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The penetration of targets by long rod projectiles [C]

D. F. T. Winter, M.A.

PD 13921

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The penetration of targets by long rod projectiles

4 D.F.T. Winter, M.A. (D4)

5 - September 1969

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Summary

Previous theoretical and experimental work on penetration by long rod projectiles is reviewed, and some parameters of importance are identified. Experiments at R.A.R.D.E. are described which include perforation of steel targets by high velocity rods, illustration of the dynamics of the penetration process, and the comparison between steel and tungsten carbide as rod materials.

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List of Symbols

B	Brinell hardness number
d	rod diameter
l	rod length
p	penetration
R	resistance of target
t	thickness of target
v	velocity of bottom of crater
V	initial rod velocity
W	weight of rod
Y	dynamic yield strength of rod
α	inclination of rod to line of flight
θ	inclination of target face normal to line of flight
ρ	density
σ	square root of density ratio

Subscripts

c	consumed (length of rod)
L	penetration limit (velocity)
p	projectile (rod)
t	target

1. INTRODUCTION

As a part of a broad programme to investigate the basic processes which occur when a high velocity projectile penetrates a target, a study has been made of the behaviour of long rod projectiles. There would appear to be several advantages in the development of an armour piercing projectile which has a higher length to diameter ratio and flies faster than the present A.P.D.S. shot, and several aspects of the external and terminal ballistics of such shapes are being examined. This paper deals specifically with the terminal ballistics of long cylinders against targets with normal and inclined faces.

When a long rod projectile is accurately aligned, the whole of its kinetic energy is concentrated over a small cross-section of the target face: the resulting crater is narrow but deep. For practical applications it is clearly necessary to perforate the target, but for comparative studies it is frequently valuable to fire into thick targets, particularly when it is not possible to control the projectile velocity accurately. Every firing where the projectile reaches the target in the correct attitude is then capable of producing a result, in contrast to the involved process of determinging ballistic limits which involve many firings at nearly identical conditions.

This paper first reviews some previous theoretical and experimental results, and then describes some experiments at R.A.R.D.E. Apart from the thick target results which form the main data, there is some information on perforation, and also on the dynamics of the penetration process.

2. REVIEW OF PREVIOUS WORK

Some of the important contributions to the study of the penetration of long rod projectiles are listed in refs. 1 to 26. In the review which follows, the author has made full use of an earlier survey by Miss E. Mann (ref.27).

2.1 Theoretical predictions

The mechanisms by which projectiles penetrate armour plate have been studied for many years. Papers such as those by Hill (refs. 1 and 2) helped in the understanding of the hole shapes found in armour, and the whole subject was comprehensively reviewed by an Ordnance Board working party in 1950 (ref.3).

There are however, certain aspects of the penetration by long rod projectiles which are unique, and the main factor is the high proportion of the penetration which is free from end effects. During this phase, the rod may be treated as part of a very long jet, and steady state formulae may be derived. The second factor applies mainly at high velocities, where the rate of momentum cha change is so large that the pressure generated is far in excess of the strength of the materials involved. This leads to the so-called hydrodynamic approximation, and the theoretical approaches to be reviewed generally make use of this approximation in some way.

The hydrodynamic approach in its simplest form considers the penetration of a small jet into a larger one. If the penetration velocity is v and the jet velocity is V, then the pressure at the interface between the jets is given by Bernoulli's equation:

$$\tfrac{1}{2}\rho_t v^2 = \tfrac{1}{2}\rho_p (V - v)^2$$

where ρ_t is the density of the target (large jet)
ρ_p is the density of the projectile (small jet)

It is easy to see that the depth of penetration p is related to the projectile length l by

$$p/l = \frac{v}{V - v}$$

and defining $\sigma^2 = \rho_p/\rho_t$ we have

$$p/l = \sigma$$

Allen and Rogers (ref.7) introduced a term into Bernoulli's equation in an attempt to make the relation fit experimental data at lower velocities. They took the velocity v_o at which the projectile would just fail to make a mark on the surface of the target, and suggested that the pressure generated at the surface in this case ($\tfrac{1}{2}\rho_p v_o^2$), being considered as a yield criterion, should be subtracted from the pressure available for penetration. Thus

$$\tfrac{1}{2}\rho_t v^2 = \tfrac{1}{2}\rho_p (V - v)^2 - \tfrac{1}{2}\rho_p v_o^2.$$

It was assumed that the whole penetration process occurred in the steady state phase of the motion, so that the depth of penetration is now given by

$$p/l = \frac{\sigma(\sigma - y)}{\sigma y - 1}$$

where $y = \left(1-(1-\sigma^2)\dfrac{v_o^2}{V^2}\right)^{\frac{1}{2}}$

For most materials, this equation could be made to fit the experimental results with a discrepancy of less than 5%. However, for gold rods, Allen and Rogers (ref.7), and also Slattery and Clay (ref.5) found deeper penetration than expected. In a co-ordinate system travelling with the velocity v of the bottom of the crater, the jet velocity is V-v and the velocity of the jet reflected from the crater bottom is 2v-V. This is the velocity retained by the mass of the jet when it has used up its entire length, and is termed the residual velocity of the jet; it may be towards or away from the original target surface. Again applying the concept of threshold, or yield, velocity, there will be secondary penetration if $V > v_o (3\sigma^2 + 1)/(\sigma^2 - 1)$.

From this equation it may be seen that secondary penetration at readily obtainable velocities will only occur if the density of the projectile is sufficiently greater than that of the target, as in the case of a gold jet into an aluminium target where the lowest velocity at which secondary penetration was observed by Allen and Rogers was 5,800 ft/sec.

For the case of heavy rods and low velocities, Allen and Rogers (ref.9) used the equation:-

$$v(\sigma^2 - 1) = \sigma^2 (V - v_o)$$

Tate (ref.26) has applied similar ideas, but has attempted to give some physical explanations for the factor introduced empirically by Allen and Rogers. Tate writes the modified Bernoulli equation as

$$\tfrac{1}{2} \rho_t v^2 + R = \tfrac{1}{2} \rho_p (V - v)^2 + Y ,$$

where R is the minimum pressure which will just force a hole through an infinite expanse of the material, and is assumed to be independent of position within the material and of impact velocity. Y is the minimum pressure in the rod for hydrodynamic behaviour, below which the rod is assumed to be rigid.

Unlike Allen and Rogers, Tate analyses the motion, and produces some particular solutions of interest. The most encouraging of these is the dynamic behaviour of an impact situation which has been observed experimentally at R.A.R.D.E., and which will be described in section 3.3.2 of this paper. The reader is referred to Tate's paper (ref.26) for details of the formulae derived.

Christman and Gehring (ref.18) have followed another approach to allow particularly for the known tendency to form hemispherical craters when comparatively short rods are fired at very high velocity. In their paper it is assumed that the rod acts in two ways: (a) nearly all the rod is consumed in penetration according to the basic theory, but (b) a portion of rod equal in length to the rod diameter forms a hemispherical crater as though it were at the target surface. This yields the empirical formula

$$p = (l - d)\, \sigma + 2.42\, d\, \sigma^{2/3} (\rho_t V^2/B)^{1/3}$$

where d is the rod diameter and B the Brinell hardness as measured immediately below the bottom of the crater.

Some work, more particularly on oblique impact, has been done at C.A.R.D.E. (refs.14 and 21). Brooks (ref.14), using Wall's theory for hypervelocity penetration, has shown theoretically the relative importance of small yaw angles on penetration depth. He also points out that indefinite increase in the length of a projectile will not necessarily lead to a continuing improvement in efficiency, because as the time for penetration at any given incident energy increases with the length of the rod, so does the time available for deformation of the projectile. This may lead to the formation of a crater larger in diameter and smaller in depth than would otherwise be expected.

Wilms and Brooks (ref.21) have considered the stresses in a projectile immediately after impact, assuming that the projectile remains intact. This problem is of course vital to the perforation of armour at low speed, although it is unlikely that this mechanism can be used with high velocity impacts because strong enough materials are unobtainable.

These theoretical papers indicate some of the possible parameters of importance in long rod penetration. There is as yet, however, insufficient understanding of the relative importance of the parameters to make definite tests, and over the years a substantial amount of empirical data has accumulated. This will now be reviewed.

