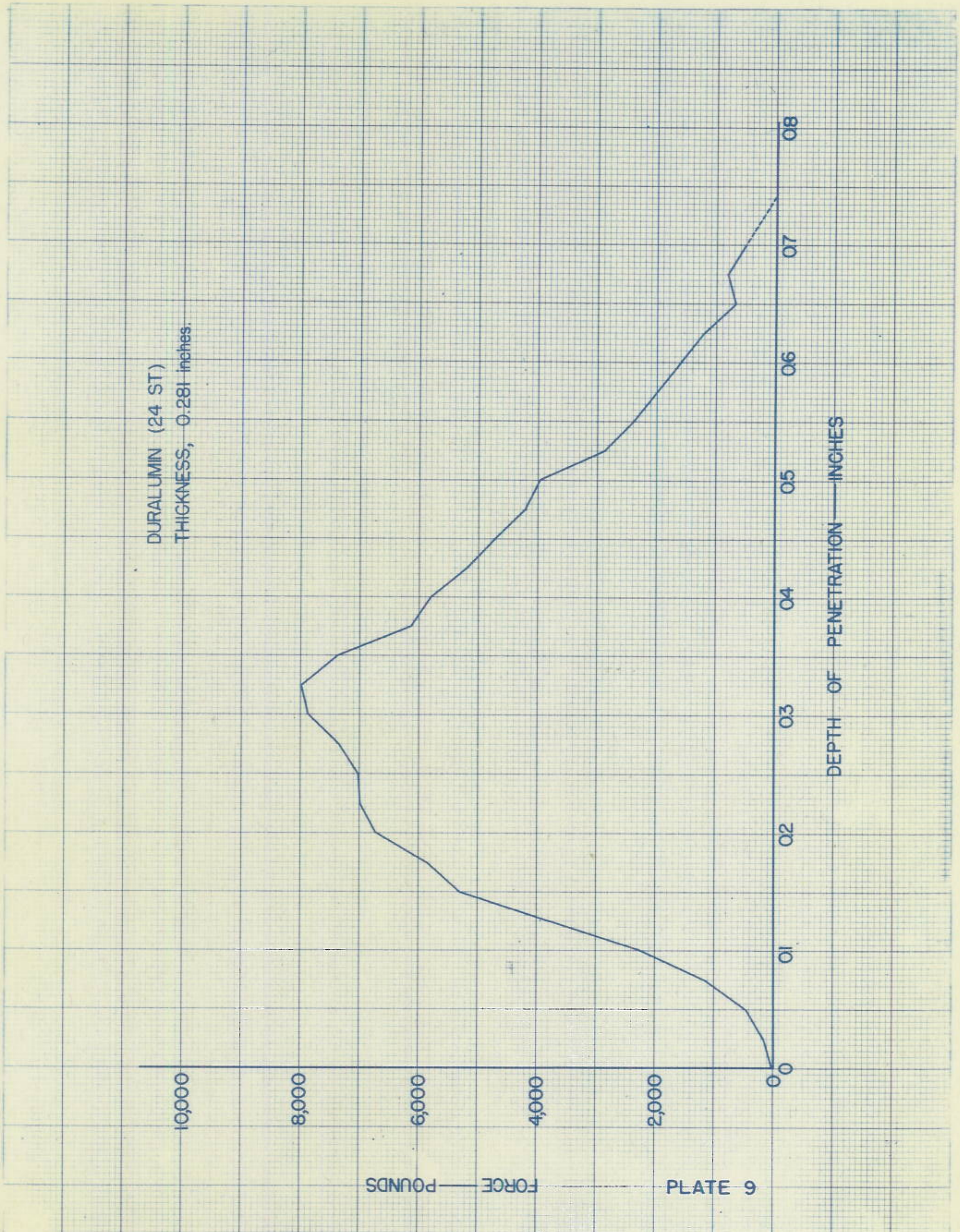

DURALUMIN (24 ST)
THICKNESS, 0.281 inches.
DEPTH OF PENETRATION — INCHES
FORCE — POUNDS
10,000
8,000
6,000
4,000
2,000
0
0
.01
.02
.03
.04
.05
.06
.07
.08

