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Sabot-Projectiles for Cannon

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(None)

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The attainment and use of high velocity by means of sabot-projectiles is discussed. Stress analyses are given for five different generalized sabot-types, and the stability factor of sub-caliber projectiles and non-spin stabilization are considered. Exterior ballistics of sub-caliber projectiles is discussed and mathematical formulas are given. The performance of sub-caliber projectiles is discussed, and compared with that of conventional projectiles of full caliber. The tactical advantages of high-velocity sabot-projectiles may be grouped as noted, into; decreased time of flight to the target, flatter trajectory, increased range, higher terminal velocity, reduction of gun recoil and versatility of gun performance.

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NATIONAL DEFENSE RESEARCH COMMITTEE

ARMOR AND ORDNANCE REPORT NO. A-234 (OSRD NO. 3010)

DIVISION 1

SABOT-PROJECTILES FOR CANNON

by

W. D. Crozier, H. F. Dunlap, C. E. Hablutzel,

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Approved on November 28, 1943
for submission to the Division Chief

E. J. Workman

E. J. Workman
Technical Representative

Approved on December 1, 1943
for submission to the Committee

L. H. Adams

L. H. Adams, Chief
Division 1
Ballistic Research

CONFIDENTIAL

Preface

This report is pertinent to the project designated by the War Department Liaison Officer as OD-52 and to the project designated by the Navy Department Liaison Officer as NO-26.

The work described was carried out and reported by the University of New Mexico as part of its performance under Contract OEMsr-668 with Division 1, NDRC.

This report is an attempt to summarize, as seen from the viewpoint of the authors, the present state of knowledge of the design and performance of sabot-projectiles for cannon. Its contents were collected during conduct of theoretical and experimental investigations at the University of New Mexico in 1942 and 1943, under the aforementioned OSRD contract with the University of New Mexico.

An attempt has been made to give credit to other investigators working in the same field, but it is certain that not all of their results have come to the attention of the authors, owing, no doubt, to wartime conditions. Some duplication of work has probably occurred. Particular attention has been called to NDRC Report No. A-233 (OSRD No. 2067), which the authors have not seen, describing experiments with sabot-projectiles carried out by the Geophysical Laboratory under Contract OEMsr-51, also under the direction of Division 1. Some personal interchange of information has taken place between the two groups, however.

Acknowledgment. — The authors wish to express their appreciation for the helpful criticism received from J. S. Burlew, C. L. Critchfield, C. W. Curtis, P. A. Fine, J. P. Marble and the members of the Technical Reports Section.

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The NDRC technical reports section
for armor and ordnance edited
this report and prepared it for duplication.

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List of Figures

SABOT-PROJECTILES FOR CANNON

Abstract

This report is concerned with the attainment and use of high velocity by means of sabot-projectiles. The first four chapters include descriptive and design material. The following three chapters deal with the performance of subcaliber projectiles and with comparisons of their performance with that of conventional projectiles of full caliber. Chapter VIII presents performance data on three selected designs of sabot-projectiles.

I. INTRODUCTION

1. Definition of sabot

For the purposes of this discussion a sabot-projectile is considered to be a projectile that separates into two or more parts after leaving the muzzle of the gun. One or more parts, comprising the sabot, are discarded, while the projectile proper proceeds along its trajectory. According to this definition the projectile proper may be either the full caliber of the gun, or it may be subcaliber, though the subcaliber projectile is of more practical interest. The definition excludes projectiles of the type ordinarily used in tapered-bore guns, where nothing is discarded after leaving the muzzle, and it also excludes the "arrowhead" type of projectile.

2. History of sabot-projectiles

It has not been possible, with limited time and resources, to conduct an adequate research into the history of sabot-projectiles, but it is known that the sabot-projectile is not a new weapon. Explosive shell appeared in general use about the middle of the sixteenth century, and cast-iron spherical cannon shell were in use up to 1871. When fired from cannon (as distinguished from mortars) they were fitted with a wooden disk sabot, attached by a copper rivet, intended to keep the fuze central when loading and to reduce the rebounding tendency of the shell as it traveled along the bore on discharge [Fig. 1(a)]. A modification

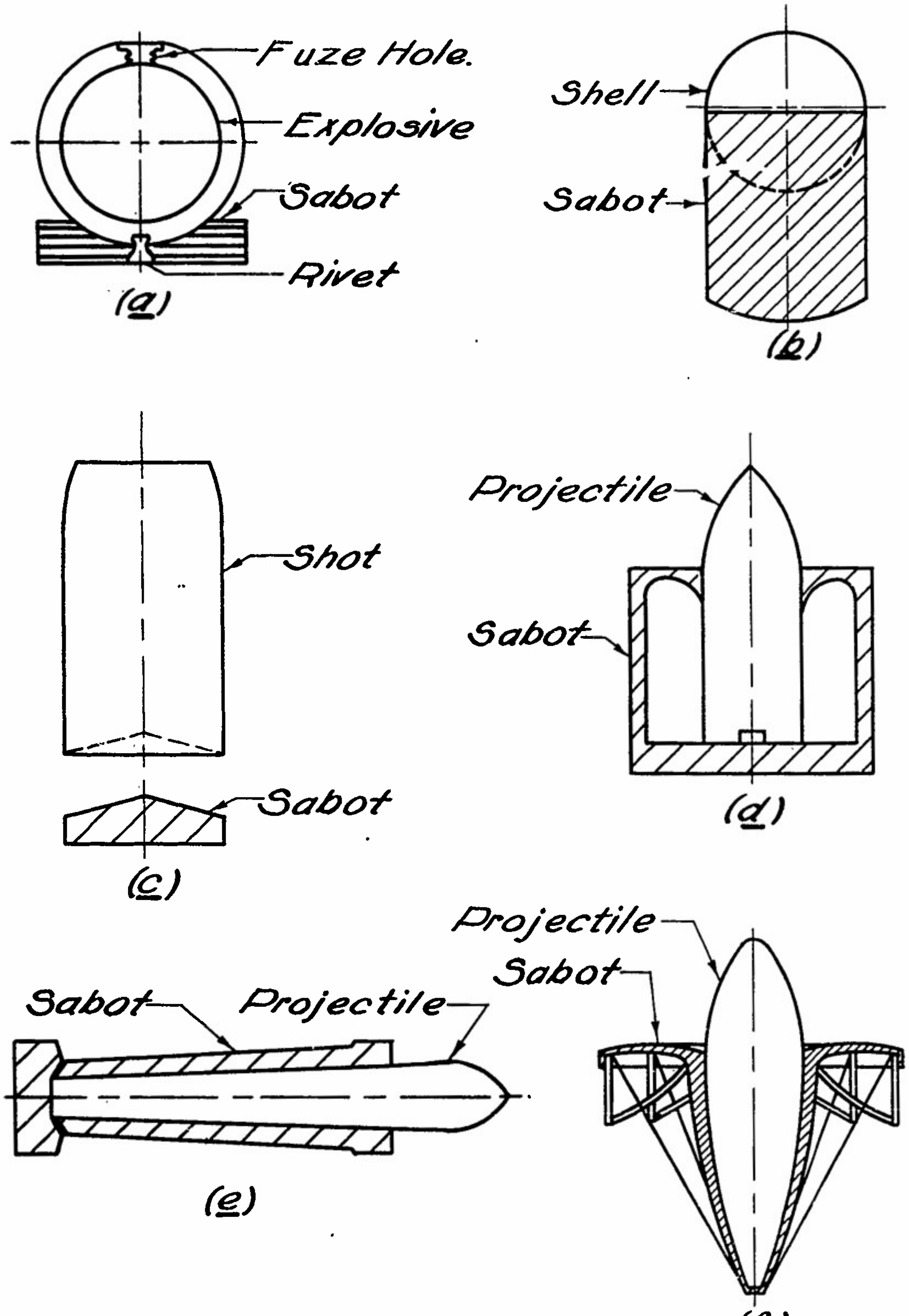

Fig.1. EARLY SABOT-PROJECTILES.

of this type of shell was filled with lead bullets either mixed with or separated by a sheet steel diaphragm from a bursting charge.1/ The Dreyse needle gun, introduced in the Prussian army in 1848, had a wooden block sabot that supported the bullet in the bore but fell off soon after leaving the muzzle. During the American Civil War and the Prussian-Austrian War of the 1860's, sabot-projectiles were in use. These apparently were intended to make possible the use in rifled guns of ball or other shot designed for smoothbore cannon. Bannerman's catalog2/ for January 1938 advertises a 12-pdr. smoothbore cannon shell fitted to sabot [Fig. 1(b)], a 6-in. Civil War parrot solid shot with large copper disk sabot [Fig. 1(c)] and a 6-pdr. shell with wood sabot.

During the first World War the French attempted the use of a 37-mm shell in their 75-mm gun, but with little success. The lack of success is not surprising, since the combination is essentially unstable. This projectile involved a cup-type sabot and depended upon centrifugal force for separation [Fig. 1(d)]. Kent reported unfavorably on the subcaliber projectile in 1942, basing his conclusions on the French 75-37 mm combination.3/ It appears that the French continued experimentation with the subcaliber projectile, as an article in the Wehrtechnische Monatshefte for March 1942 describes a 75-58 mm combination: "After leaving the muzzle the supporting cage spreads apart because of centrifugal force, thus releasing the shell, and then is left behind with the sabot because of high wind resistance."

S. J. Zaroodny in a recent report4/ discusses experiments with a subcaliber projectile that depends on centrifugal force and wind

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1/ See "Ammunition," Encyclopedia Britannica, ed. 11.

2/ Francis Bannerman Sons, 501 Broadway, New York, N.Y.

3/ R. H. Kent, "The performance of subcaliber projectiles compared with that of conventional types," Aberdeen Proving Ground Ballistic Res. Lab. Rept. No. 265, Jan. 9, 1942 (confidential).

4/ S. J. Zaroodny, "Experimental subcaliber AP projectile for the 37-mm Aircraft Gun, M4," Aberdeen Proving Ground Ballistic Res. Lab. Rept. No. 323, Jan. 8, 1943 (secret).

resistance for separation. In this report he lists a number of patents on subcaliber projectiles. In looking over patents on this subject one cannot help but be impressed by the bizarre designs. Although detailed specifications are in general lacking, the illustrations show a complete disregard for the principles of interior and exterior ballistics. In Patent No. 1 368 057, two projectiles using cup-type sabots are shown. The projectiles have such a large length-to-diameter ratio that they appear to be unstable. In one modification the release is effected by wind pressure [Fig. 1(e)]. In the other, it is aided by a time fuze, powder chain and explosive designed to shatter the sabot. Patent No. 2 247 563 covers a teardrop projectile with a cup-type sabot in the form of a web [Fig. 1(f)]. One would anticipate failure in the gun. It is not surprising that many of these designs have aroused scepticism. It is hoped that the present report will demonstrate that sabot-projectiles can be designed which have real and important tactical advantages.

3. Purpose of sabot-projectiles

The purpose of the modern sabot-projectile, as well as of the arrowhead and tapered-bore types just mentioned, is through reduction of projectile mass to attain higher useful muzzle velocities than are attainable with conventional projectiles fired from conventional guns. The mere attainment of high velocity is not particularly difficult, but high velocity alone is of no practical value. It is necessary that the projectile also have such useful characteristics as a high ballistic coefficient, satisfactory armor penetration, satisfactory stability, and ease of manufacture. In the attainment of these features is found the principal interest and importance of the problem.