2.2 Experimental data on long rod performance

Although some authors have considered other factors as well, the main interest in long rod projectiles lies in their ability to perforate armour. A series of reports from Frankford Arsenal (refs. 4, 11, 20, 22 to 24) has produced a considerable amount of information on the attack of specific rolled homogeneous armour, having a Brinell hardness of about 300.

Curtis et al (ref.4) fired projectiles made from drill rod into targets inclined at 60°, to the normal to the line of flight with projectile velocities up to 7,000 ft/sec. and length/diameter ratio up to 17. They found that

$$WV_L^2/d^3 = 1.86 \times 10^7 (t/d - 0.73) [1 + 0.15 (l/t)^2]$$

where W is the projectile weight (lb)

V_L is the perforation limit velocity (ft/sec.)

d is the rod diameter (inches)

t is the target thickness

l is the rod length.

Kymer and Baldini (ref.11) extended the range of results to include length/diameter ratios up to 30 and targets at normal as well as inclined incidence. Unlike Curtis et al (ref.4), they do show some effect of scale a projectile four times as heavy with the same shape perforating only 1.2 times the thickness of armour, i.e. only 75% of the relative thickness. Effects of varying length/diameter ratio do appear to follow the trend shown by Curtis, and the thickness perforated at normal incidence is roughly twice the thickness at 60° to the normal.

By 1966, Kymer (ref.20) had produced results ranging from normal to 70° to the normal incidence, with projectiles of length/diameter ratios between 3 and 13.2. He gives a correlation formula similar to that of Curtis except in the method for dealing with target thickness, and claims this is accurate to 4% in the range studied. The formula is

$$WV_L^2/d^3 = 2.45 \times 10^6 (t/d)^{1.69} (\sec\theta)^{1.52} [1+0.6(l/t \sec\theta)^2]$$

where θ is the obliquity or angle between the normal to the target surface and the line of flight and the other symbols are defined above.

Over the range considered, the two formulae differ by a maximum of about 30%. Kymer comments that projectile yaw greater than 3° affects the results significantly.

Kase and Fatzinger (ref.22) have tested tungsten carbide as well as steel drill rod. The tungsten carbide projectiles are superior to steel of the same weight and shape, except that long projectiles above 4,000 ft/sec. are susceptible to fracture during launch. They are also very much less efficient at angles of yaw above 3°. As with Kymer (ref.11), Kase and Fatzinger found that large projectiles are relatively less efficient than small ones.

The two other papers from Frankford Arsenal (refs. 23 and 24) contain comparisons of several materials and general conclusions cannot be drawn. The comment is made in ref.23, however, that there is little difference between steels of two hardnesses, or between projectiles of different head shapes, at velocities of about 4,000 ft/sec.

Ricchiazzi et al (ref.6) fired two types of rod-steel and Mallory metal. The Mallory rod was twice as heavy as the steel, and perforated armour twice the thickness of that perforated by the steel projectile at the same velocity (4,200 ft/sec.). The length of the steel rod was four times the thickness of armour perforated, and this puts it well outside the range of experimental data from Frankford; nevertheless it is rather surprising that the ballistic limit velocity differs by 40% from that given by Kymer's formula.

Grabarek and Herr (ref.10) fired steel and tungsten carbide rods, with length/diameter ratios from 10 to 40 and weighing between one and two pounds, at velocities up to 7,300 ft/sec. Various targets were used at 60° obliquity, and a typical result is that a tungsten carbide projectile enclosed in a steel sheath, total weight 1.36 lb. and length/diameter ratio of 25 just penetrated 6 in. of RH armour at 7,025 ft/sec. This would appear to agree with the order of Curtis' and Kymer's results. Grabarek and Herr stress the importance of projectile hardness. Replacing steel projectiles by tungsten carbide of the same weight reduced the ballistic limit velocity by 10-15%.

Slattery and Clay (ref.5) fired aluminium spheres at 8,500 ft/sec. at fixed rods of various materials and diameter 0.001 to 0.1 in. (length/diameter ratio very large). From the spheres, which were subsequently recovered and examined, it was found that the penetration was given by the empirical formula

$$p = l_c \, \sigma^{2/3}$$

where l_c is the length of rod consumed, and the other symbols have been defined above. This conclusion is for one velocity only, and does not necessarily contradict the high velocity result that $p = l \, \sigma^{1/2}$, or Tate's equations (ref.26), since for any material there is a relation between density and strength which may give the appearance of being a power law. It is well known, however, that the fitting of a power law to data is very inaccurate.

Slattery and Clay found that the type of crater formed was critically dependent on both the mass of the rod and the velocity of sound in the rod material. Subsonic velocities were observed to produce craters with a conical bottom and supersonic velocities to produce cylindrical craters, as was also noted by Hill (ref.2). This is because the shock wave in the rod can initiate lateral motion in the case of subsonic impacts.

Nysmith, Summers and Denardo (refs. 12 and 19) also fired aluminium spheres at long copper filaments, in this case at velocities about 15,000 ft/sec. They found that deep penetration occurred when the rod was inclined within 4° to the line of flight, but later in ref.19 they fitted all the results by the single formula

$$\frac{p}{l} = \sigma \left[1 + 0.01 \left(\frac{l}{d}\right)^{3/2} \alpha^{2/3}\right]^{-1}$$

where α in radians, is the inclination of the rod axis to the line of flight. (This does not produce the same effect as having the target surface inclined, as in Kymer's work, for instance).

The group of papers from General Motors Defense Research Laboratories (refs. 16 to 18) all show penetrations which are greater than the simple jet theory would predict. The formula and explanation given in ref.18 have already been quoted in the theoretical section. Also of significance in ref.18 is the illustration of penetration by X-ray photography. The similarity to jet action in penetration was also noted by Clayden (ref.8) who commented that even at low velocity, an aluminium rod appeared to have flowed back round the edge of the crater. A later observation by Hickey(ref.25) shows that the outside shape of the rod affects the formation of the crater; he found that a threaded section of rod had become engaged on the edge of the crater. (A similar observation for short projectiles had been made by Cable, ref.28).

3. EXPERIMENTAL WORK AT R.A.R.D.E.

3.1 Apparatus

Rods which were basically $\frac{1}{4}$ inch in diameter and between $1\frac{1}{4}$ and $2\frac{1}{2}$ inches long, mostly stabilised by means of conical afterbodies were fired from the R.A.R.D.E. light gas launcher (ref.29) using 1 inch diameter sabots (fig.1). The launcher is a two-stage gun, in which helium at 4,000 p.s.i. drives a polythene piston weighing 3.7 lb. into a 5 inch diameter tube, 21 feet long, compressing gas initially at 150 p.s.i. pressure to drive the sabot. Variations in projectile velocity were achieved by selecting the molecular weight of the gas, from 2 (hydrogen) to 28 (nitrogen), the lighter gas giving higher velocity. The peak pressure during the compression stroke rises to about 200,000 p.s.i. with corresponding high gas temperature, and the gas drives the sabot weighing about 0.1 lb. down a 1 inch diameter barrel 8 feet long. The resulting velocity is up to about 9,000 ft/sec. with the long rod projectiles, though velocities of up to 18,000 ft/sec. may be reached with lighter projectiles.

When the sabot emerges from the barrel into air at about atmospheric pressure, the sabot pieces start to separate and are trapped on a disc having a small hole through which the rod passes. After the sabot pieces have been removed, the rod passes through two microwave beams. Each acts as a trigger to a Flexitron Model 525 flash X-ray head, which produces a shadow photograph of the rod in flight. Fiduciary marks enable the velocity to be calculated when the time between the flashes has been measured. The photographs also indicate that the rod is undamaged and flying true. After a total flight of 40 feet, the rod hits the target.

For some experiments on the dynamics of penetration, the flash X-ray units were mounted as in fig.2 and triggered after a suitable delay from the rod making contact across a foil switch at the target face. In this experiment and in the first experiment with finite targets, pre-impact velocity was determined by contact switches, and this gave an accurate velocity measurement when they functioned. The microwave triggers were more consistently reliable however.

A summary of the specifications of the materials used as rods and targets is given in Table 1.