PLATE 9

CAL. 27 SOLID STEEL BULLET

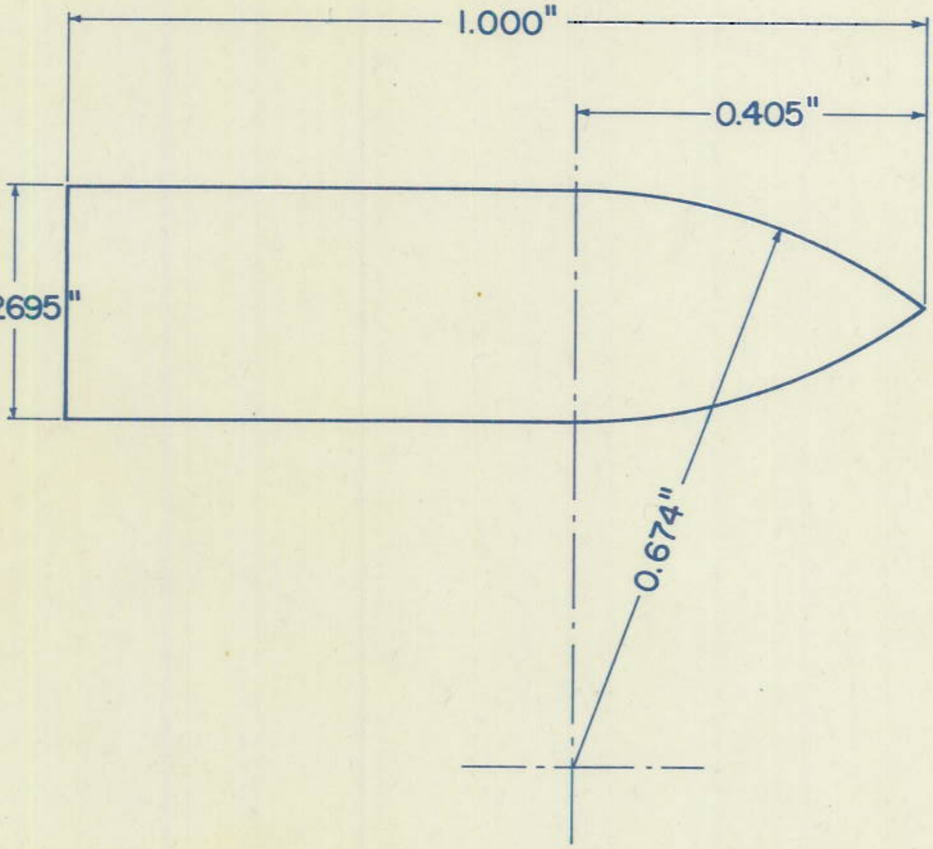


PLATE 10

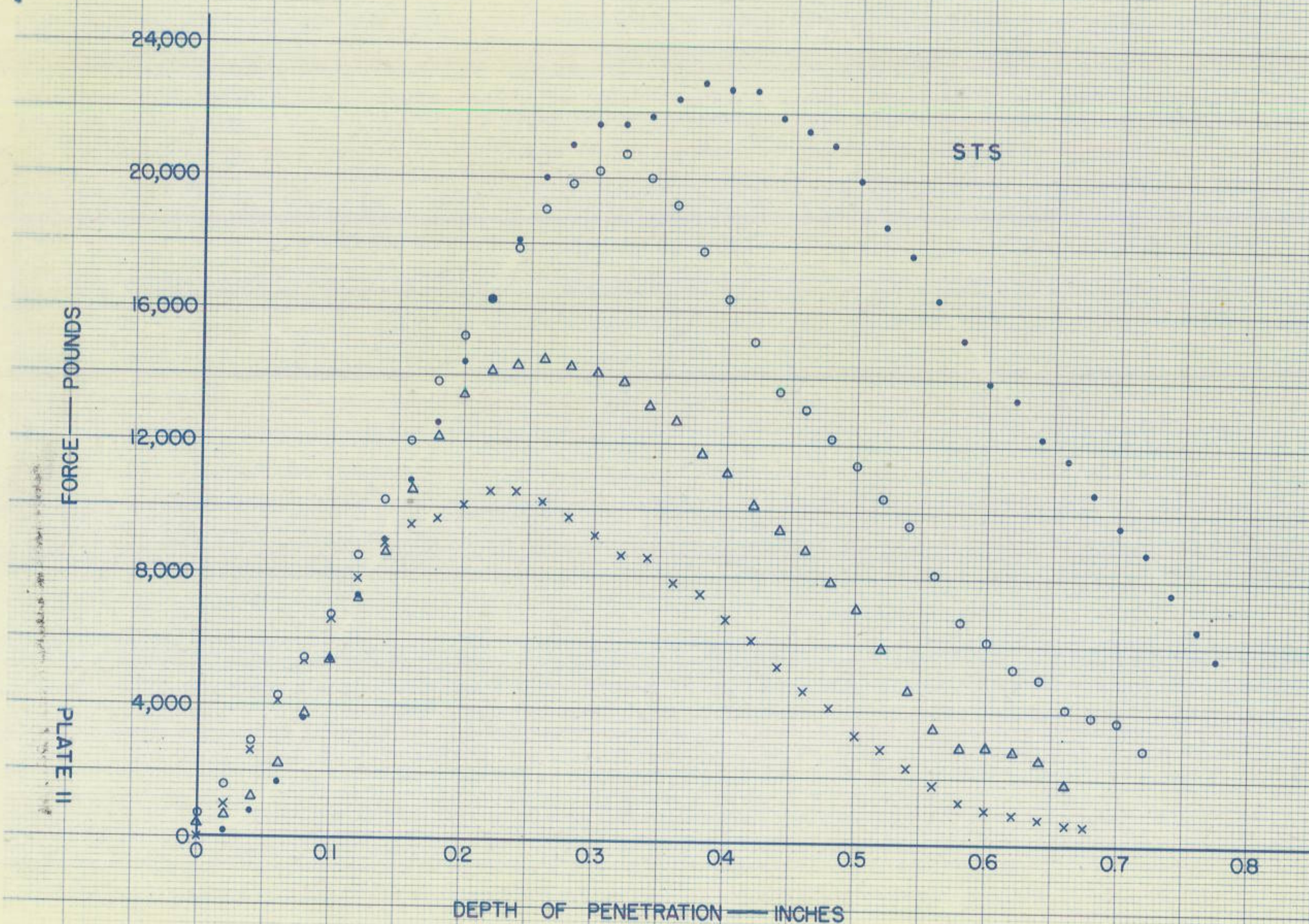

STS
FORCE —— POUNDS
24,000
20,000
16,000
12,000
8,000
4,000
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
DEPTH OF PENETRATION —— INCHES