4. Relation between projectile mass and attainable velocity

Figure 2 is a typical ballistic drawing in which the ordinates are pressures and the abscissas are distances of the projectile from the starting point, measured along the bore of the gun. The ordinates of line A represent theoretical limiting pressures determined by the strength of the gun barrel as the projectile moves along the

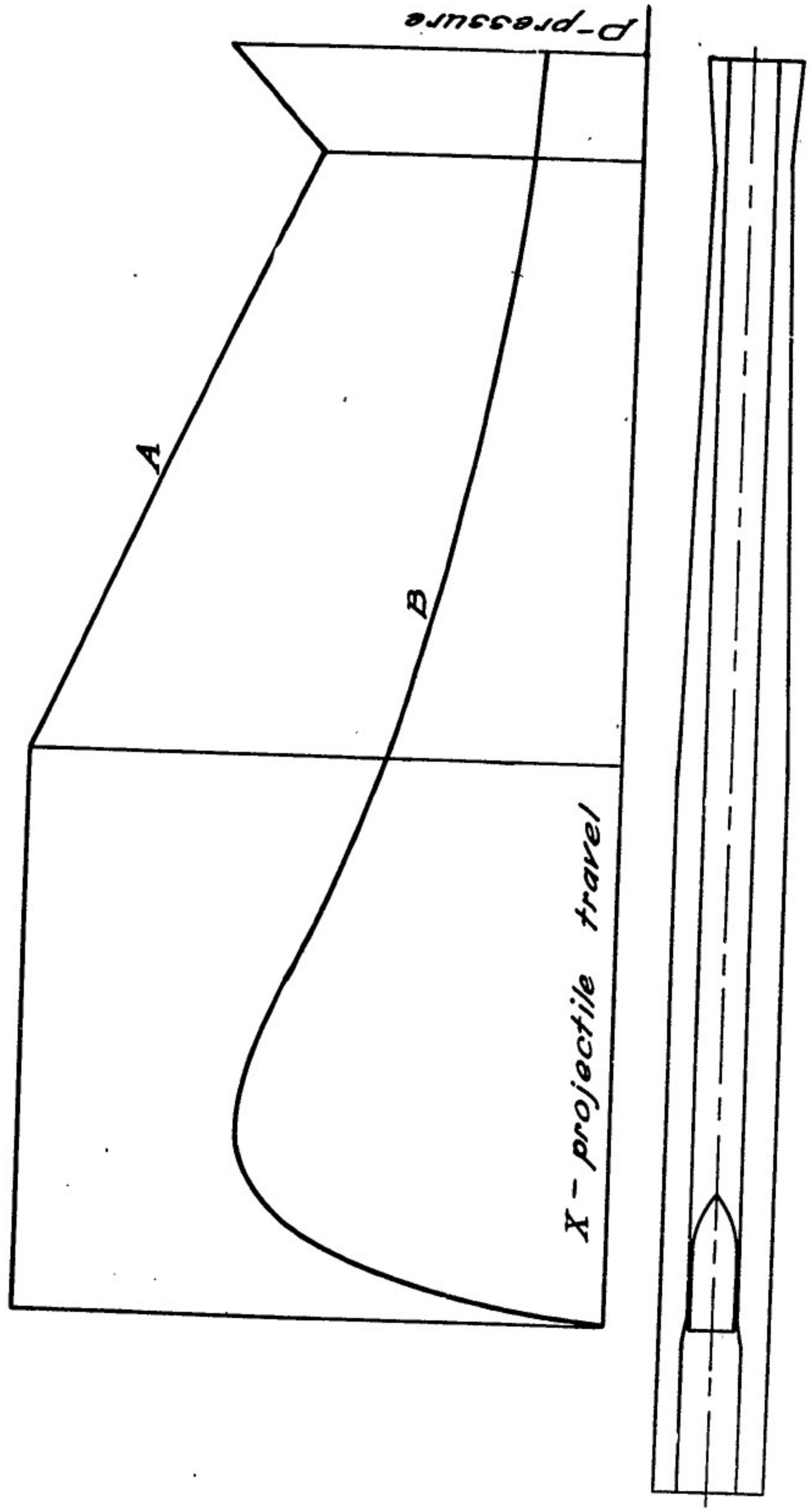

FIG. 2. BALLISTIC DRAWING.

bore. The ordinates of curve B represent pressures produced in the burning of an actual powder charge as the projectile moves along the bore. For the purpose of this analysis these pressures are considered to be measured by a series of pressure gages distributed along the barrel, each gage being read just an instant after the projectile has passed it. The ratio of an ordinate of A to the corresponding ordinate of B is the factor of safety. Let the equation $P = P(x)$ express the pressure P as a function of the displacement x of the projectile from the starting point in curve B. If a bore of uniform cross section H_0 is assumed, we have for the muzzle energy E,

$$E = \eta H_0 \int_0^L P(x)\,dx, \tag{1}$$

where L is the distance traveled by the projectile base from the rest position to the muzzle, and η is a factor introduced to take care of the loss of energy in friction. The propulsive effect of the muzzle blast, after the projectile has emerged from the muzzle, is ignored.

Equation (1) is, of course, a statement of the fact that the muzzle energy is equal to H_0 times the area under curve B.

Now, the muzzle energy E must appear as kinetic energy of the projectile. If M_0 is the mass of projectile, or, in the case of a sabot-projectile, the mass of projectile plus sabot, and v_0 is the muzzle velocity and if we neglect the small kinetic energy of spin, we have,

$$E = \tfrac{1}{2}M_0 v_0^2, \quad \text{or } v_0 = \sqrt{2E/M_0}. \tag{2}$$

If we wish to preserve the factors of safety in a given gun the function $P(x)$ will be kept unchanged. Then, if we assume that η is a constant, Eq. (2) tells us that the muzzle velocity will be inversely proportional to the square root of the mass M_0 of the projectile. The factor η is, of course, not strictly constant since the rotating band and the rotating band support are likely to be varied from one sabot design to another, but the variations are not likely to result in more than a few percent variation in muzzle velocity.

We are assuming, too, that propellants are available that will provide the same function P(x) with various projectile masses. In general, this is possible to a fair degree of approximation. In any event, Eq. (2) describes an upper limit of velocities attainable with various projectile masses and a given gun.

The line AA in Fig. 3 is the graph of Eq. (2) for a 57-mm gun, Mk VII, with both velocity and mass plotted to logarithmic scales, using the muzzle energy obtained with the standard charge. The points plotted represent velocities experimentally observed for a wide range of projectile masses in this gun. Experimental points that fall below the line AA indicate powder charges that were not quite adjusted to give the standard muzzle energy. The few points that fall above line AA indicate powder charges that gave muzzle energies exceeding the standard, probably with some reduction of the safety factor in the gun barrel.

Applying Eq. (2), expressed in the form,

$$v_o = K/\sqrt{M_o}\,, \tag{3}$$

to the illustrative case of the 75-mm gun which normally gives a 14.9-lb projectile a muzzle velocity of 2000 ft/sec, we have listed in Table I the velocities for various projectile masses.

Table I. Projectile velocities attainable in the 75-mm gun for projectiles of various masses.

M_o (lb)	14.9	10	8.5	7	5	2	1
v_o (ft/sec)	2000	2440	2650	2920	3450	5460	7720

5. Comparison of sabot-projectile with other types

It appears from Table I that with a given gun we may attain muzzle velocities of almost any magnitude by constructing a projectile of the proper mass and choosing the proper powder to go with it. In some of the early experimental work, intended to check Eq. (3), ring or "biscuit cutter" projectiles were used, as shown in Fig. 4. According

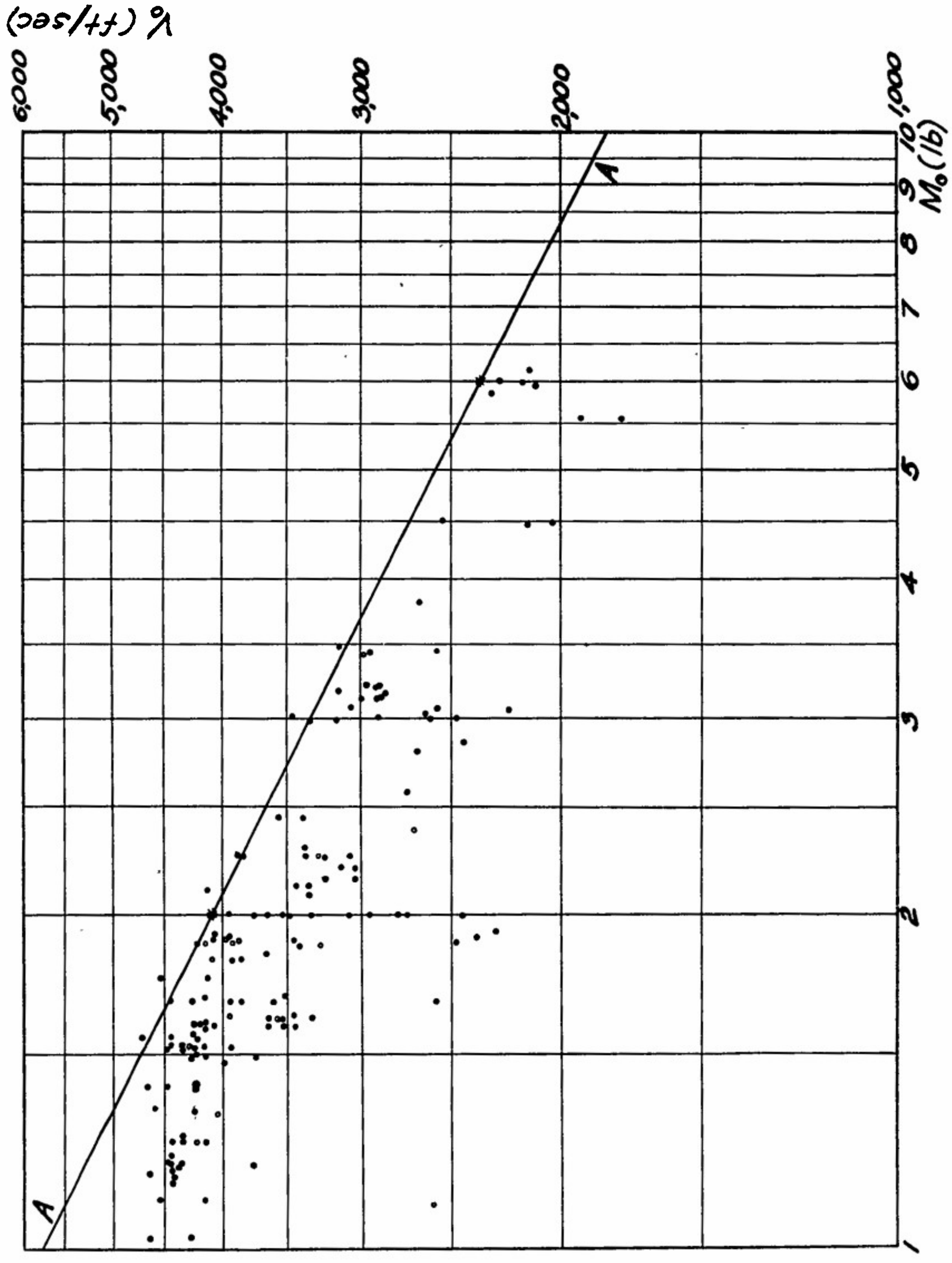

FIG.3. PROJECTILE MASS versus MUZZLE VELOCITY FOR 57-MM GUN.

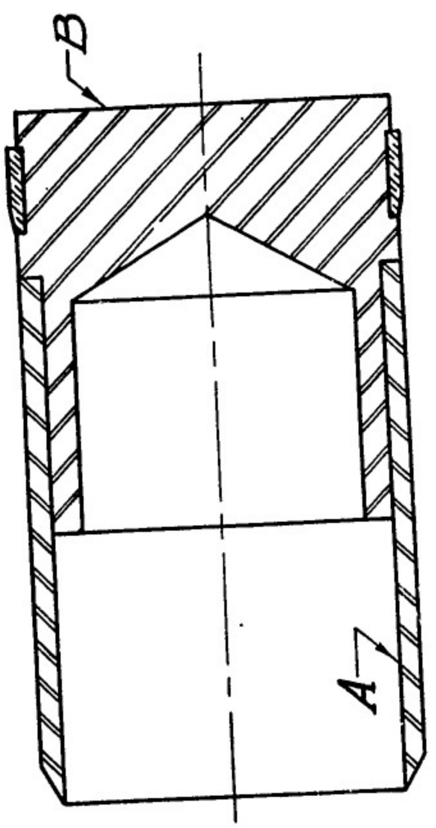

FIG.4."BISCUIT CUTTER" SABOT-PROJECTILE.

to our definition, they are sabot-projectiles: because of differential air resistance the base B falls behind the ring A soon after leaving the muzzle. Their only merit lies in the small total mass and the high stability of the ring. In other experiments, reduction of mass was effected simply by shortening the projectile, which resulted in a fair stability but a low ballistic coefficient.

Projectiles of these two types are of no practical value, of course, but the same considerations have led to the design of the so-called "arrowhead" projectiles in which the over-all proportions of the projectile are more or less conventional, but the mass is reduced by removing metal from various portions, sometimes replacing it by materials of smaller density.

If a high muzzle velocity for firing at very short range were the only desideratum the arrowhead type would probably be chosen as being simpler in construction than the sabot type. However, the ballistic coefficient of the arrowhead projectile is inevitably unfavorable, particularly if the mass is made much smaller than that of the conventional projectile of the same caliber. In the sabot-projectile the ballistic coefficient of the projectile proper may be made as high as in any projectile of the same mass.

It might be argued that the arrowhead projectile has an advantage in that no mass is discarded at the muzzle, and so the projectile continues to carry full muzzle energy. However, it will be found that for anything above the shortest ranges the sabot-projectile will still arrive at the target with greater kinetic energy than will the comparable arrowhead projectile, owing to the low ballistic coefficient of the latter. Even at short ranges the higher energy of the arrowhead projectile does not necessarily make it more effective, because of difficulties met in making all of its mass effective in armor penetration.

In comparison with the arrowhead projectile it seems evident that the sabot-projectile should be given careful consideration for practically all applications.

Stability considerations place limitations upon the proportions of sabot-projectiles, and Chapter II will be devoted to this matter. Final choice between the arrowhead and sabot-projectile will depend on a number of factors — mass of projectile, rifling pitch, desired penetration, desired ballistic coefficient, tactical use of projectile, and so forth. Detailed discussion of these various matters will be given later.

Comparisons will now be made with the tapered-bore method of attaining high velocity. Both sabot and arrowhead projectiles attain high velocities without the use of a special gun. If there is a tactical advantage in being able to fire several types of projectile from the same gun, the sabot or arrowhead projectile is to be preferred.