3.2 Experimental programme

Three main series of tests have been done at R.A.R.D.E. In the first, steel rods of 7 and 10 calibres were fired against finite steel targets, and a critical perforation limit was determined. This is defined in this paper as the condition for which the rear surface of a target starts to crack, but no material is detached - at higher impact velocities than the limit velocity a given thickness of target would spall. For targets which are not perforated, it is possible to say that a target just as thick as the depth of the crater would certainly be perforated, and so to bracket the critical perforation.

The second series of tests was concerned with the dynamics of perforation, and aluminium rods were fired into polythene targets so that the rather weak X-rays being used could penetrate the targets. In order to determine the rod penetration rate over the whole process, the firings were limited to one pre-impact velocity of 5,400 ft/sec. Two photographs were taken per firing, which with the initial data in each case provided a very repeatable set.

In the third series of tests, steel and tungsten carbide rods of 5 and 10 calibres were fired at thick targets, which had faces normal to the line of flight, or at 30° or 60° to this direction. The objects were first to determine the variation of penetration with rod length and density in the region where strength effects were important, and then to find the effect of target surface angle.

3.3 Results

3.3.1 Series 1 - Finite targets

Figs.3 and 4 show the data obtained from the firings described above. In order to define the curve of critical perforation, where the rear surface of the target is cracked but not spalled, it is necessary to join the points so marked "perforated". The lines drawn indicate one possible solution, but their behaviour at the high velocity end cannot be accurately predicted. It would, however, to reasonable to expect a sharp change in the behaviour of the results at target thicknesses greater than the rod length. At the lower end of the velocity scale, the lines must pass through the origin, unlike the data for thick targets where there is still zero penetration at a finite velocity (see for instance ref.7).

Also on figs.3 and 4 are plotted the predictions of Kymer's formula (ref.20). It may be seen that this gives very reasonable correlation over the range of velocities studied.

3.3.2 Series 2 - Dynamics of penetration

The results obtained from firing aluminium and aluminium alloy rods into polythene targets are shown in figs.5 and 6. The results originating from a pair of photographs are indicated by the same letter (a, b, c) and the lines show the behaviour predicted by Tate (ref.26) assuming various values for the resistance of polythene (R). The interpretation of these curves is discussed fully in ref.26, but briefly shows that reasonable values for the strengths of the materials used will allow correlation between theory and experiment.

3.3.3 Series 3 - Penetration into thick targets

Figs.7 and 8 show measurements of depth of penetration which have been obtained from sectioned targets. In the case of inclined target faces, the depth has been measured normal to the face.

Fig.9 shows the reduced results for steel rods. It will be seen that by calculating the penetration in the direction of flight (p sec θ), the angled target results correlate fairly well with the normal target results. Furthermore, dividing the actual depth of penetration by the rod length gives good correlation between 5 and 10 calibre rods. The theoretical curve on fig.9 applies to the case of steels having similar properties for rod and target, and $R/Y = 3$. It might be possible to obtain an even better fit by choosing slightly more realistic material properties.

Fig.10 shows the corresponding tungsten carbide results. Again the correlation between 5 and 10 calibre rods is good, but in this case the angled target face causes difficulty, and considerably less penetration occurs than would be expected from the kind of considerations which have applied to the remainder of this paper. This trouble has been known for many years, of course, (ref.3) and is attributed to the brittleness of tungsten carbide which causes the rod to fail under bending stress at initial impact.

Comparison between steel and tungsten carbide is made in fig.11. It may be seen that as in ref.6 but contrary to initial expectation, the density ratio, rather than its square root σ, provides the correlation here. It is thought that this is also a consequence of the brittle behaviour of tungsten carbide. Ref.15, for instance, quoted a greater penetration than expected for rods which did not flow easily. Nevertheless, for given kinetic energy at the target, a steel rod will be more efficient in general because of its better performance against angled targets.

These conclusions apply specifically to mild steel targets, although section 3.3.1 has shown fair correlation of some results with firings against armour plate.

4. CONCLUSIONS

A review of available theories for long rod penetration has indicated some parameters of importance, but shows also that insufficient is known about the process to enable a definite conclusion to be stated. Empirical formulae have been produced which fit experimental data over limited ranges of materials and velocities.

Experiments at R.A.R.D.E. have shown the following features.

1. In the range of velocities from 3,000 to 7,000 ft/sec, the penetration limit velocity for a steel rod perforating a given mild steel target is not much less than that found elsewhere for armour plate targets of the same thickness.

2. The dynamics of the penetration process may be demonstrated using X-ray photography with aluminium rods and polythene targets, and analysis of the process taking reasonable values for the strengths of materials agrees well with theoretical prediction.

3. Good agreement with theory has been obtained for steel rods penetrating thick steel targets, the effect of inclined target face on penetration along the line of flight being very small.

4. A comparison between the penetration into a normal target by a tungsten carbide rod and a steel rod at the same velocity showed that the tungsten carbide rod penetrated farther by the factor of the ratio of densities of the materials, but that the penetration of a tungsten carbide rod into a target with its face at 60° to normal was only slightly more than the penetration of a steel rod at the same velocity.

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Table 1

Specifications for materials used

Rods

Silver steel (as supplied) to B.S.1407

C 0.95-1.25%	Density
Si < 0.3	
Mn 0.25-0.45	7.82 gm/cm^3
Cr < 0.5	
S < 0.045	
P < 0.045	

Tungsten carbide	Density
Sintered with 12% Co	14.4 gm/cm^3

Aluminium to B.S.1476: E1C/M

Cu < 0.1%	
Si < 0.5	Density
Fe < 0.7	
Mn < 0.1	2.70 gm/cm^3
Zn < 0.1	
Al > 99	

Aluminium alloy to B.S. 1476: HE30 WP (as supplied)

Cu < 0.1%	
Mg 0.4 to 1.4	Density
Si 0.6 to 1.3	
Fe < 0.5	2.70 gm/cm^3
Mn 0.4 to 1.0	
Cr < 0.3	
Zn < 0.1	

Targets

Mild steel to B.S. 970 En 3A

C 0.15-0.25%	Density
Mn 0.4 to 0.9	7.87 gm/cm^3
Si 0.05 to 0.35	

Polythene to B.S. 2782

Density 0.92 gm/cm^3.