PLATE II

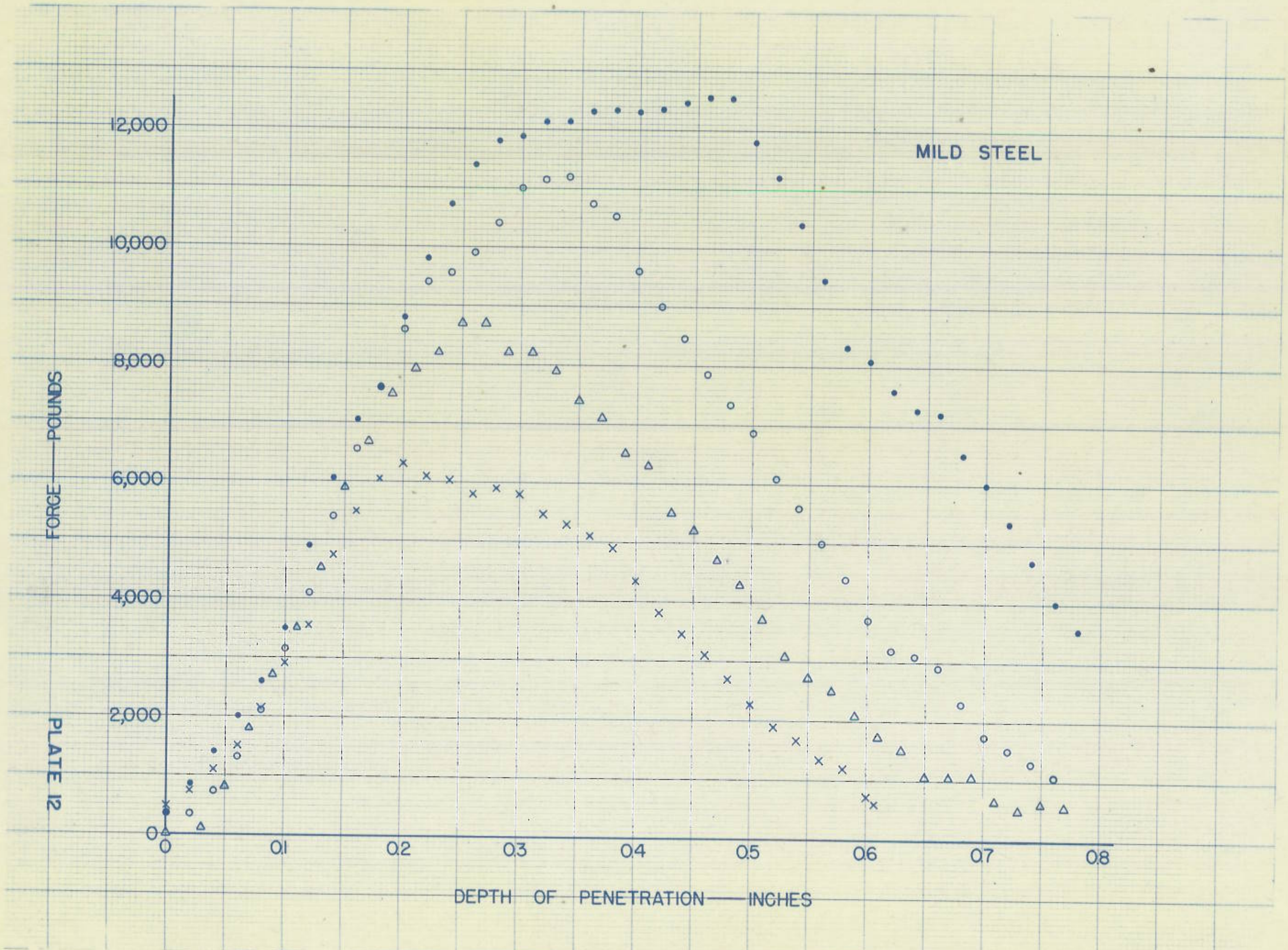

MILD STEEL
FORCE — POUNDS
12,000
10,000
8,000
6,000
4,000
2,000
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
DEPTH OF PENETRATION — INCHES