The tapered-bore projectile does not discard any of its mass or kinetic energy at the muzzle, and with its good ballistic coefficient may thus have some advantage over the sabot-projectile. However, with the tapered-bore projectile, as with the arrowhead, there is difficulty in making all of the mass effective in armor penetration.

Since the area of a tapered bore varies with the distance $\underline{x}$ along the bore, the factor H_0 in Eq. (1) is no longer a constant, but is a function of $\underline{x}$, that is,

$$H = H(x), \quad \text{where} \quad H(o) = H_0. \tag{4}$$

Equation (1) then becomes

$$E = \eta \int_0^L H(x)\, P(x)\, dx. \tag{5}$$

Since $H(x)$ diminishes with $\underline{x}$, and $P(x)$ is the same as in Eq. (1), the muzzle energy in the tapered-bore case of Eq. (5) is less than in the uniform-bore case of Eq. (1). Of course, if the tapering is confined to a relatively short length near the muzzle the difference may not be very large, a fact recognized by the designers of tapered-bore guns. In general, however, it may be said that the attainment of a given high velocity with given projectile mass, bore length and breech diameter, will require a somewhat higher pressure in the tapered-bore gun than in the uniform-bore gun, and consequently will require a somewhat stronger gun.

It may well happen that the factor of gun erosion must be ultimately taken into consideration in choosing between the tapered-bore and the uniform-bore gun with sub-weight projectiles. It is understood that in early tapered-bore guns erosion was a serious problem. It seems probable that it is not so serious in guns of the Littlejohn type.

In the case of sub-weight projectiles it seems that erosion in a given gun may be less than when the standard projectile is used, at least for a given type of propellant. This results from the fact that the hot gases are in contact with the bore for a shorter length of time with the sub-weight projectile. It has been informally reported that this is borne out in British experience with sabot-projectiles.

6. Classification of sabot-projectiles

Sabot-projectiles fall into two general classes: (i) full-caliber types, and (ii) subcaliber types.

The full-caliber types seem at the moment to be principally of academic or historical interest. The "biscuit cutter" (Fig. 4) is an example. In some of the early types, mentioned in Sec. 2, the projectile was of full caliber and the primary function of the sabot seems to have been either to impart spin to the projectile or to effect a gas seal.

The subcaliber types fall into two main groups, which are each subdivided into a number of types as shown in the following outline.

I. Cup-type sabot-projectiles.
    a. Deep-cup types:
        1. Full cup [see Figs. 5(a), 5(b) and 7(a)];
        2. Ventilated cup [see Fig. 5(c)].
    b. Shallow-cup, or disk, types:
        1. Solid disk [see Figs. 6 and 7(b)];
        2. Ventilated disk [see Figs. 6 and 7(c)].

II. Ring-type sabot-projectiles.

a. Cantilever type (see Figs. 8 and 9);

b. Thread-or groove-anchored type (see Figs. 11, 12, 13 and 14).

Each of the subcaliber types may be further classified (with the exception of the deep-cup sabots) into two subtypes depending on whether a separate ring bourrelet or a sleeve bourrelet is used. The deep-cup type, in general, acts as its own bourrelet. Figure 9 shows several cantilever types, both ring and sleeve bourrelets being represented.

7. Design requirements

In the chapters that follow, various considerations relating to the practical design of sabot-projectiles will be discussed. A successful design must meet four requirements if it is to emerge from the gun with the desired high velocity and begin its flight without excessive yaw. They are:

(i) Neither sabot nor projectile may fail under the stresses encountered in the gun.

(ii) Full spin must be transmitted from the sabot to the projectile, unless stability is to be provided by means other than spin.

(iii) The sabot must release quickly and without materially disturbing the flight of the projectile.

(iv) The sabot must provide a satisfactory gas seal while in the gun.

In addition to these conditions, if the projectile proper is to perform a useful function it must have the following characteristics:

(v) Stability in flight.

(vi) Satisfactory ballistic coefficient.

(vii) Capability of penetrating armor or inflicting other damage at the end of its flight.

Chapters II and III will be concerned with conditions (i) to (iv) while Chapters IV, V and VI will deal with conditions (v) to (vii).

In addition to the foregoing fundamental requirements various practical requirements will arise, such as:

(i) The parts must be firmly held together to withstand rough handling.

(ii) Means must be provided for mounting in the powder case, if fixed ammunition is required.

(iii) Materials used must be mechanically stable under anticipated variations of temperature and humidity.

II. DESIGN CONSIDERATIONS: STRESS ANALYSES

This chapter is concerned mainly with the design of sabots and projectiles of sufficient strength to stand up under the forces encountered in the bore of the gun. It will be necessary also to consider the stress aspects of release mechanisms, the transmission of spin, and the maintenance of the gas seal.

Since the stress analysis is essentially the same for many variations of certain types of sabot, it will be sufficient to consider in detail the analysis for five generalized sabot types.

8. The deep-cup sabot

This type is considered first because of its simplicity and historical interest. The general type is shown in Fig. 5 and Fig. 7(a) is a photograph of a model designed for the 20-mm Hispano-Suiza cannon. Let M_s be the mass of the sabot in pounds; M_p, the mass of the subcaliber projectile in pounds; D_p, the diameter of the subcaliber projectile in inches; D_g, the diameter of the sabot (or caliber of the gun) in inches; L_t, the total length of the sabot in inches; L_s, the length of the sabot to the rear of the projectile in inches; and $\underline{P}$, the maximum powder pressure encountered in the gun barrel, in pounds per square inch.

The total maximum force acting on the base of the sabot is $\frac{1}{4}\pi PD_g^2$ lb. The acceleration of the projectile plus sabot, expressed in terms of $\underline{g}$, the acceleration due to gravity, will be given by $a = \frac{1}{4}\pi PD_g^2/(M_s + M_p)$. The force F_p that must act on the subcaliber projectile to give it an acceleration $\underline{a}$ is given by $F_p = aM_p$ lb, where $\underline{a}$ is expressed in terms of $\underline{g}$.

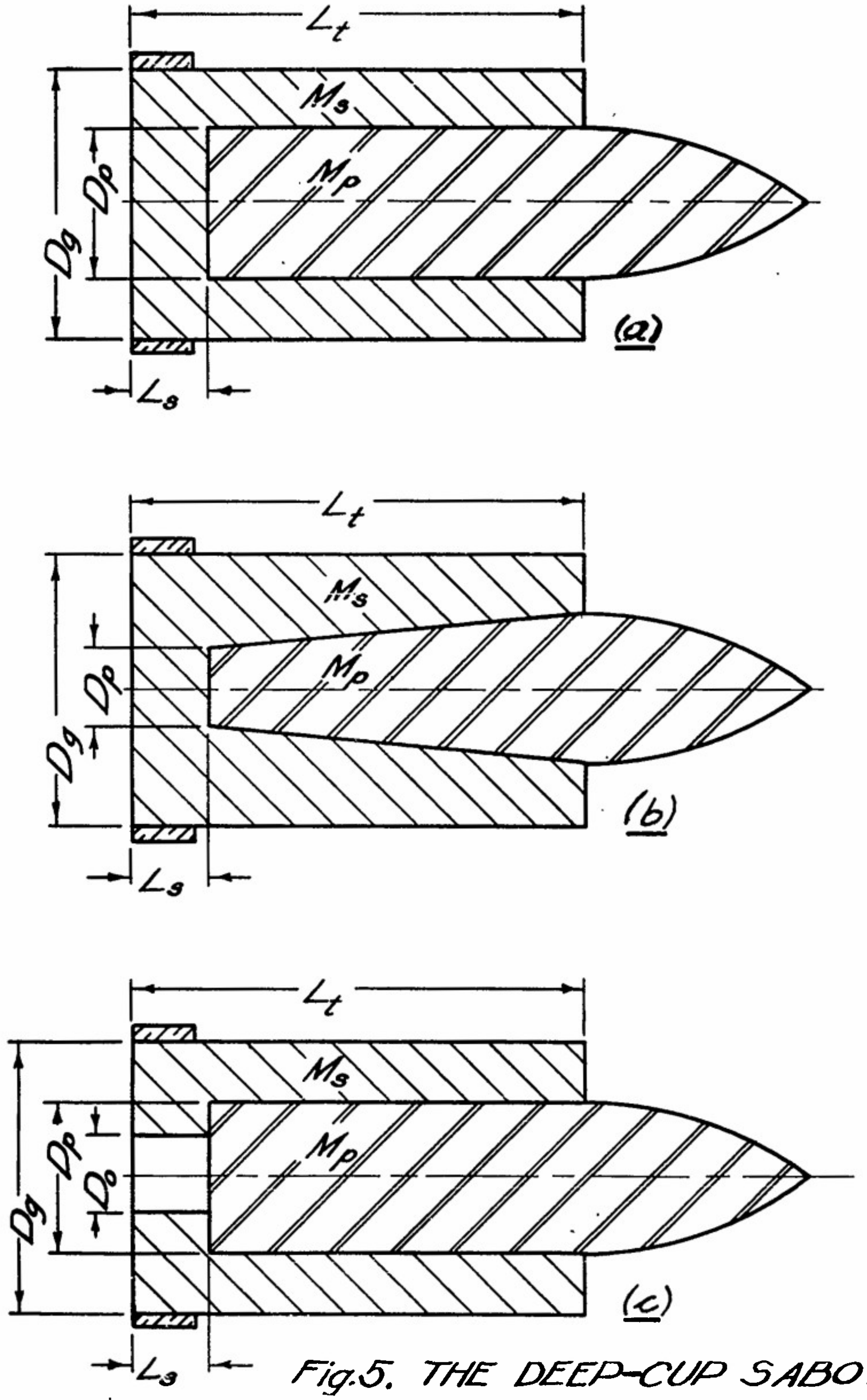

Fig.5. THE DEEP-CUP SABOT.

This force must be supplied by the sabot pushing against the base of the projectile. Hence the average compressive stress S_c over the contact area in both the sabot and projectile is given by

$$S_c = \frac{F_p}{\frac{1}{4}\pi D_p^2} = P \frac{D_g^2}{D_p^2} \frac{M_p}{M_s + M_p} \text{ lb/in}^2$$

This figure for the compressive stress is probably lower than the stress that actually exists around the edge of the projectile base, because of the stress concentration around the re-entrant corner of the sabot. Hence, a reasonable safety factor must be allowed. Experience has shown that a safety factor of 2 is adequate.

The force tending to shear out the base of the sabot is given by

$$\frac{1}{4}\pi D_g^2 P \left[\frac{M_p}{M_s + M_p}\right] - \frac{1}{4}\pi D_p^2 P = \frac{1}{4}\pi P \left[\frac{M_p}{M_s + M_p} D_g^2 - D_p^2\right] \text{ lb.}$$

Hence the shearing stress S_s acting on the sabot around the edge of the projectile is given by

$$S_s = \frac{P\left[\frac{M_p}{M_s + M_p} D_g^2 - D_p^2\right]}{4 D_p L_s} \text{ lb/in}^2$$

Here again an adequate safety factor should be allowed, say 1.5. If Y_c is the compressive yield point of the weaker of the materials used in the sabot and projectile, and if, Y_s is the yield point in shear of the sabot material, then adequate strength in this type sabot requires that

$$Y_c \geqq 2P \frac{D_g^2}{D_p^2} \frac{M_p}{M_s + M_p} \tag{6}$$

and

$$Y_s \geqq \frac{1.5P\left[\frac{M_p}{M_s + M_p} D_g^2 - D_p^2\right]}{4 D_p L_s}. \tag{7}$$

Let us now consider the transmission of spin from the sabot to the projectile. Although in a cup-type sabot it is always possible to key the sabot to the projectile, and thus to insure adequate torque transmission, we shall consider the possibility of the torque being transmitted solely by friction between the sabot and projectile. If r_g (in.) is the radius of the bore of the gun, n is the rifling pitch in calibers per turn, F_t (lb) is the tangential force required to spin the projectile when applied at a distance r_2 (in.) from the axis, A (lb in.^{2}) is the moment of inertia of the projectile, and a is the longitudinal acceleration of the projectile in units of g, then it follows that

$$F_t = aA\pi/nr_g r_2.$$

This force must be supplied by the friction between the sabot and projectile, which enables us to specify a minimum allowable value for the coefficient of friction between these surfaces. Since the total normal force between the sabot and projectile is given by $F_p = \frac{1}{4}\pi D_g^2 P M_p/(M_s + M_p)$, the tangential force that this will produce is given by $F_t' = fF_p$, where f is the coefficient of friction between the sabot and projectile. If the projectile is to spin, we must have $F_t' \geqq F_t$, whence

$$f \geqq \frac{aA\pi}{nr_g r_2 F_p} = \frac{\pi A}{nr_g r_2} \cdot \frac{\frac{1}{4}\pi D_g^2 P}{M_s + M_p} \cdot \frac{M_s + M_p}{\frac{1}{4}\pi D_g^2 P M_p},$$

or

$$f \geqq \pi A/nr_g r_2 M_p. \qquad (8)$$

If we assume uniform stress over the base of the projectile, r_2 can be taken as $D_p/3$ for the cup-type sabot. If we further take $A = kM_p D_p^2$, Eq. (8) becomes

$$f \geqq \frac{3 \times 2\pi k M_p D_p^2}{nD_g D_p M_p} = \frac{6\pi k}{n} \cdot \frac{D_p}{D_g}. \qquad (8a)$$

Taking, for example, $D_p/D_g = 0.76$ (57-mm in 75-mm), n = 25 and k = 0.14 (given by Hayes[5/] as applying to the average projectile), we obtain from Eq. (8a), $f \geqq 0.08$. If, for the materials concerned, $f \geqq 0.08$, friction alone will suffice for torque transmission.