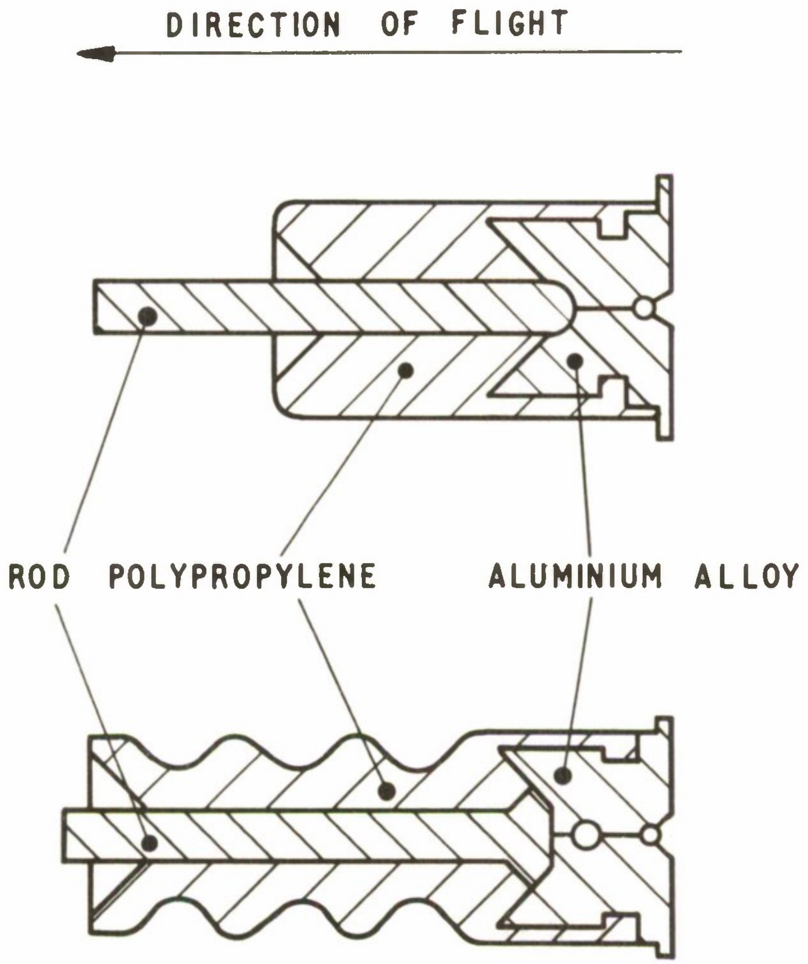
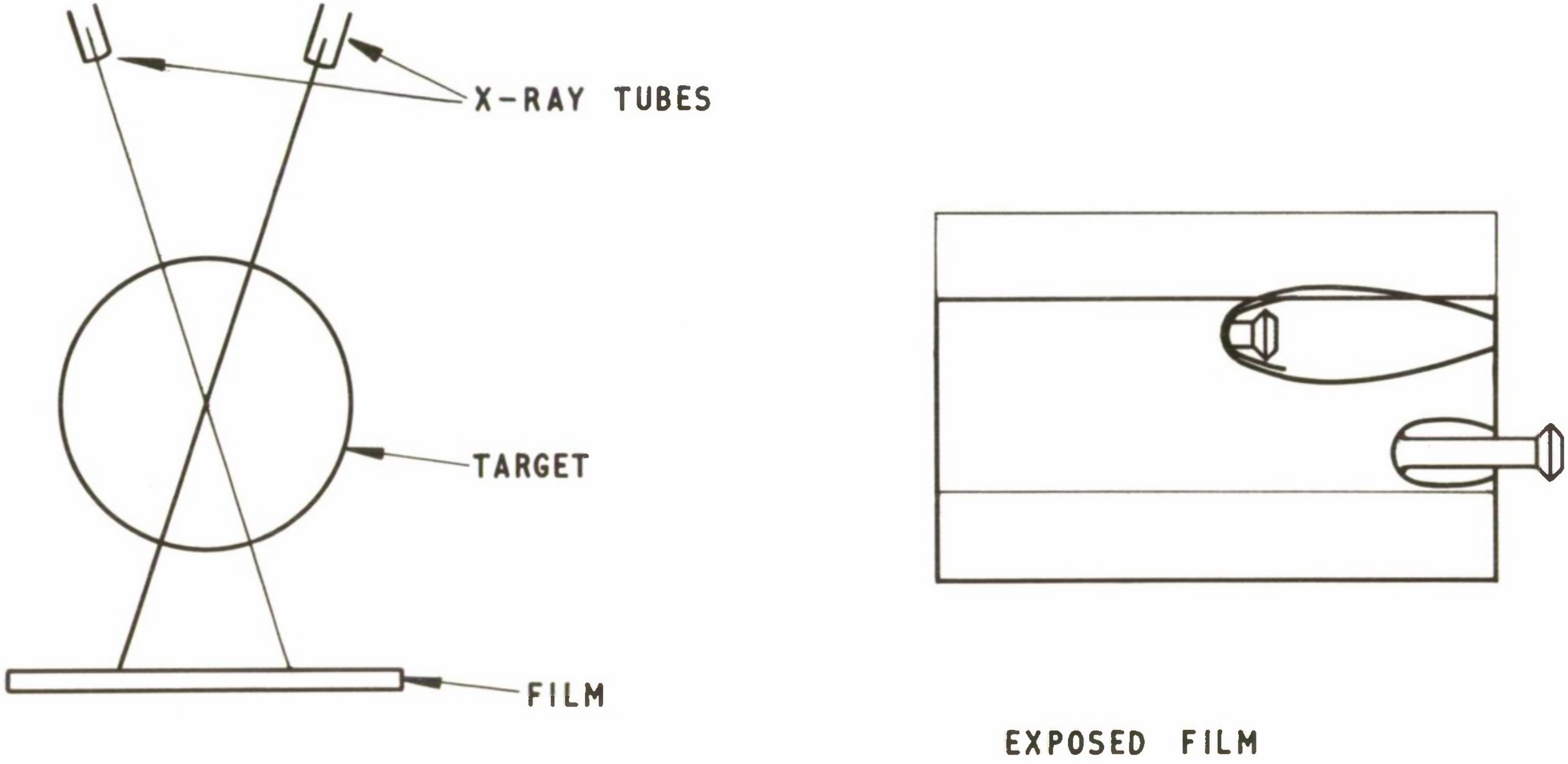