PLATE 12

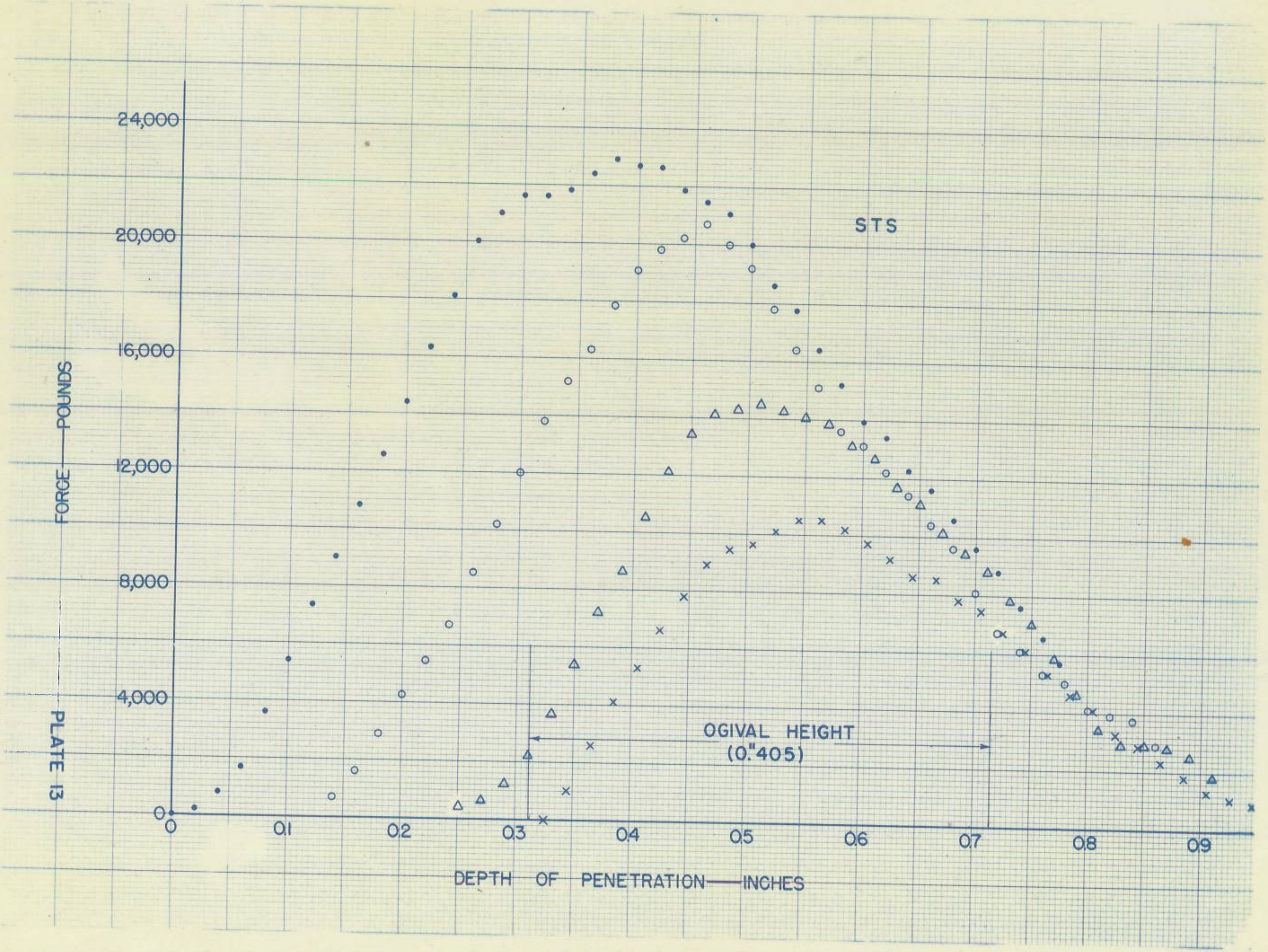


PLATE 13

[redacted]