5/ Hayes, Elements of ordnance (Wiley, 1938).

For most materials and most practicable ratios of D_p/D_g, the metal-to-metal friction is sufficient. In those cases where it is not, the coefficient of friction can be increased to the required value by knurling the base of the projectile. Note that the expression for $\underline{f}$ is not a function of the acceleration $\underline{a}$, or of the powder pressure $P(x)$. This means that if the friction is sufficient to spin the projectile at any point along the travel in the gun, then for uniform pitch of rifling it is sufficient at every point.

The release of cup-type sabots is axial -- owing to the greater air retardation of the sabot than of the projectile. Although quantitative estimates of the forces developed in this process are at present impossible because of our lack of knowledge of the pressure distribution over the front of projectiles, experience has shown that this type of sabot is usually completely separated from the projectile at 90 ft from the muzzle.

Unfortunately, it seems that this type of sabot can not be made to release without seriously disturbing the flight of the projectile. Every sabot of this type that we have tried has tumbled in flight. Other investigators have had the same experience, as far as has come to our attention. The precise reason for this is not clear, and we make no attempt at explanation.

If the seat of the projectile in the deep-cup sabot is tapered, this disturbance at release may be avoided. This modification is shown in Fig. 5(b). Models built along these lines have proved successful. It is essential in this type of sabot that clearance be provided so that the bearing surface will be on the base of the projectile and not on the conical surface. This is required in order to avoid wedging the sabot and projectile firmly together during setback. The stress analysis for this type of sabot is exactly the same as that previously given for the cup-type sabot.

In both these types, as well as in all other types, it is desirable that the length L_t of the sabot be at least $1.5D_g$ to insure against excessive ballotment, with possibility of bourrelet failure in the gun, or excessive initial yaw. However, many successful designs have been made in which L_t is as small as $0.9D_g$, so the point is not stressed.

An important modification of the cup-type sabot is the ventilated cup type, illustrated schematically in Fig. 5(c). This allows part of the powder pressure to act directly on the base of the projectile. The sabot is generally lightened by this process, which is desirable, and the stress calculations are changed as follows.

The force on the projectile required to produce an acceleration a is again $F_p = M_p a$. However, in this case, the powder pressure acting through the hole of diameter D_o contributes a force $\frac{1}{4}\pi D_o^2 P$, so that the net force that must be supplied by the sabot is given by

$$F = M_p a - \frac{1}{4}\pi D_o^2 P = \frac{1}{4}\pi P\left[\frac{M_p}{M_s + M_p} D_g^2 - D_o^2\right].$$

The compressive stress S_c is then given by

$$S_c = \frac{F}{\frac{1}{4}\pi(D_p^2 - D_o^2)} = P\left[\frac{D_g^2}{(D_p^2 - D_o^2)} \cdot \frac{M_p}{M_s + M_p} - \frac{D_o^2}{D_p^2 - D_o^2}\right].$$

The shearing stress S_s as before is given by

$$S_s = \frac{P}{4 D_p L_s}\left[\frac{M_p}{M_p + M_s} D_g^2 - D_p^2\right].$$

Using the appropriate safety factors as before, we have that the compressive and shearing yield points of the materials used must be

$$Y_c \geq 2P\left[\frac{D_g^2}{(D_p^2 - D_o^2)} \cdot \frac{M_p}{M_p + M_s} - \frac{D_o^2}{D_p^2 - D_o^2}\right] \tag{9}$$

and

$$Y_s \geq \frac{1.5P}{4 D_p L_s}\left[\frac{M_p}{M_p + M_s} D_g^2 - D_p^2\right]. \tag{7}$$

In this design, Y_c is somewhat higher than before, Y_s is the same, and the sabot has been materially lightened.

The matter of torque transmission is approached as before, using the formula $f \geq aA\pi/nr_g r_2 F_p$, except that the net force F is used instead of F_p, and using $r_2 = \frac{1}{4}(D_o + D_p)$ as a conservative value. The result is

$$f \geqq 8\pi A D_g / n(D_o + D_p)[M_p D_g^2 - (M_s + M_p) D_o^2]. \qquad (9a)$$

The sabot is released by the same mechanism as before, and as before it appears that only a tapered cup is capable of releasing the projectile without disturbing its flight.

9. <u>The disk sabot</u>

The solid disk type, shown in Figs. 6 and 7(b) and (c) is distinguished from the cup type in that the bourrelet is a separate structure and may be weakened by two or more radial slots cut part way through the bourrelet. The base plate is a solid disk, and may or may not be ventilated to allow the powder gases to act on the base of the projectile. The release of the bourrelet is centrifugal, that is, the bourrelet bursts owing to the centrifugal stresses set up in rotation. The base plate is lost since the retardation of the base plate is greater than that of the projectile. It is usually desirable to center the projectile with respect to the base plate by recessing it slightly, say 0.1 in., into the base plate. Of interest is the fact that though the base plate constitutes a shallow cup, the sabot release characteristics now seem to be quite satisfactory.

The stress calculations are the same as in the case of the cup-type sabots. Equation (6) or Eq. (9) holds for the compressive stresses, and Eq. (7) holds for the shearing stresses. However, in this case it may also be desirable to consider the tensile stresses occurring in the base plate owing to its bending. This was not considered in the case of the cup-type sabot since it is a somewhat more rigid structure than the flat plate. Actually, the exact calculation of the beam stresses in a thick circular plate are beyond the scope of this paper, and the formulas given are fairly accurate only when the thickness is not greater than about $\frac{1}{4}$ of the least

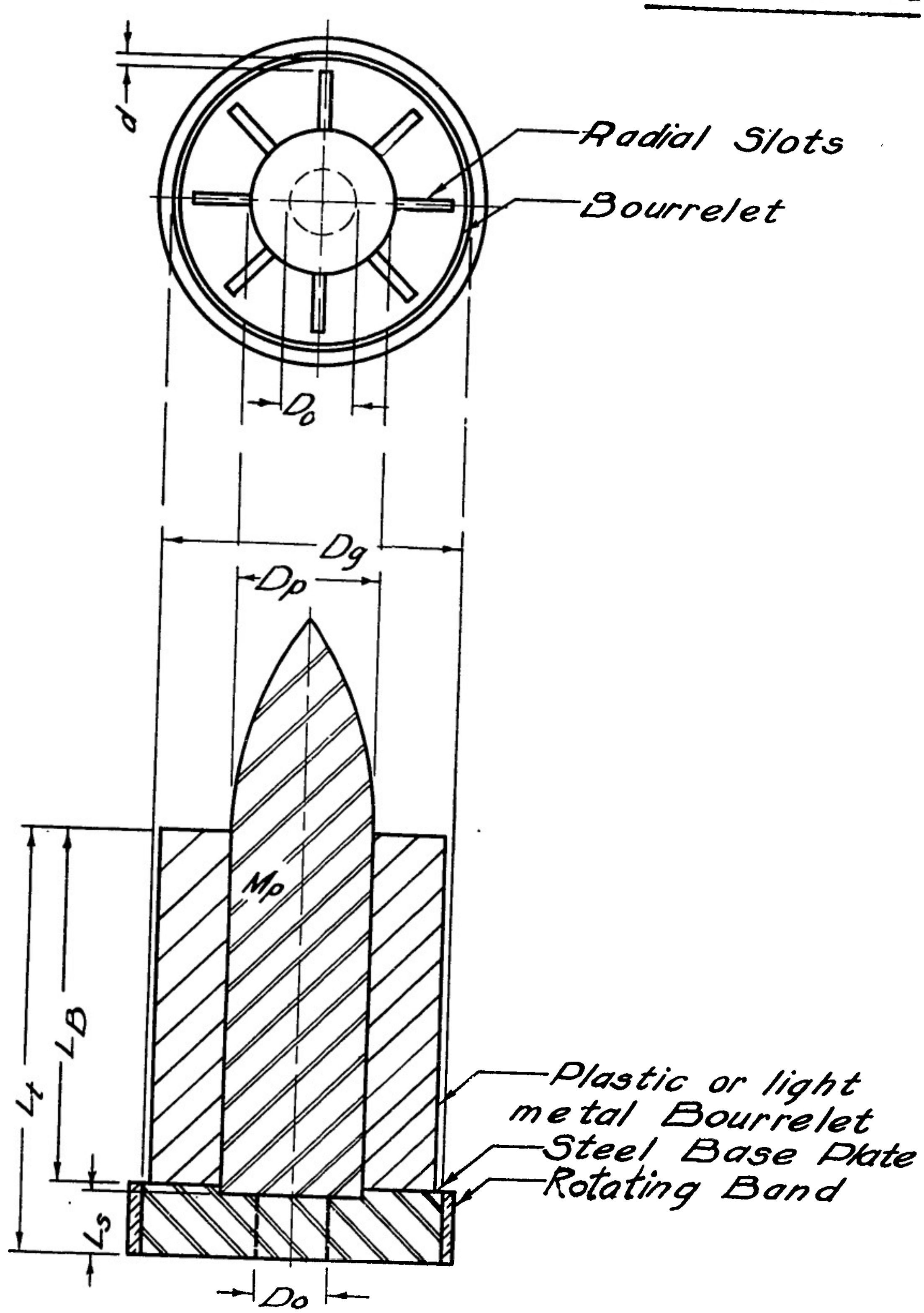

Fig.6. THE DISK SABOT.

transverse dimension. As derived from formulas given by Roark,[6] the maximum tensile stress S_t due to the bending of a solid circular plate loaded as in the gun is given by

$$S_t = \frac{3F_p}{2\pi m L_s^2}\left[(m+1)\log_e \frac{D_g}{D_p} + \frac{1}{4}(m-1)\left(1 - \frac{D_g^2}{D_p^2}\right)\right], \qquad (10)$$

where F_p (lb) is the force with which the sabot presses on the base of the projectile, m is the reciprocal of Poisson's ratio and L_s, D_g and D_p are dimensions as indicated in Fig. 6.

For the case of the ventilated base plate, the maximum tensile stress S_t', as derived from Roark's[7] formulas is,

$$S_t' = \frac{3F}{mL_s^2(D_g^2 - D_p^2)}\left[\frac{D_g^2}{4}(m+1)\log_e \frac{D_g}{D_o} + \frac{D_g^2 D_o^2}{4} + \frac{D_g^2}{16}(m-1) - \frac{D_o^2}{16}(m+3)\right], \qquad (11)$$

6/ Roark, Formulas for stresses and strains, (McGraw-Hill), Eq. 11, p. 173.

7/ Reference 6, Relation 16, p. 175.

Fig. 7. Cup and disk sabots.

(a) A deep-cup sabot by the side of its projectile. This model is designed for the 20-mm Hispano-Suiza cannon, but as with all deep-cup sabots tested, does not prove successful in tests. After release the projectile seems always to tumble.

(b) A disk sabot Model 25-75A. In the center is a 57-mm APC projectile, M86 as it would appear in flight. On the right are all the parts in process of assembly. The projectile is resting on the disk: the plastic sleeve bourrelet is to be pressed down and attached to the disk by self-tapping screws. On the left is the disk alone, recovered after being fired, showing the screws and the flaring of the base skirt, that, apparently results from the impact of the muzzle blast. The skirt is a means of mounting the assembly in the 75-mm powder case as fixed ammunition. This model performed fairly satisfactorily.

(c) A top view of two disk sabots; the one on the left before firing, the one on the right after firing. The projectile base is knurled to insure torque transmission and the right disk shows how this knurling is imprinted on the sabot. The bending of the screws is interesting as indicating the direction of departure of the bourrelet segments at release.