FIG.1 TYPICAL SABOT DESIGNS



ELEVATION

EXPOSED FILM

FIG. 2 ARRANGEMENT OF X-RAY TUBES TO PHOTOGRAPH DYNAMICS OF PENETRATION

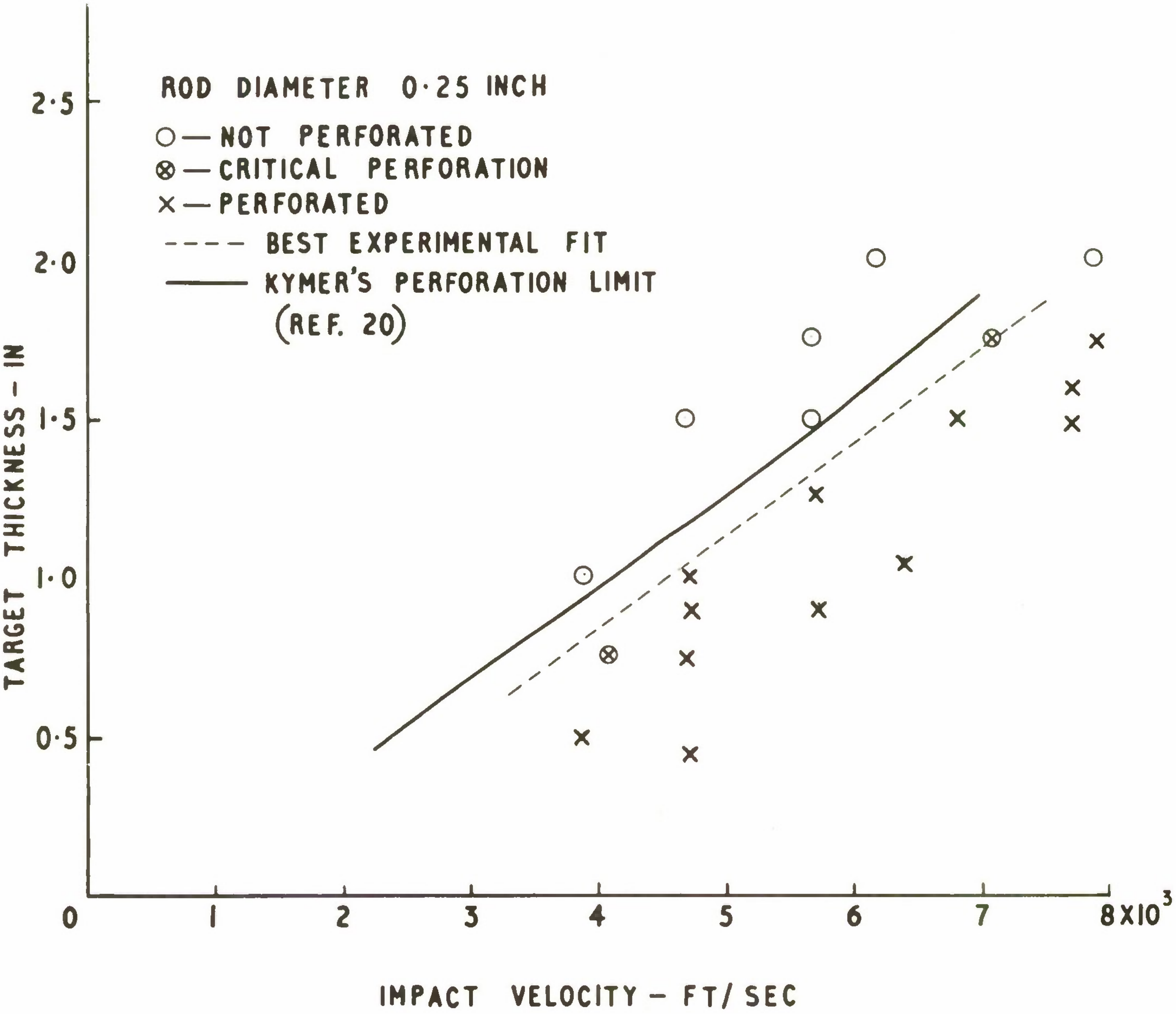


FIG. 3 PERFORATION OF FINITE TARGETS BY 7 CALIBRE STEEL RODS

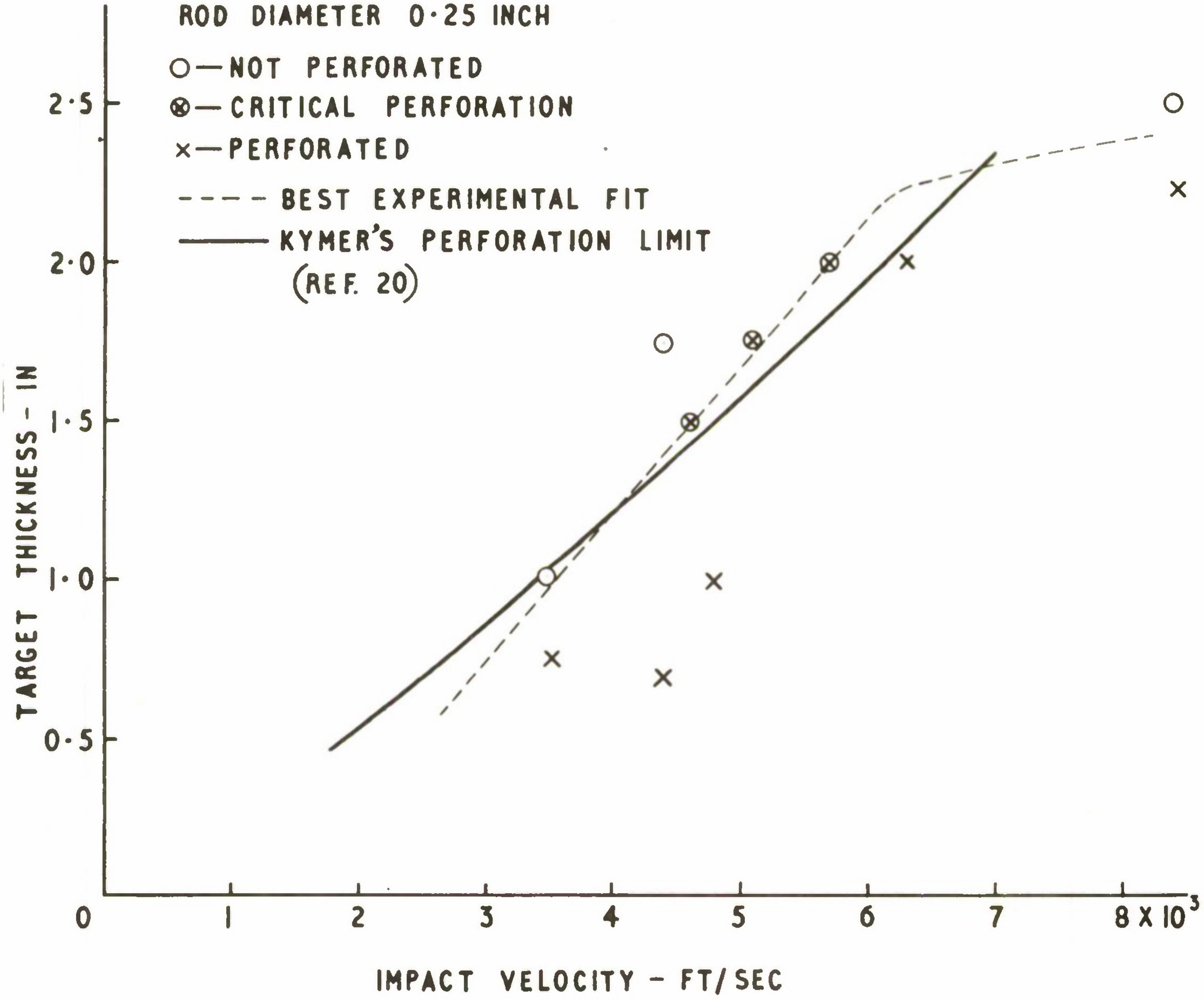


FIG. 4 PERFORATION OF FINITE STEEL TARGETS BY 10 CALIBRE STEEL RODS

FIG. 5

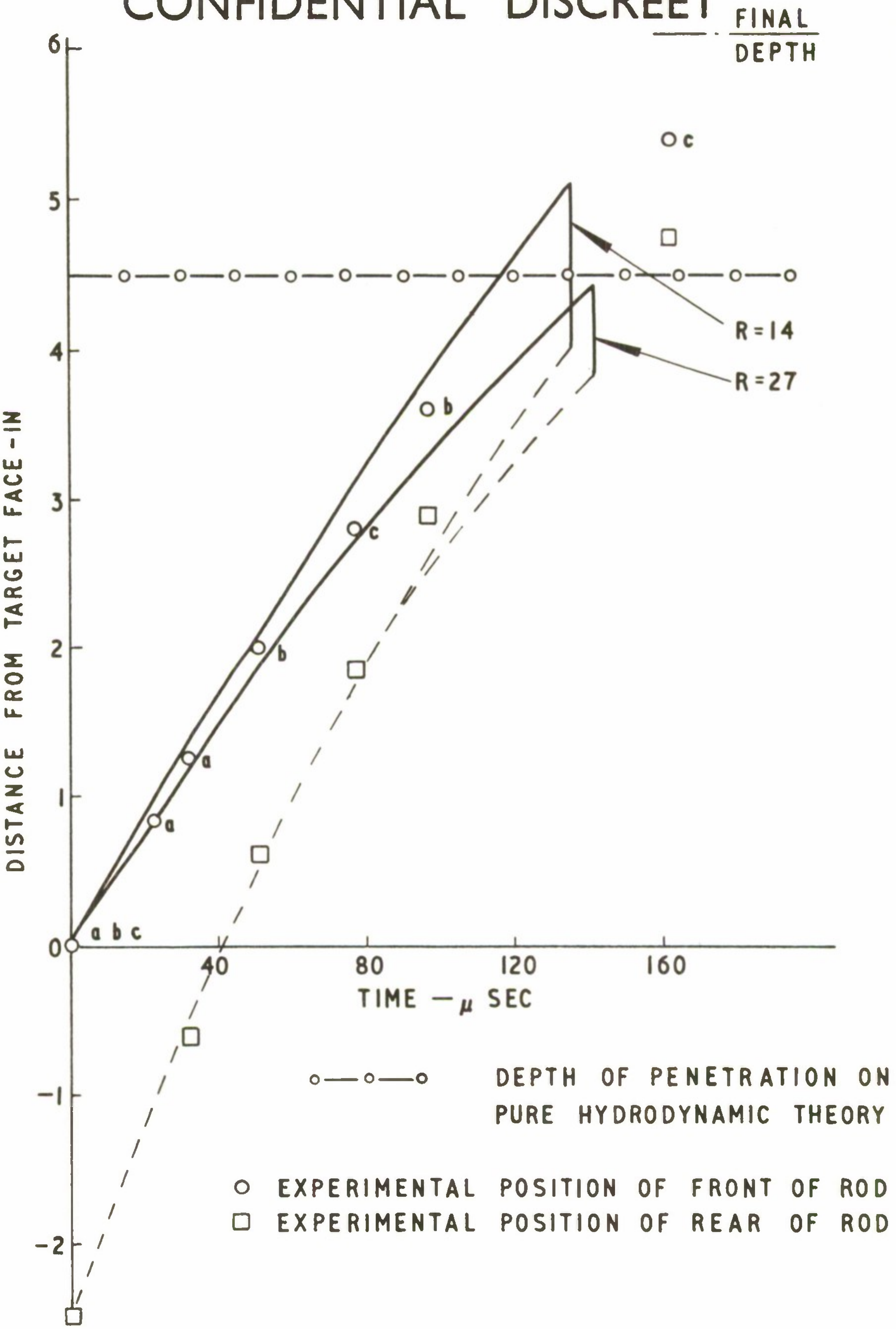