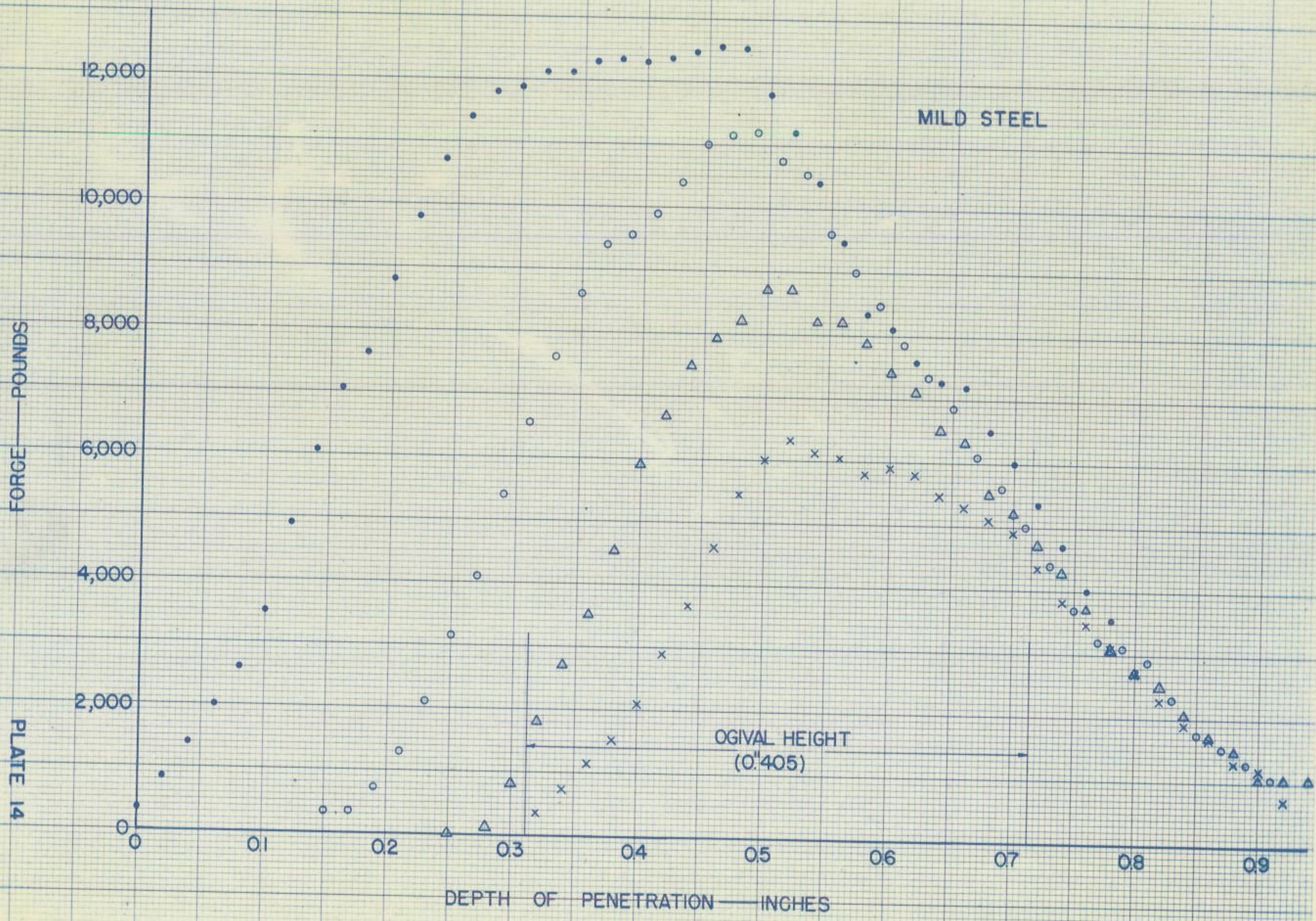


PLATE 14

[redacted]

MILD STEEL | STS

A

LIMIT ENERGY 186 FT. LB.

3"/16

E

LIMIT ENERGY 322 FT. LB.

B

LIMIT ENERGY 263 FT. LB.

1"/4

F

LIMIT ENERGY 450 FT. LB.

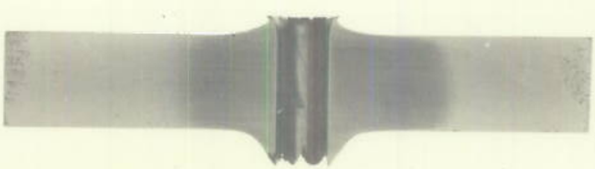
C

LIMIT ENERGY 377 FT. LB.

3"/8

G