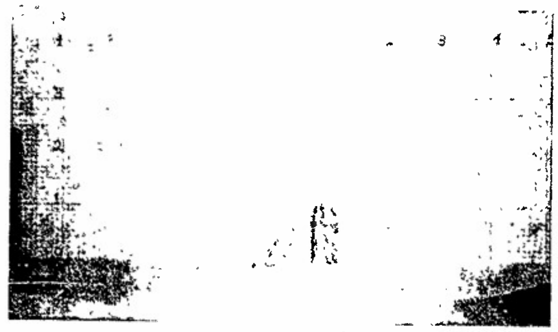

Fig. 7(a)

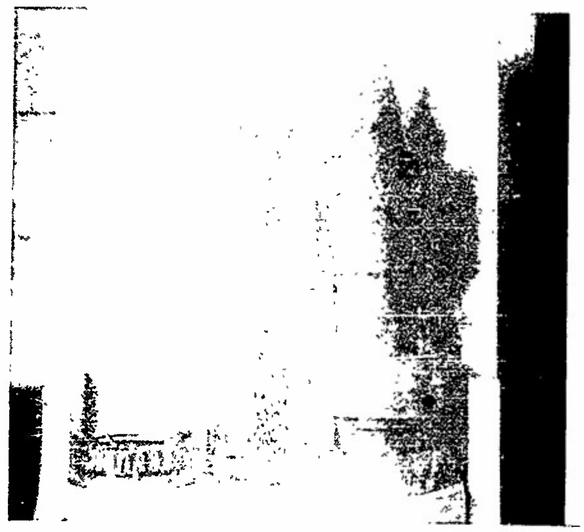

Fig. 7(b)

Fig. 7(c)

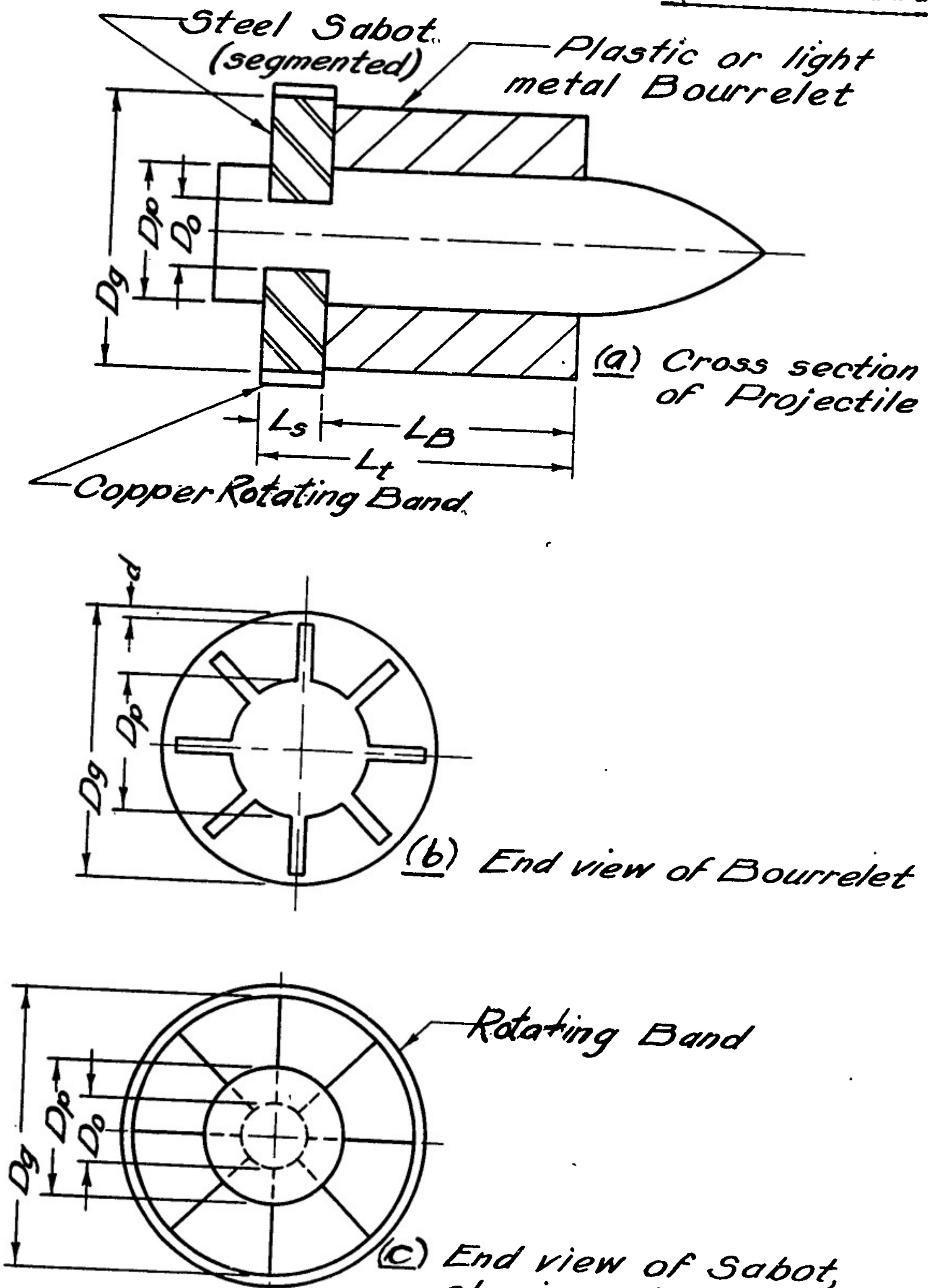

Fig. 8 THE CANTILEVER SABOT.

where P (lb/in^2) is the maximum powder pressure acting on the base plate, m is the reciprocal of Poisson's ratio, and D_o, D_g, L_s, are as indicated in Fig. 6.

Actually, Eqs. (10) and (11) give upper bounds on the stress in the plate due to bending, since they are derived with the outer edge assumed not restrained. The gun barrel through friction undoubtedly offers some support to this edge, although the edge cannot be regarded as fixed. Also, Eq. (11) is derived on the assumption that the projectile reaction F_p occurs along an edge of diameter D_o, whereas actually it occurs over the area included between D_o and D_p, and this area is supported below somewhat by the powder pressure P. The error may be large if D_p is much larger than D_o. In such case, however, a solid disk is likely to be used.

For a given material, the thicknesses L_s required to satisfy Eqs. (10) and (11) are usually somewhat greater than those required to satisfy the shearing stress condition given by Eq. (7) so that in this type of sabot the bending stresses rather than the shearing stresses ordinarily fix the thickness L_s.

The condition for adequate torque transmission from the base plate to the projectile is given, as before, by Eq. (8) or Eq. (9a).

Since in this model the release of the forward portion, or bourrelet, is by failure of the material under centrifugal force, we must study the mechanism involved and provide an ample margin of certainty for the release. In general, it is necessary to weaken the bourrelet to insure its bursting, so let us suppose the bourrelet to be slotted radially with two or more slots, from the inside to within a distance d of the outside diameter. If the length of the bourrelet is L_B (in.), the mass of the bourrelet is M_B (lb), the centrifugal acceleration at 1 in. from the axis is G (with acceleration of gravity as the unit, and the center of gravity of one half the bourrelet is R (in.) from the axis, then the force tending to burst the bourrelet is given by $F_B = \frac{1}{2} M_B R G$ lb, which results in a tensile stress in the bourrelet of $S_t = \frac{F_B}{2\,dL_B}$ lb/in². This stress S_t must exceed the ultimate tensile strength of the bourrelet material if the bourrelet is to burst. These relations can be expressed in terms of the muzzle velocity and in calibers per turn of the rifling as follows.

Let the muzzle velocity be v_o (ft/sec), and let the calibers per turn of rifling be n. Then the muzzle spin S (rev/sec) will be given by $S = v_o \frac{12}{nD_g}$, D_g being in inches. The centrifugal acceleration per inch from the axis of the projectile is given by

$$G = \frac{4\pi^2}{386.4}\left(\frac{12\,v_o}{n\,D_g}\right)^2 = 14.71\left(\frac{v_o}{nD_g}\right)^2 .$$

The distance R to the center of gravity of one half the bourrelet of radii r_p and r_g is given by

$$R = \frac{4}{3\pi}\left(\frac{r_g^3 - r_p^3}{r_g^2 - r_p^2}\right).$$

Expressed in terms of the diameters, this is

$$R = \frac{2}{3\pi}\left(\frac{D_g^3 - D_p^3}{D_g^2 - D_p^2}\right),$$

and the tensile stress in the bourrelet will be given by

$$S_t = \frac{M_B}{3\pi}\left(\frac{D_g^3 - D_p^3}{D_g^2 - D_p^2}\right)\frac{14.71}{2\,dL_B}\left(\frac{v_o}{n\,D_g}\right)^2 \text{ lb/in}^2 \qquad (12)$$

As we noted before, this stress should exceed the ultimate tensile strength of the bourrelet material if the bourrelet is to burst.

Some evidence has been recently obtained, however, which suggests that the bursting of the bourrelet may be less simple than implied in the foregoing analysis. A number of samples in the 75-57 mm combination have been fired with no weakening slots whatever in the plastic bourrelet. Despite the fact that the tensile stress as computed from Eq. (12) is only 1700 lb/in² the bourrelets have burst in very satisfactory fashion. For the plastics used, the tensile strength should be of the order of 5000 to 12000 lb/in² in large samples. There probably are small regions within which the strength is considerably less than this.

Various theories have been advanced to account for these results, but until further data are obtained they must be regarded as unexplained, in general. Factors that may possibly be involved are: local weakening of the plastic by inhomogeneities of filler, and the like; local weakening at the rear of the bourrelet caused by the compressive stress carried during maximum acceleration; an increase of the peripheral tensile stress resulting from the presence of longitudinal compressive stress while the projectile is very close to the muzzle; and inertial or vibration effects following emergence from the muzzle. Tests on a particular molded plastic from which bourrelets were machined showed that the bourrelets had two planes of weakness 180° apart where the tensile strength was only about one third that given for this particular material.

In Chap. III will be found further discussion of the action in this kind of centrifugal release.

The disk sabot has, in general, given quite satisfactory results. Release has been attained without disturbance of the flight of the projectile, and the dispersion has been practically the same as that obtained with standard ammunition.

10. The cantilever sabot

This type of sabot is shown in Figs. 8 and 9. Here the release is entirely centrifugal. The bourrelet is slotted, as in the previous type, with two or more slots to within a distance $\underline{d}$ of the outside diameter. Here we shall use the term "sabot proper" to designate the principal stress-carrying structure as distinguished from the bourrelet, which carries minor stresses and serves only to center the projectile in the barrel. The sabot proper is segmented into four or more sections, inserted into a deep groove in the projectile, and held together by the rotating band, which is shrunk over the sabot. The stresses due to centrifugal force at the muzzle are sufficient to burst both bourrelet and rotating band, and the projectile continues in flight alone. The stress calculations follow for this type of projectile.

As always, the maximum acceleration $\underline{a}$ in the barrel is $\frac{1}{4}\pi PD_g^2/(M_s + M_p)$, with the acceleration of gravity as the unit. The force due to the powder pressure acting directly on the base of the projectile is given by $\frac{1}{4}\pi D_p^2 P$ lb, while the force required to give the projectile of mass M_p an acceleration $\underline{a}$ is $\frac{1}{4}\pi D_p^2 PM_p/(M_s + M_p)$ lb. Therefore the force with which the sabot must press on the projectile is given by

$$F_p = \frac{1}{4}\pi P\left[\frac{M_p}{M_s + M_p} D_g^2 - D_p^2\right] \text{lb.} \tag{13}$$

This force is borne in compression by the annulus of radii $\frac{1}{2}D_o$ and $\frac{1}{2}D_p$, which has an area of $\frac{1}{4}\pi(D_p^2 - D_o^2)$. Hence the average compressive stress on this shoulder due to the propulsive force is given by

$$S_{c_1} = \frac{P}{D_p^2 - D_o^2}\left[\frac{M_p}{M_s + M_p} D_g^2 - D_p^2\right] \text{lb/in}^2$$

In addition to the compressive stress just considered, the powder pressure acting on the exposed portion of each sabot segment will result in an overturning moment which must be resisted by the front and back faces of the groove, and by the pressure of the rotating band against the gun barrel. If we assume no radial support from the gun barrel through the rotating band, we find that in many cases no reasonable dimensions will give permissible stresses at the faces of the groove. In such cases we must therefore depend upon the assistance of radial forces from the barrel, and the section of the segment must be geometrically such that this support is effective.

Figure 10 is a cross section of an idealized cantilever segment in which the curvature of the cantilever anchorage is neglected. If $\underline{w}$ is the number of segments in the design used, the load on the beam may be taken as F_p/w, applied at c.g., the center of gravity of the exposed area. The overturning couple is $F_p\ell_c/w$, where ℓ_c is determined in a manner to be discussed later. Here we must then have $f_a - f_b = F_p/w$. The overturning couple is balanced by the sum of two couples $f_r\ell_a$ and $f_b\ell_b$. The precise points at which f_r, f_a and f_b, may be considered to act depend upon the geometry of the segment and the clearances originally present, but for simplification it is assumed that $\ell_a = 2L_s/3$.

Let us assume that the metal in the groove faces is stressed past the yield point, so that f_b may be regarded as equal to Y_c times the area effective in supplying f_b (which we will call X), and similarly for f_a. If A is the total area of one face of the groove, then

$$\frac{f_a}{f_b} = \frac{F_p/w + f_b}{f_b} = \frac{A - X}{X} = \frac{A - f_b/Y_c}{f_b/Y_c},$$

or,

$$wY_cA - wf_b = F_p + wf_b.$$

This gives

$$f_b = \tfrac{1}{2}(Y_cA - F_p/w). \tag{14}$$

This analysis is somewhat conservative in most of its steps. The frictional forces at all points of contact are in such a direction as to oppose the overturning, and the curvature of the groove serves to make the cantilever anchorage stronger than assumed. As a matter of fact, final approval of such a design must rest upon the results of actual tests, and the computations based upon the foregoing analysis are valuable principally as preliminary guides.