FIG. 5 DURALUMIN SHOT ENTERING A POLYTHENE TARGET AT A FREE FLIGHT VELOCITY OF 5400 FT/SEC

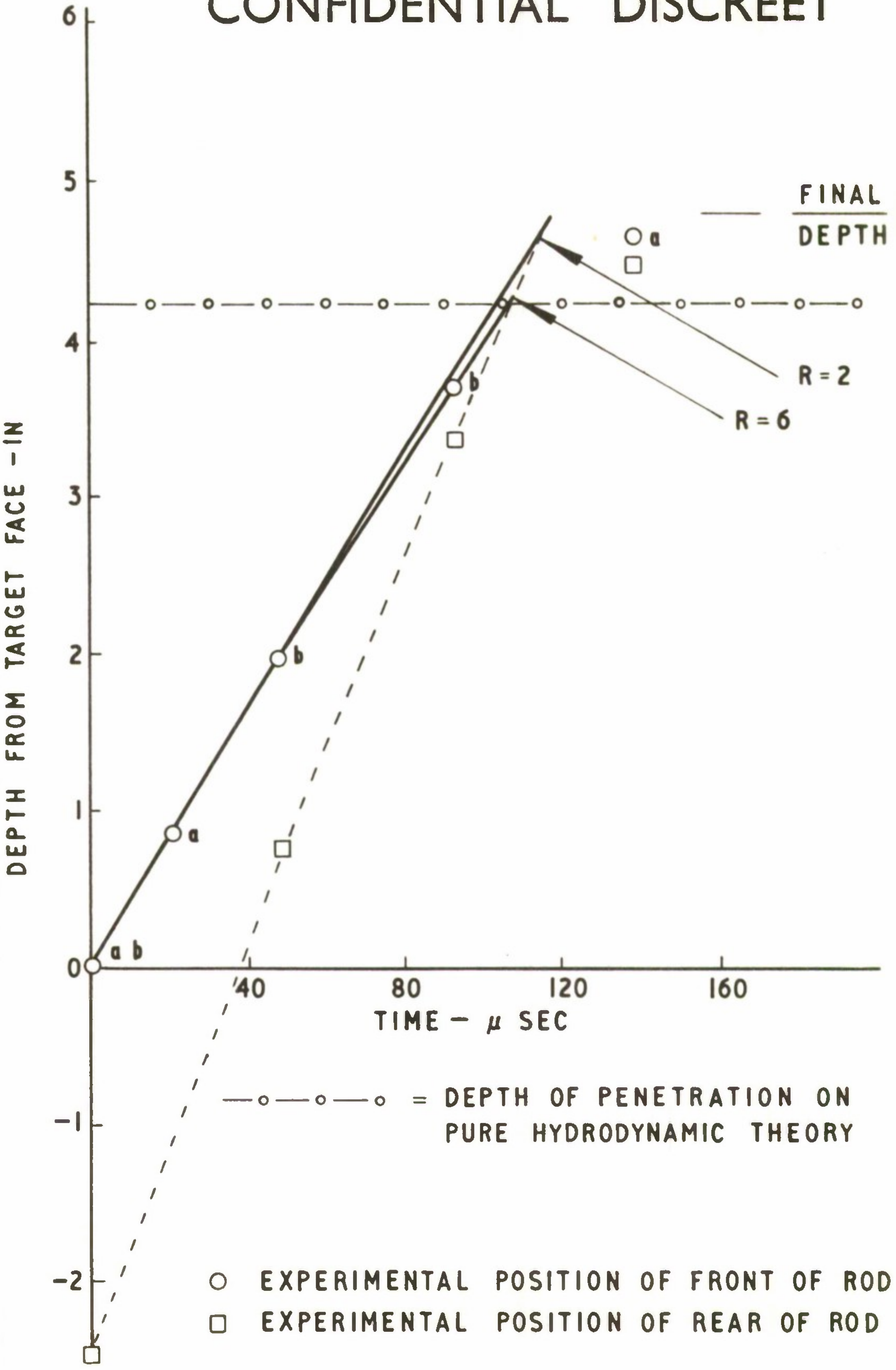


FIG. 6 ALUMINIUM SHOT ENTERING A POLYTHENE TARGET AT A FREE FLIGHT VELOCITY OF 5400 FT/SEC

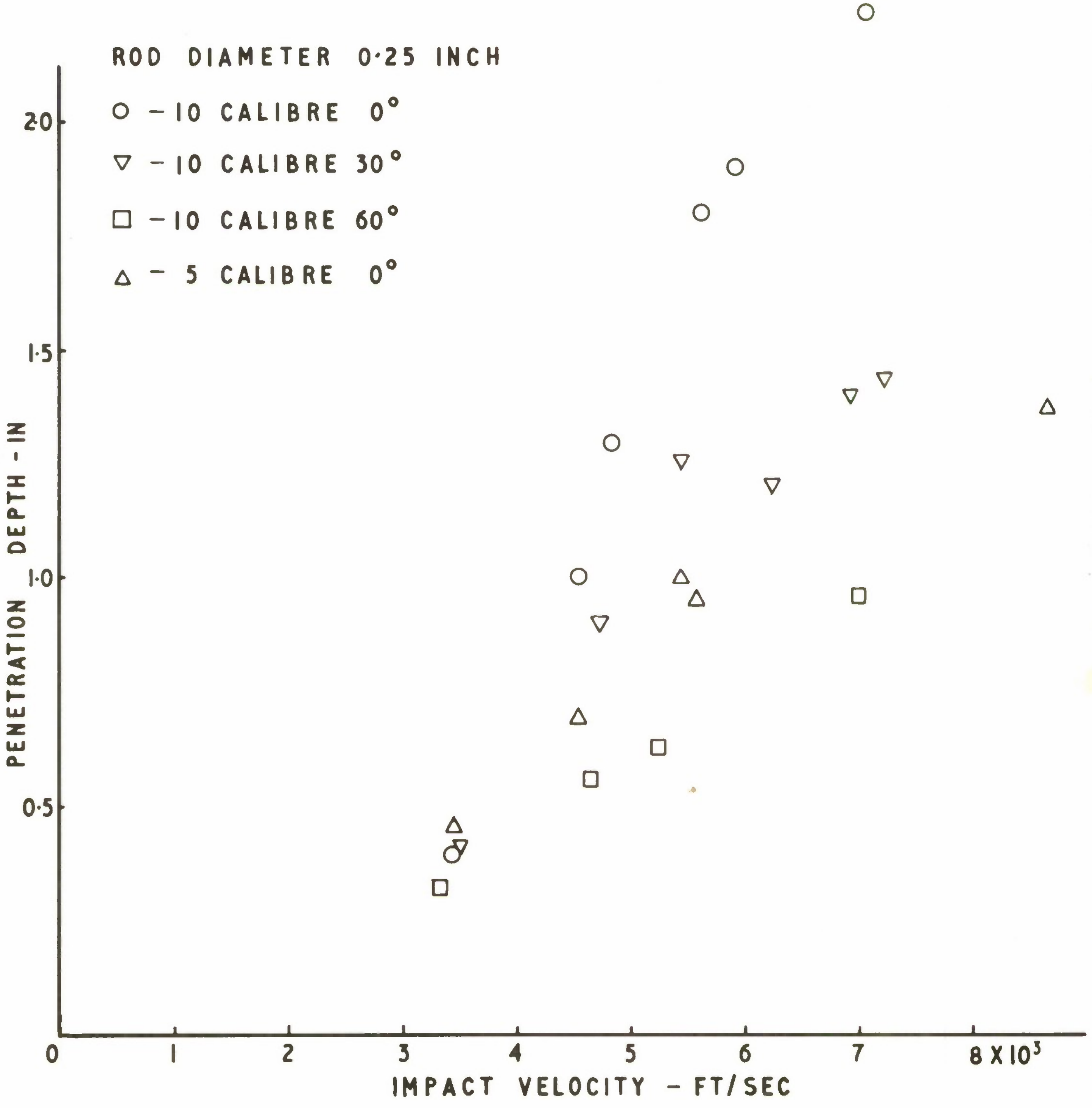


FIG. 7 PENETRATION OF STEEL RODS INTO THICK STEEL TARGETS

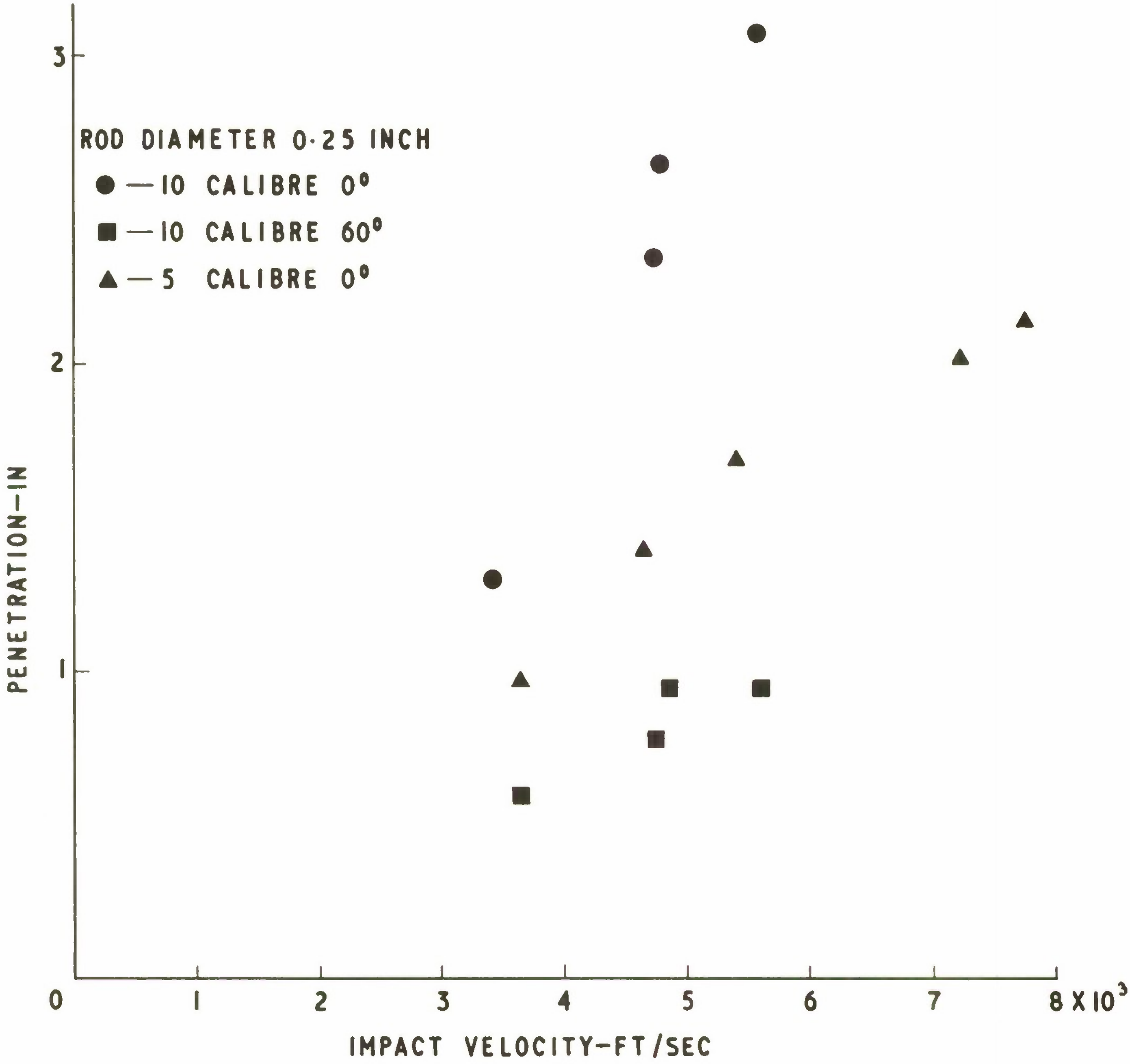


FIG. 8 PENETRATION OF TUNGSTEN CARBIDE RODS INTO THICK STEEL TARGETS

FIG. 9

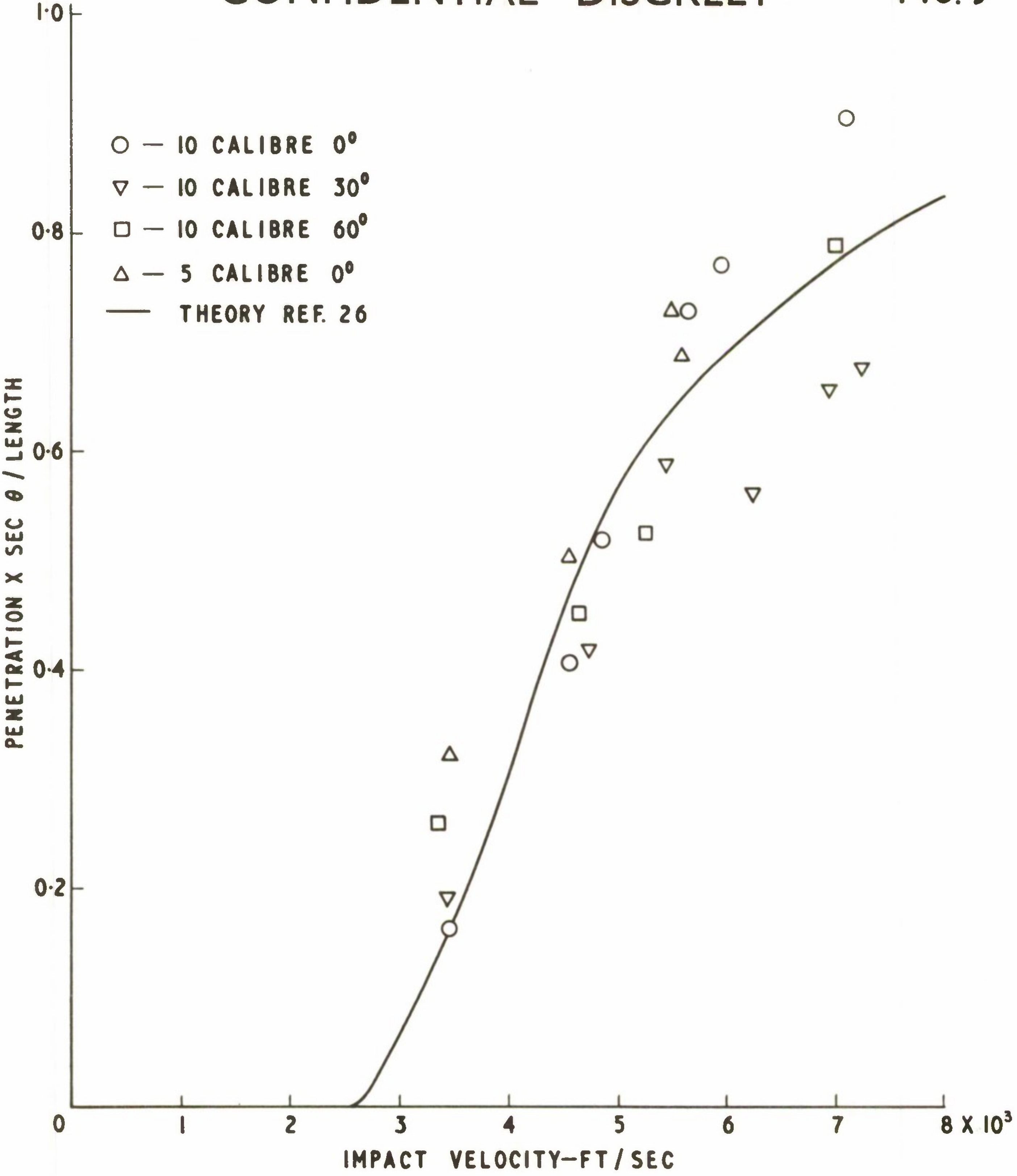