LIMIT ENERGY 675 FT. LB.



D

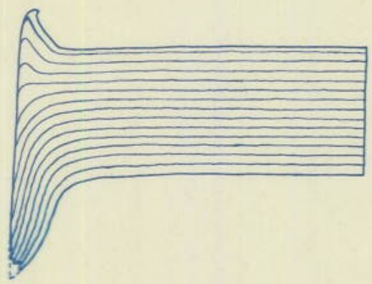
LIMIT ENERGY 559 FT. LB.

1"/2

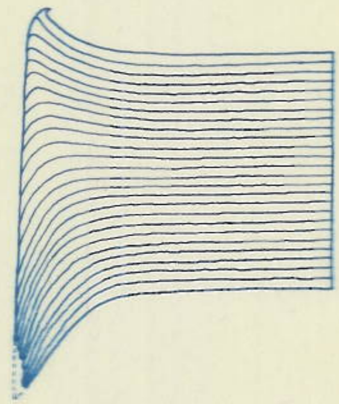
H

LIMIT ENERGY 954 FT. LB.

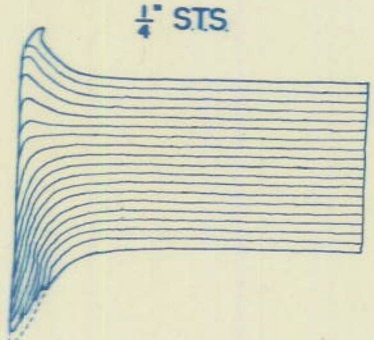
$\frac{3}{16}$" S.T.S.



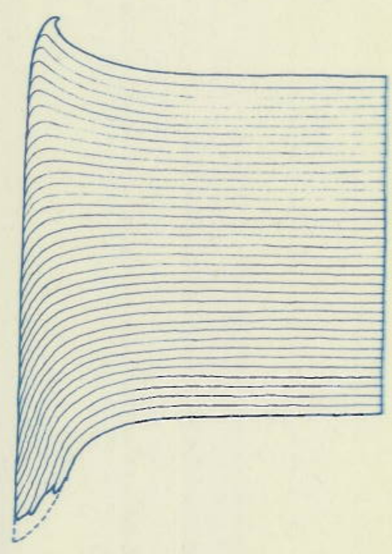
$\frac{3}{8}$" S.T.S.