Fig. 9. Cantilever sabot-projectiles designed for the old Navy 6-pdr. deck gun, Mk VII. All three performed quite satisfactorily.

(a) A projectile with a segmented cantilever sabot assembled on it, the sleeve bourrelet being shown separately. The bourrelet shows the radial saw cuts which weaken it to insure its bursting for release. This particular sabot is of oak wood.

(b) A cantilever sabot-projectile Model 48-57A, assembled ready to fire. The sleeve bourrelet in this case is of laminated phenolic plastic.

(c) A variation using the same cantilever sabot but having a steel segmented ring bourrelet mounted in a groove on the forward part of the projectile. The ring is held together by a shrunk-on copper band which breaks for centrifugal release. The left view shows the projectile as it would appear in flight while the right view shows the complete assembly ready for firing.

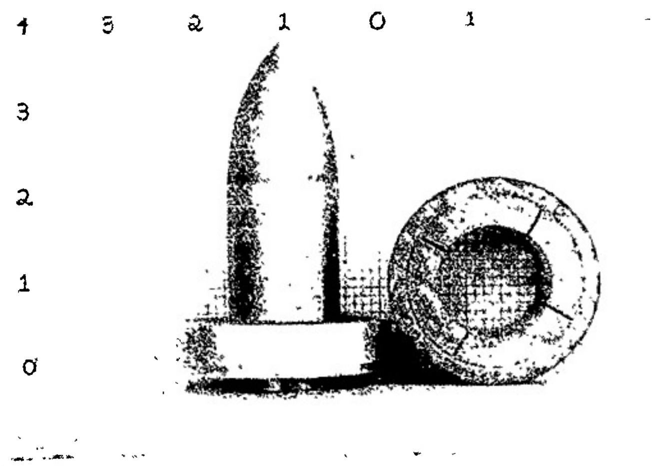

Fig. 9(a)

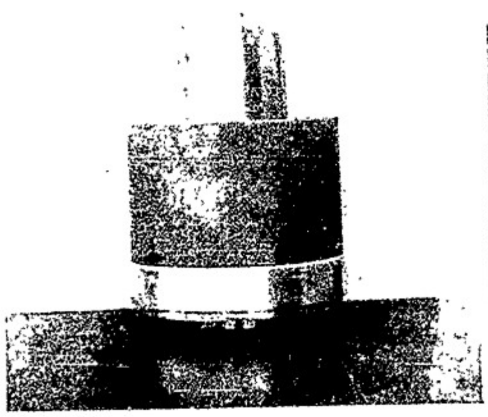

Fig. 9(b)

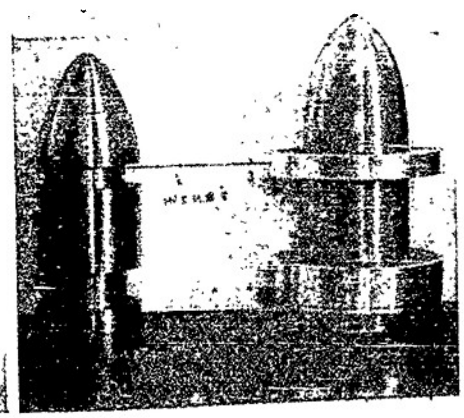

Fig. 9(c)

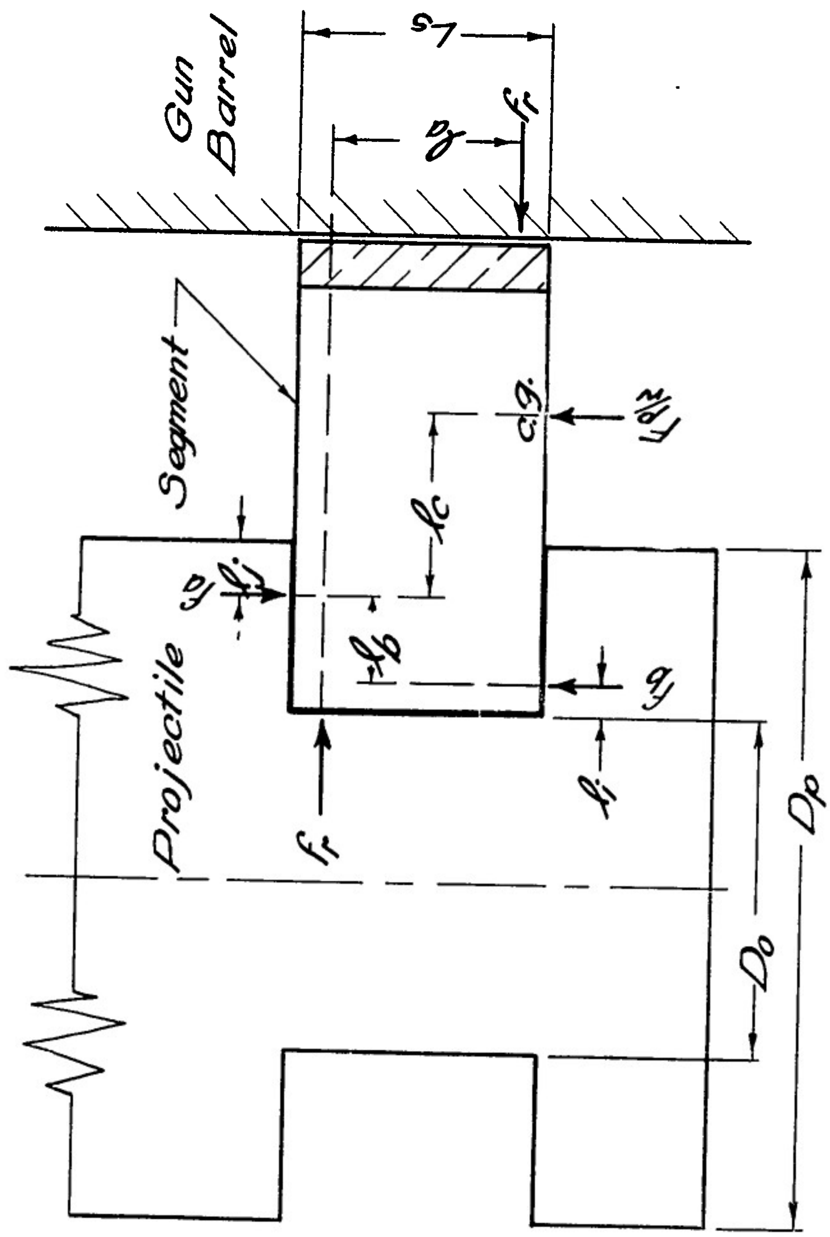

FIG. 10. CROSS SECTION OF CANTILEVER SEGMENT.

In actual designs, where there may be four or fewer segments, it is possible that the center of gravity (c.g. in Fig. 10), as computed from

$$R = \frac{w}{3\pi}\left(\frac{D_g^3 - D_p^3}{D_g^2 - D_p^2}\right) \sin\frac{\pi}{w}$$

may actually be found inside the periphery of the projectile, whereupon, at first glance, the overturning moment will disappear. However, the depth L_s (Fig. 10) is rarely great enough to furnish sufficient lateral stiffness to permit the full benefit of this effect.

In the case of segments of large angle it should also be pointed out that the bearing stress will not be distributed uniformly in the peripheral direction along the rotating band, but will tend to be higher in the center of the segment than at its ends.

Suppose that ℓ_i is the distance from the base of the slot to the midpoint of the area $\underline{X}$; then ℓ_i is given approximately by

$$\ell_i = \frac{wA}{4\pi D_o} - \frac{F_p}{4\pi Y_c D_o}, \qquad (15)$$

If ℓ_j is the distance from the outside of the slot to the midpoint of the area A - X, then ℓ_j is given by

$$\ell_j = \frac{(A - F_b/Y_c)w}{2\pi D_p}. \qquad (16)$$

We have also, $\ell_b = \ell_i + \ell_j$.

If the number of segments $\underline{w}$ is large, the position of the center of gravity of the exposed portion of each segment is given approximately by

$$R = \frac{1}{3}\left(\frac{D_g^3 - D_p^3}{D_g^2 - D_p^2}\right).$$

(The approximation involved is that of substituting half the angle subtended by the segment for the sinc of half the angle.)

Knowing the position of this center of gravity, we can write an expression for ℓ_c, namely,

$$\ell_c = \frac{1}{3}\left(\frac{D_g^3 - D_p^3}{D_g^2 - D_p^2}\right) - \frac{D_p}{2} + \ell_j. \qquad (17)$$

The equation for equilibrium is seen to be

$$\frac{F_p}{w} \ell_c = \frac{2}{3} f_r L_s + f_b \ell_b, \tag{18}$$

since we have assumed that $\ell_a = 2L_s/3$. We can solve this for f_r, all the other quantities being known.

The bearing stress on the rotating band due to f_r must depend on the area of the rotating band that is effective in resisting the overturning moment of the segment. This is unknown, but a value of the right order of magnitude may be obtained by assuming uniform pressure over half the length of the band, in which case the bearing stress is

$$S_b = 2w\underline{f_r}/\pi D_g L_s. \tag{19}$$

As to the bearing stress S_b that may be permitted upon the rotating band, we must be guided by experience. For example, the cantilever sabot shown in Fig. 9(a) gives a bearing pressure of about 28500 lb/in^2 as computed from Eq. (19). Under this pressure there is appreciable erosion of the rear portion of the rotating band; but, nevertheless, the design has been very satisfactory in performance.

The powder pressure on the projectile base must be transmitted through the necked-in portion at the groove level. With powder pressure $\underline{P}$, and the mass of the part of the projectile back of the necked-in portion equal to M_n (lb), we have for the compressive stress S_{c_2} in the necked-in portion,

$$S_{c_2} = \frac{P}{D_o^2}\left(D_p^2 - D_g^2 \frac{M_n}{M_s + M_p}\right) - \left(\frac{4wf_b}{\pi D_o^2}\right), \tag{20}$$

f_b being taken from the analysis just given. Equation (20) indicates a possibility that S_{c_2} may be negative, representing a tension in the necked-in portion. It is rather unlikely that such a condition will be met in practice, however.

The average vertical shearing stress is borne over an area of $\pi L_s D_p$ so that the vertical shearing stress in this type of sabot is given by

$$S_s = \frac{P}{4L_sD_p}\left(\frac{M_p}{M_s + M_p} D_g^2 - D_p^2\right) \text{ lb/in}^2 \qquad (21)$$

According to Boyd,[8/] the maximum shearing stress in a rectangular beam occurs along the neutral axis, and is $1\frac{1}{2}$ times the average vertical shearing stress. Thus, if Y_s is the yield point in shear of the sabot material, we must have

$$Y_s > \frac{1.5P}{4L_sD_p}\left(\frac{M_p}{M_s + M_p} D_g^2 - D_p^2\right) \text{ lb/in}^2 \qquad (22)$$

It is now necessary to examine the bending stresses in the segment, regarding it as a radial beam. The segment acts principally as a cantilever beam, though there is some support at the outer end due to friction against the gun barrel. The maximum bending moment will be found at the edge of the groove and will have the value,

$$M = \frac{F_p}{w}\left[\frac{1}{3}\left(\frac{D_g^3 - D_p^3}{D_g^2 - D_p^2}\right) - \frac{D_p}{2}\right] - f_r \frac{L_s}{4} \text{ lb in.} \qquad (23)$$

where f_r is determined by Eq. (18) and the choice of the moment arm as $\frac{1}{4}L_s$ is based on the assumption that the beam tends to turn about an axis $\frac{1}{2}L_s$ from the bottom and that f_r is applied $\frac{1}{4}L_s$ from the bottom. The second term of Eq. (23) is thus not known with much precision, but, fortunately, it is usually small in comparison with the first term. Then, if I (in.^{4}) is the moment of inertia of the cross section of the beam with respect to its neutral axis and c (in.) is the distance from the neutral axis to the outside edge, the maximum tensile stress in the beam is given by

$$S_t = Mc/I \text{ lb/in}^2 \qquad (24)$$

For a rectangular cantilever beam uniformly loaded, $c = \frac{1}{2}L_s$; and, to a good approximation, I is given by $I = \pi(D_p + D_g)L_s^3/24w$. The maximum tensile stress S_t that exists in the beam is then given by

8/ Boyd, Strength of materials, p. 211.

substitution in Eq. (24) of these values for I and c, and of M from Eq. (23). The stress S_t must be held below the tensile yield point of the material.