FIG. 9 REDUCTION OF STEEL ROD RESULTS

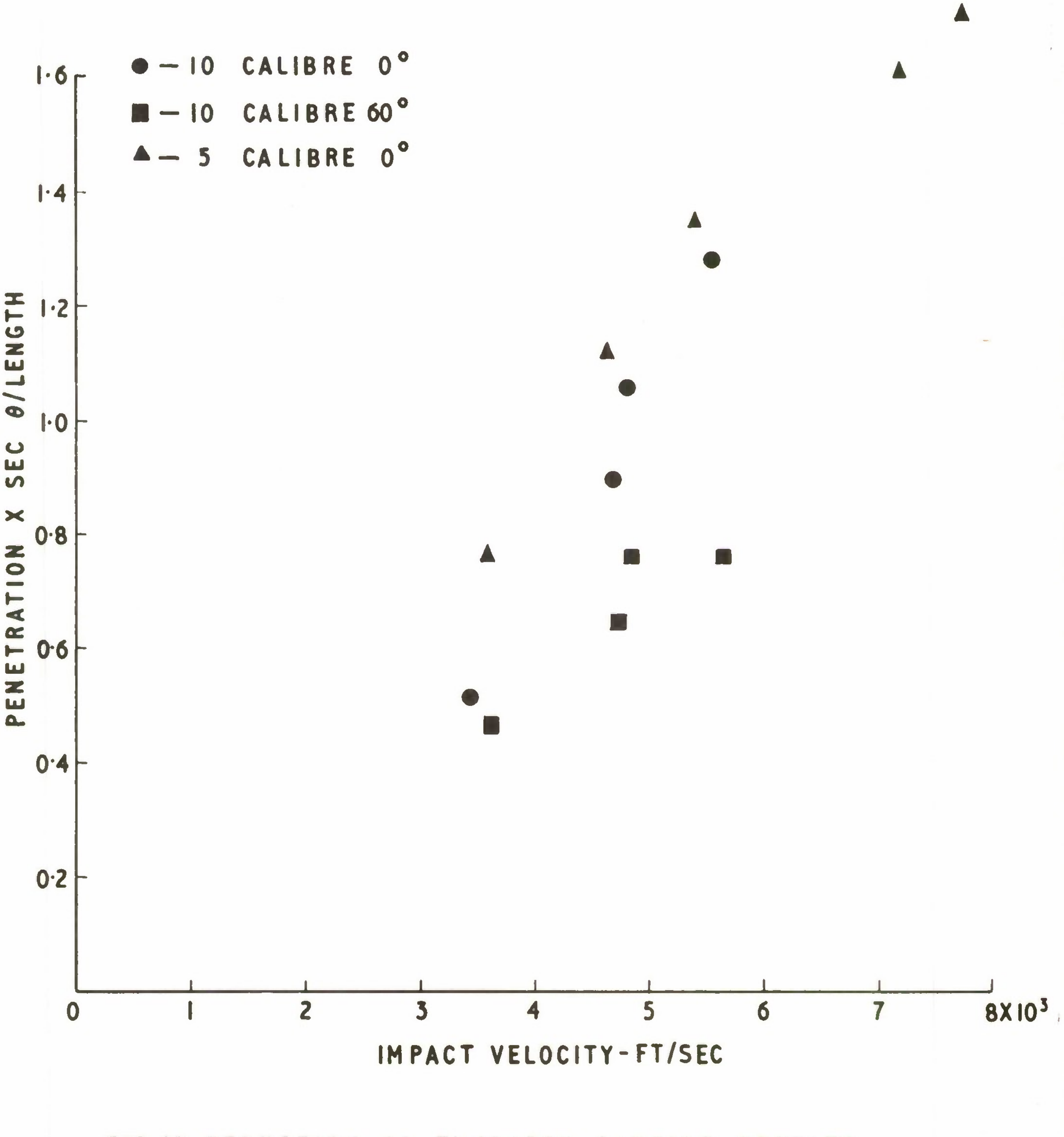


FIG. 10 REDUCTION OF TUNGSTEN CARBIDE RESULTS

FIG. 11

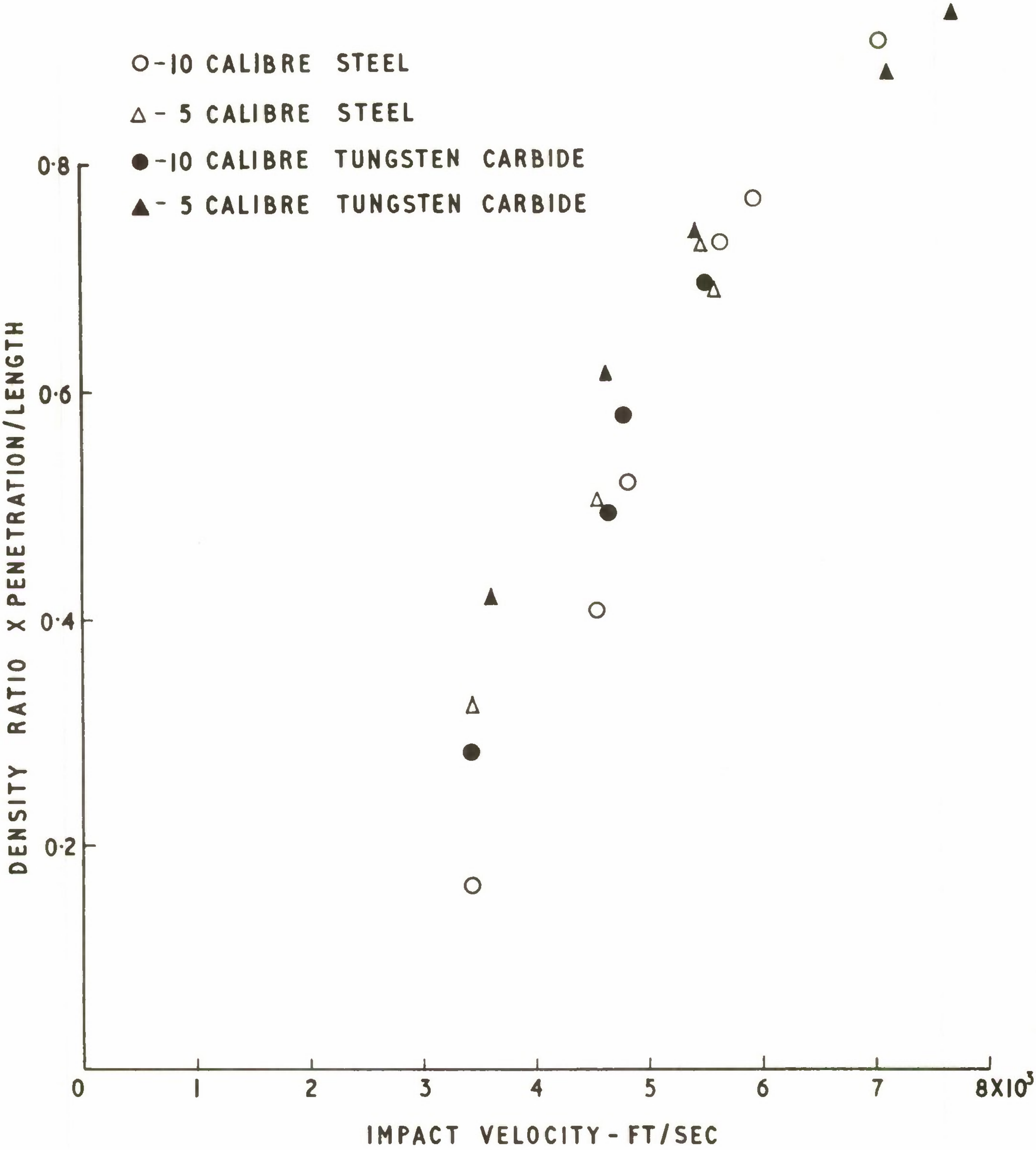


FIG. 11 CORRELATION OF STEEL AND TUNGSTEN CARBIDE RESULTS AT NORMAL INCIDENCE

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The penetration of targets by long rod projectiles.
D. F. T. Winter

September 1969

Previous theoretical and experimental work on penetration by long rod projectiles is reviewed, and some parameters of importance are identified. Experiments at R.A.R.D.E. are described which include perforation of steel targets by high velocity rods, illustration of the dynamics of the penetration process, and the comparison between steel and tungsten carbide as rod materials.

12 pp. 11 figs. 1 tab. 29 refs.

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