$\frac{1}{4}$" S.T.S.

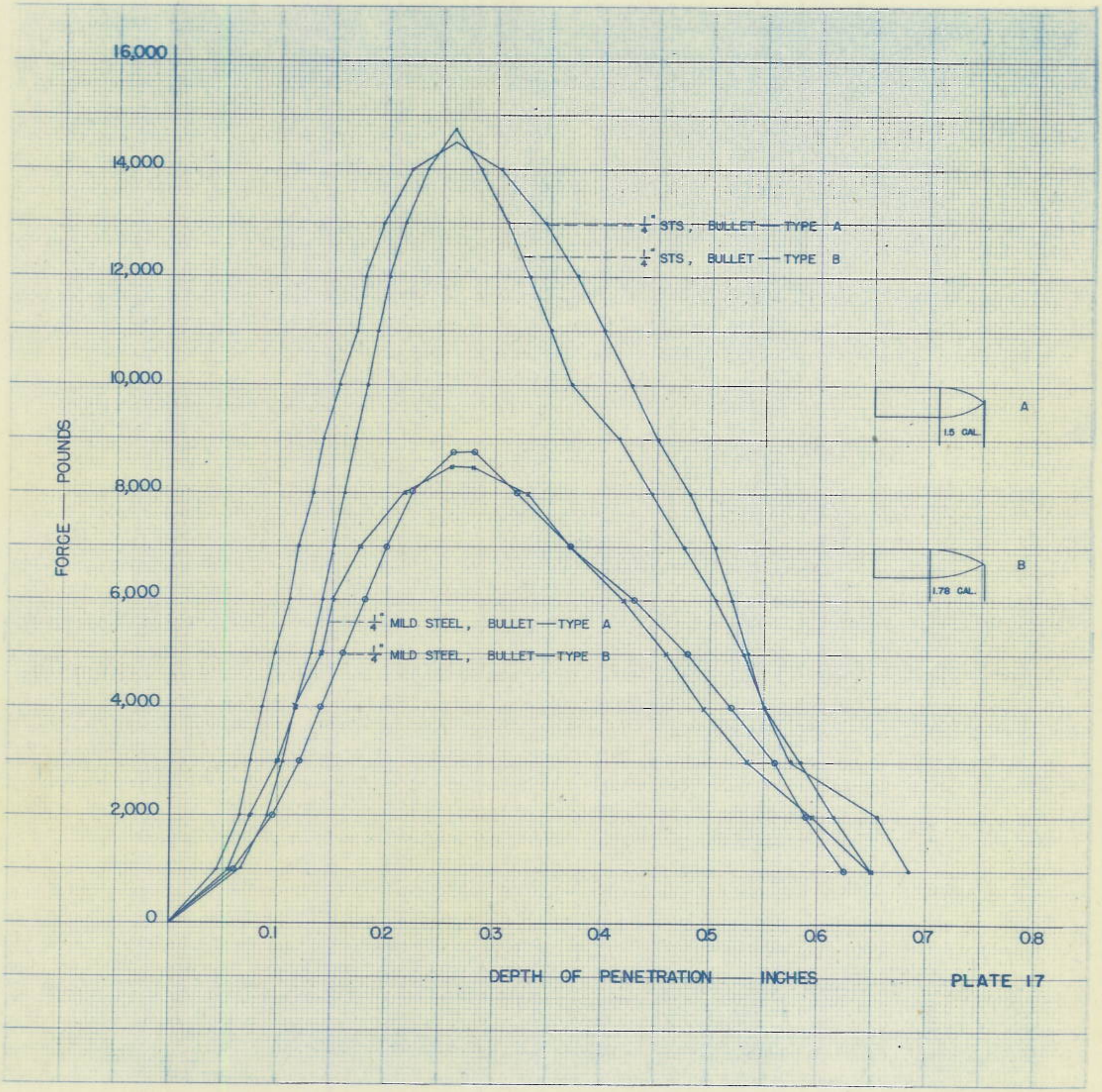


$\frac{1}{2}$" S.T.S.