Thus far we have considered the stresses as acting independently; in other words, we have tacitly assumed that if S_s is the shearing stress due to one set of forces at some point in the material, and if S_t is the tensile stress at this point due to another set of forces independently considered, then the presence of S_s in no way affects the value of S_t, and vice versa. Actually, this is not the case. According to Boyd[9/] if S_s' is the maximum shearing stress, and S_t' is the maximum tensile stress, resulting from the simultaneous application of S_s and S_t, then

$$S_s' = \sqrt{S_s^2 + (\tfrac{1}{2}S_t)^2} \text{ and } S_t' = \tfrac{1}{2}S_t + \sqrt{S_s^2 + (\tfrac{1}{2}S_t)^2}$$

In most beams S_s is a maximum when $S_t = 0$, and S_t is a maximum when $S_s = 0$. Hence Eqs. (21) and (24) will usually suffice also for S_t' and S_s'. An exception to be noted is the case when $S_t > 2S_s'$. In this case S_t is not zero when S_s is a maximum, hence $S_s' > S_s$.

The condition for torque transmission is in this case approximately that exhibited in Eq. (9a). Actually, the torque will be transmitted with a value of f somewhat lower than that given by Eq. (9a), because of the wedging action in the groove, produced by the overturning moment.

The release of the bourrelet and sabot is, as stated before, centrifugal. The discussion of the bursting of the bourrelet is exactly as given for the flat disk type sabot discussed just previously; that is, the ultimate tensile strength of the bourrelet material must be less than the tensile stress S_t, where S_t is given by Eq. (12).

The discussion of the release of the sabot is quite similar, and differs only because of the variation in density of the sabot and rotating band material. If the mass of the rotating band is N_t (lb), the

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9/ Reference 8, pp. 295-298.

distance from the axis of the projectile to the center of gravity of one half the rotating band is R_t (in.), and the centrifugal acceleration per inch from the projectile axis is G (in units of acceleration of gravity), then the bursting force due to the rotating band alone is $\frac{1}{2}M_tR_tG$. If the semi-annulus considered is thin, R_t is given by

$$R_t = \frac{2}{\pi}\frac{D_g}{2} = \frac{D_g}{\pi}.$$

The bursting force due to the segmented sabot under the rotating band is obtained by exactly the same analysis as was used in obtaining Eq. (12). Hence the total force tending to burst the rotating band is given by

$$\frac{14.71}{2\pi}\left(\frac{v_o}{nD_g}\right)^2\left\{M_tD_g + \frac{M_D}{3}\left[\frac{(D_g - 2t)^3 - D_o^3}{(D_g - 2t)^2 - D_o^2}\right]\right\} \text{ lb},$$

where t (in.) is the thickness of the rotating band and M_D is the mass of the segmented steel under the rotating band. Thus the tensile stress in the rotating band will be given by

$$S_t = \frac{14.71}{4\pi tL_s}\left(\frac{v_o}{nD_g}\right)^2\left\{M_tD_g + \frac{M_D}{3}\left[\frac{(D_g - 2t)^3 - D_o^3}{(D_g - 2t)^2 - D_o^2}\right]\right\} \text{ lb/in}^2 \qquad (25)$$

The ultimate tensile strength of the material of the rotating band must be less than or equal to this S_t if the sabot is to burst. Quite often it happens at high velocities (of the order of 4000 to 5000 ft/sec) that the rotating band bursts of its own weight, so that it is not necessary to calculate the additional stress due to the weight of the sabot.

It should be pointed out that, while in both Figs. 8 and 10 and in the foregoing analysis it is assumed that the rotating band covers the entire length of the sabot, this may not always be the case and appropriate changes must be made in the formulas when this occurs.

This type of sabot has been found to be very successful. The sabot gives practically no disturbance to the projectile as it releases, and the subsequent flight of the projectile is not disturbed.

11. Threaded-base sabot

The threaded-base type is shown schematically in Fig. 11(a), and photographs of two models are given in Figs. 12 and 13. The principal change from the cantilever sabot is that the sabot is now held to the projectile by threads, thus eliminating the deep groove in the projectile. The sabot may be completely segmented radially into two or more segments held together by the rotating band, or it may be only partially segmented and held together by the uncut portion and the rotating band. The bourrelet, as before, is slotted with two or more radial slots carried to a distance d from the outside diameter. The release of both the sabot and bourrelet is centrifugal.

The stress calculations for this type of projectile are as follows.

By exactly the same analysis as for the cantilever-type sabot (Sec. 10) the force with which the sabot must press on the projectile is given by

$$F_p = \tfrac{1}{4}\pi P\left[\frac{M_p}{M_p + M_s} D_g^2 - D_p^2\right] \text{ lb.}$$

If the projectile has T threads per inch, of thread depth h (in.), the compressive stress on the thread faces is

$$S_c = \frac{P}{4TL_sD_ph}\left[\frac{M_p}{M_p + M_s} D_g^2 - D_p^2\right] \text{ lb/in}^2$$

If the weaker of the materials of the sabot and projectile has a compressive yield point of Y_c, we must have

$$Y_c > \frac{P}{4TL_sD_ph}\left[\frac{M_p}{M_p + M_s} D_g^2 - D_p^2\right] \text{ lb/in}^2 \qquad (26)$$

If the yield point in shear of the sabot material is Y_s, we must have (remembering that the maximum shear is 1.5 times the average vertical shear),

$$Y_s > \frac{1.5P}{4D_pL_s}\left[\frac{M_p}{M_s + M_p} D_g^2 - D_p^2\right] \text{ lb/in}^2 \qquad (27)$$

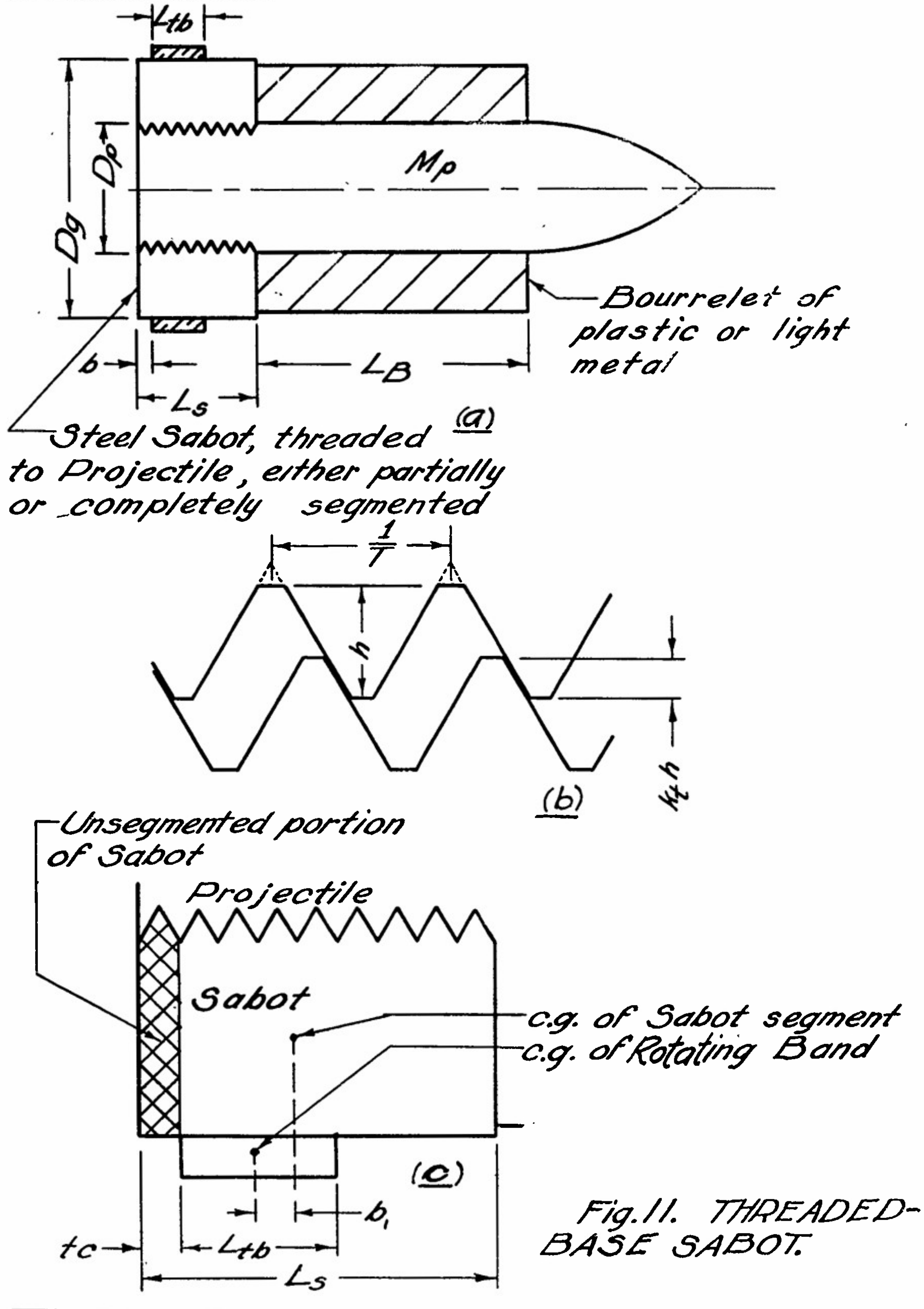
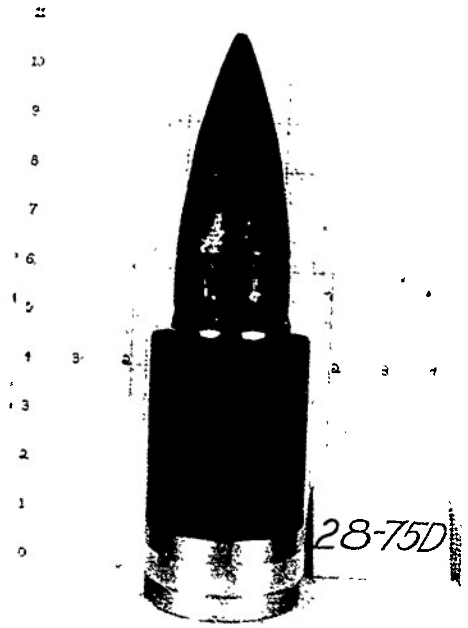
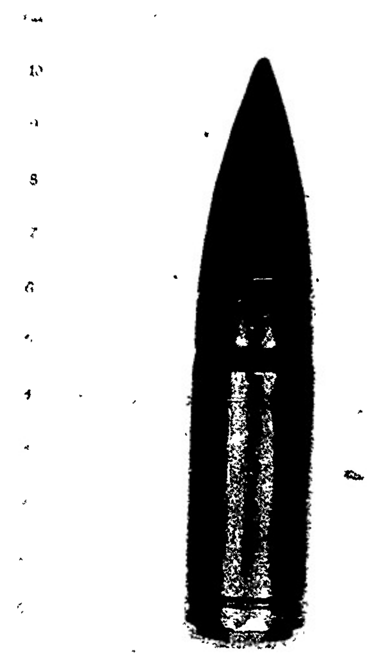


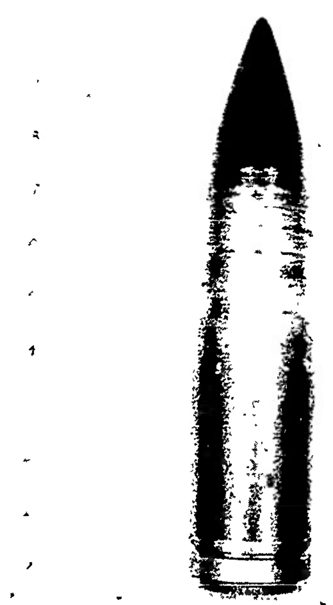
Fig. 11. THREADED-BASE SABOT.



(a)



(b)



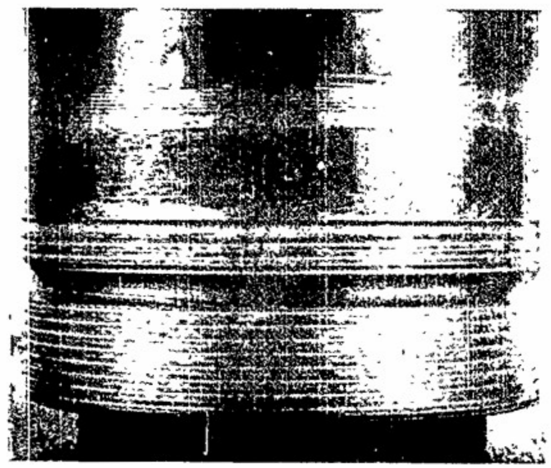
(c)

(a) The assembled projectile with sabot, ready to fire.

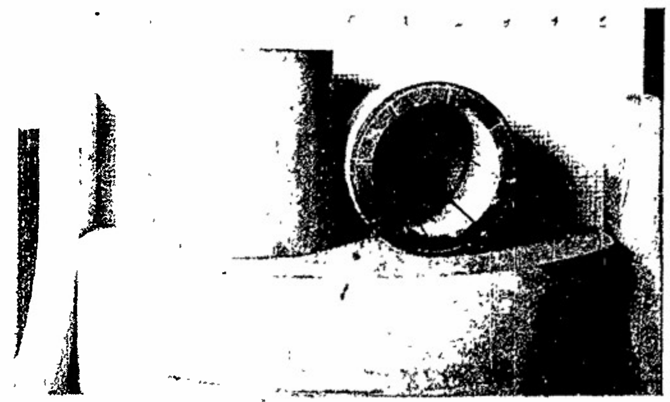
(b) The projectile proper as received from the factory.