[redacted]

PLATE 16



16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
0
FORCE — POUNDS
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
DEPTH OF PENETRATION — INCHES
1/4" STS, BULLET — TYPE A
1/4" STS, BULLET — TYPE B
1/4" MILD STEEL, BULLET — TYPE A
1/4" MILD STEEL, BULLET — TYPE B
A
1.5 CAL.
B
1.78 CAL.

PLATE 17

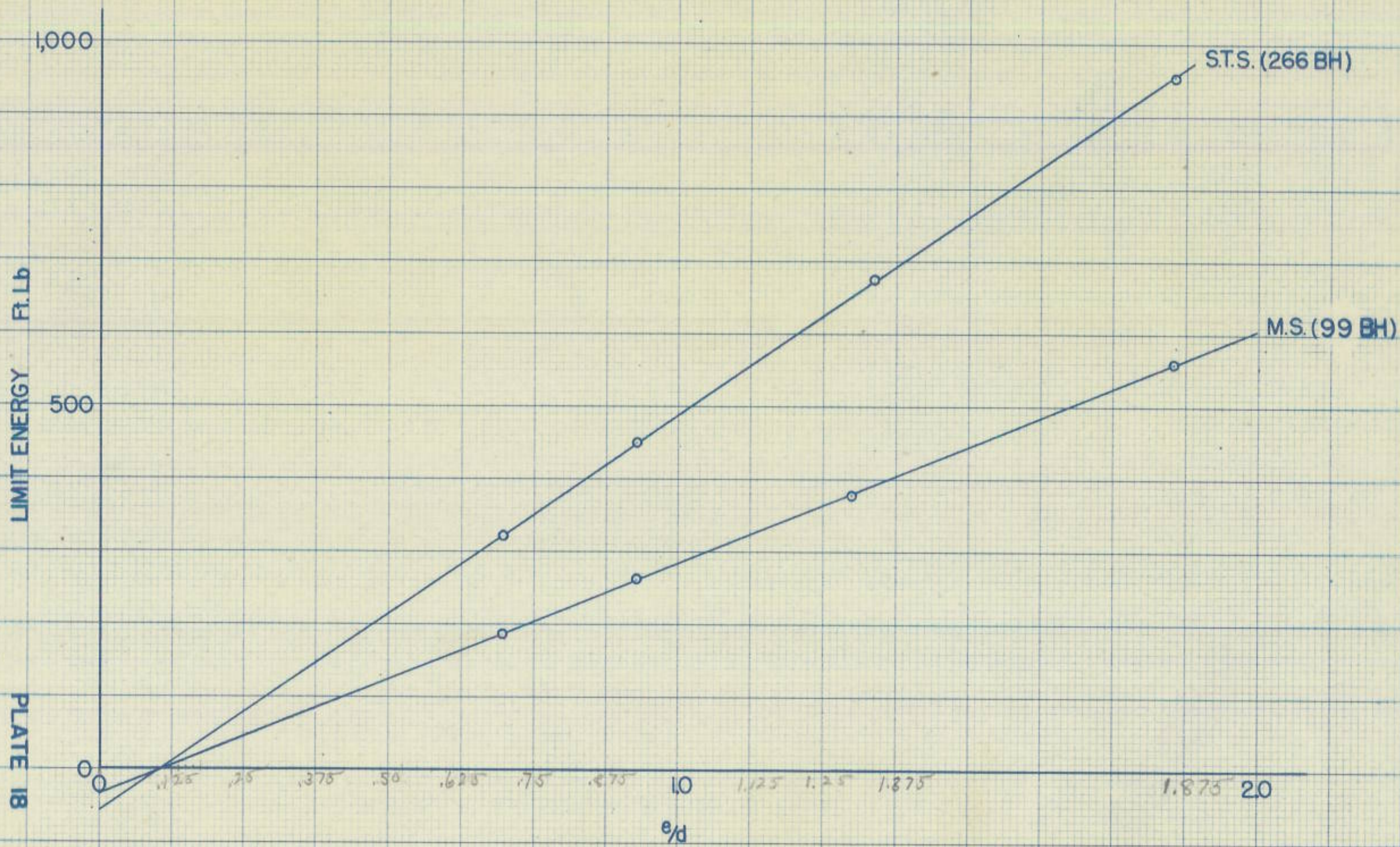


PLATE 18

[redacted]