(c) The projectile proper with base threaded, as it would appear in flight.

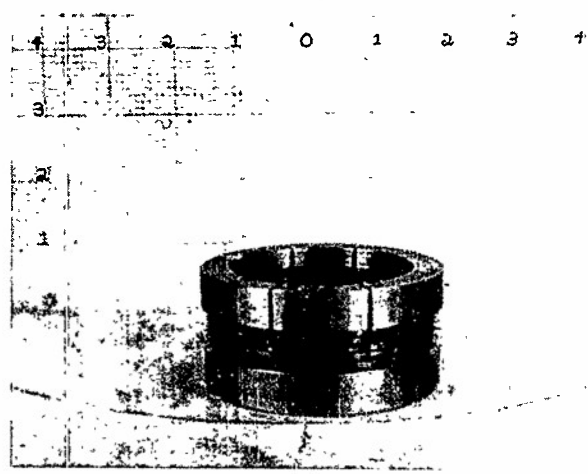
Fig. 12. Threaded-base sabot Model 28-75D for the 57-mm APC projectile, M86 in the 75-mm gun. A very successful design.



(d)



(f)



(e)

(d) A close-up of the threaded base. The groove shown in the upper portion of the threads was a crimping groove in the original projectile and has no function in this design.

(e) The sabot before banding. Note that this is a partially segmented sabot, the saw cuts extending only to a point under the rear of the rotating band. Though not evident in the figure, the rear portion of the sabot is turned out, forming a skirt for crimping in the powder case.

(f) The sleeve bourrelet. The material in this example is a phenolic plastic with macerated fabric filler. Bourrelets of various other plastics have been tried with practically uniform success.

Fig. 12. (Continued.)

This neglects any flats at the crest or base of the thread, and assumes the entire length L_s to be threaded. If only a portion of L_s is threaded, the length of the threaded portion should be used instead of L_s in Eqs. (26) and (27). Appropriate safety factors in steel have been found to be 1.5 for both compression and shear.

Equations (26) and (27) represent the conditions for a fully meshed thread. If, however, for some reason the threads become partially disengaged, as in Fig. 11(b), the situation is as follows.

Suppose the threads are meshed for a fraction k_t of their depth, so that the depth effective to take compressive stresses is hk_t instead of h. Then Eq. (26) becomes

$$Y_c > \frac{P}{4TL_sD_phk_t}\left[\frac{M_p}{M_s + M_p} D_g^2 - D_p^2\right] \text{ lb/in}^2 \qquad (28)$$

Also, the thickness per thread effective for shear stresses is k_t/T instead of $1/T$. Hence Eq. (27) becomes

$$Y_s > \frac{1.5P}{4D_pL_sk_t}\left[\frac{M_p}{M_s + M_p} D_g^2 - D_p^2\right] \text{ lb/in}^2 \qquad (29)$$

Each thread is also loaded as a cantilever beam, and stresses due to the bending must be considered. To a good approximation, the load on the cantilever beam thus formed is a point load at a distance $h - \frac{1}{2}hk_t$ from the base. The maximum tensile stress due to the bending is given by $S_t = Mc/I$, where these symbols have been defined in Sec. 10, the discussion of the cantilever sabot. Here $c = 1/2T$ (in.),

$$M = \tfrac{1}{4}\pi P\left[\frac{M_p}{M_s + M_p} D_g^2 - D_p^2\right][h - \tfrac{1}{2}hk_t],$$

and I, the moment of inertia of the section at the base of the thread, is $\pi D_pL_s/12T^2$. Consequently we may write,

$$S_t = \frac{3TP}{2L_sD_p}\left[\frac{M_p}{M_s + M_p} D_g^2 - D_p^2\right][h - \tfrac{1}{2}hk_t] \text{ lb/in}^2 \qquad (30)$$

The yield point in tension of the sabot material must be greater than or equal to S_t as given by Eq. (30). In practice, k_t usually exceeds 3/4, and a value of $k_t = \frac{1}{2}$ probably gives an adequate safety factor. It should be kept in mind that near the muzzle the centrifugal force may spread the sabot closing up any clearance between the lands and sabot and partially disengaging the threads. When this occurs, P is small of course. A more serious effect lies in the tendency of the completely segmented sabot of this type to overturn under powder pressure. Here the rear portion of the thread becomes partially disengaged at a time when P is large. The design should be such that this effect is geometrically limited, and a proper safety factor should be provided in accord with Eqs. (28), (29) and (30). The type with an unsegmented rear section is free from this overturning tendency if the unsegmented section is of sufficient strength.

While the foregoing discussion of thread strengths probably approximates the truth, we have found that experimental testing of the various threads is the surest and quickest way to determine their strength. Thus it has been found (at least in some materials) that the number of threads per inch has an important effect on the strength of the thread, although according to our simple theory this should not enter. [In Eq. (26) the product of T and h is a constant equal to 0.6495 for U.S. standard threads.]

The condition for torque transmission is given as previously by $f \gtrsim a\pi A/nr_2r_gF_p$, where now $r_2 = \frac{1}{2}D_p$, and F_p is given by

$$F_p = \frac{1}{4}\pi P\left[\frac{M_p}{M_p + M_s} D_g^2 - D_o^2\right]$$

and as before $a = \frac{1}{4}\pi PD_g^2/(M_s + M_p)$. Making these substitutions the condition becomes

$$f \geqq 4\pi AD_g/nD_p[M_pD_g^2 - (M_s + M_p)D_o^2].$$

This analysis holds exactly for buttress-type threads. If the threads are of V form, the wedging action of the inclined surfaces tends to increase the force normal to the thread face, which allows even a smaller value for the coefficient of friction. Another factor that has not been considered and one which permits a smaller value of f is the fact that for a right-hand thread on the projectile the sabot screws against a shoulder equal to the depth of the thread. In general, this type of sabot is quite free from difficulty with torque transmission.

The overturning tendency of the segments, particularly in the case of complete segmentation, must be resisted by bearing pressure on the rotating band as in the cantilever sabot. The overturning moment becomes smaller as the number of segments decreases, since the center of pressure on each segment then moves farther in toward the axis of the projectile. Indeed, for most usable ratios of projectile to gun diameter, if the number of segments is two, the center of pressure is inside the edge of the projectile and the segment cannot overturn. In many cases, however, the center of pressure will be outside the edge of the projectile and an overturning moment will exist. If such is the case, it has been found in practice that if $L_s \geqq D_g - D_p$, and the rotating band is well back on the sabot, there is little likelihood of trouble.

The release of the bourrelet is exactly the same in this case as in the two cases previously discussed, and Eq. (12) still applies for the tensile stress in the bourrelet.

The bursting of the rotating band which holds the sabot together needs to be discussed for two cases. These are when (i) the rotating band is centered over the center of gravity of the sabot, and (ii) the center of gravity of the rotating band is displaced forward or backward from the center of gravity of the sabot by a distance b_1 (in.). Consider first case (i). Here the stresses are exactly the same as in the cantilever-type sabot, and Eq. (25) gives the bursting stress in the band.

In case (ii), the sabot will act as a lever and the bursting stress in the band will be larger than in case (i). The stress in the band due to its own mass [given by the first term in Eq. (25)] is

$$\frac{14.71}{4\pi t L_{tb}}\left(\frac{v_o}{nD_g}\right)^2 M_t D_g \text{ lb/in.}^2$$

The stress in the band due to the steel sabot is given by the ordinary relation for forces in a lever. Thus the moment of a sabot-segment about its base (using a two-segment sabot for simplicity) is given by

$$M_r = \frac{14.71 M_s}{3\pi}\left(\frac{v_o}{nD_g}\right)^2 \left[\frac{D_g^3 - D_p^3}{D_g^2 - D_p^2}\right] \frac{L_s}{2} \text{ lb in.} \qquad (31)$$

This produces a force F_s on the rotating band, given by

$$F_s = M_r/(\tfrac{1}{2}L_s - b_1)$$

and the stress due to the steel sabot is $S_t' = F_s/2L_{tb}t$ lb/in.² Thus the total stress tending to burst the rotating band is given by

$$S_t = \frac{14.71}{4\pi t L_{tb}}\left(\frac{v_o}{nD_g}\right)^2 \left[M_t D_g + \frac{M_s L_s}{3(\tfrac{1}{2}L_s - b_1)}\left(\frac{D_g^3 - D_p^3}{D_g^2 - D_p^2}\right)\right] \text{lb/in.}^2 \qquad (32)$$

The ultimate tensile strength of the rotating band S_{tb} must be less than S_t as given by Eq. (32). The foregoing analysis applies satisfactorily to the completely segmented type of sabot. It is sometimes convenient, however, to segment the sabot only partially. This not only serves to resist the tendency of the segments to overturn, but also the unsegmented portion can be made to extend all the way across the rear face of the sabot to serve as a gas seal, eliminating the necessity of making closely fitted segments, which is necessary in the completely segmented type.

If the sabot is only partially segmented, the bursting tensile stress is calculated as before, except that now the sabot must, in addition to furnishing the necessary moment to burst the rotating band, also supply the moment necessary to break the uncut portion of the sabot. If the ultimate tensile strength of the sabot material is S_u, then $M_u = S_u I/c$ is the moment required to break this uncut portion. Here $\underline{I}$ and $\underline{c}$ are as defined previously. Suppose, for example, the uncut portion of the sabot to be of thickness t_c and of rectangular cross section as shown in Fig. 11(c). Then, for this particular case, substituting the appropriate values for I and c, we have,

$$M_u = S_u(D_g - D_p)t_c^2/12 \text{ lb in.}$$

The moment furnished by the sabot mass is M_r in Eq. (31). We must now have $M_r > 2M_u + 2M_v$, M_v being the portion of the moment required to break the rotating band, and being given by

$$M_v = \left[S_{tb}L_{tb}t - \frac{14.71}{4\pi}\left(\frac{v_o}{nD_g}\right)^2 M_tD_g\right][\tfrac{1}{2}L_s - b_1] \text{ lb in.},$$

where S_{tb} is the ultimate tensile strength of the rotating band material, and the other quantities are as previously defined.

While the foregoing analysis has been carried out for a two-segment sabot, it will be found that exactly the same equations apply to a sabot of any number of segments.

This type of sabot has given good results. The sabot releases with very little disturbance of the projectile, and dispersions of from 1 to 2 minutes of arc have been obtained on a target at 1000 yd.

12. The all-plastic sabot

The all-plastic type is pictured in Fig. 14 and shown schematically in Fig. 15. It is essentially the same as the threaded-base sabot, except that the grooves (or threads) usually run a considerable distance along the projectile. The release is centrifugal. The sabot and bourrelet are of the same material (plastic) so that it is unnecessary to distinguish between them. The rotating band is grooved (or threaded) on the lathe and is then molded (or screwed) onto the sabot. The sabot itself is molded (or screwed) onto the projectile.

The all-plastic type offers many advantages to the sabot designer. If the sabot is molded onto the projectile, the manufacturing problems are less difficult than for a machined type. The mass of the sabot can be made quite small thus allowing the attainment of higher velocities for a given projectile mass than with any other type of sabot. Since the sabot fragments are lighter, the range of these fragments is less than for corresponding steel fragments, and the danger from these fragments is correspondingly reduced. On the debit side of the picture appears the fact that the projectile must be altered (threaded or grooved) for a considerable portion of its length, with perhaps unfavorable effects on its piercing characteristics and ballistic coefficient. Also, (at least at the present state of development) occasional unexplained failures (of the order of 15 percent) of this sabot type occur in the gun, even for a design that ordinarily gives quite good results. For want of a better explanation, these failures have been attributed to lack of uniformity in the plastic.

Fig. 13. Threaded-base sabot designed for the Navy 6-pdr. gun. On the right is the assembled projectile, on the left is the assembly without the sleeve bourrelet, while the plastic bourrelet is shown in the center. This design was not too successful in tests, probably due to low stability of the projectile proper. It is to be pointed out that the sabot — completely segmented in this case — is not particularly well guarded geometrically against overturning. However, through the conical rear portion, the powder pressure provides a moment resisting the overturning, if there is no leakage of the powder gases into the threads. This assumption is perhaps not too well justified.

Fig. 14. An all-plastic sabot designed for the Navy 6-pdr. and made by molding the plastic around the projectile, the rotating band being an insert in the mold. Weakening of the bourrelet is obtained by preformed plastic inserts secured before molding by staking in the longitudinal slots shown in the projectile. These projectiles, together with numerous other designs, have been fairly successful though it has so far been impossible to eliminate occasional failures (see Sec. 12).

(a) Left to right, the completed assembly, the projectile proper before molding, a projectile recovered after firing, an inside view of a segment of the plastic sabot removed from an unused projectile, one of the plastic fin inserts, and an inside view of a plastic segment recovered after firing.

(b) Left to right, a base view of the complete assembly showing the plastic fins, a rotating band before molding, and an outside view of a segment recovered after firing.

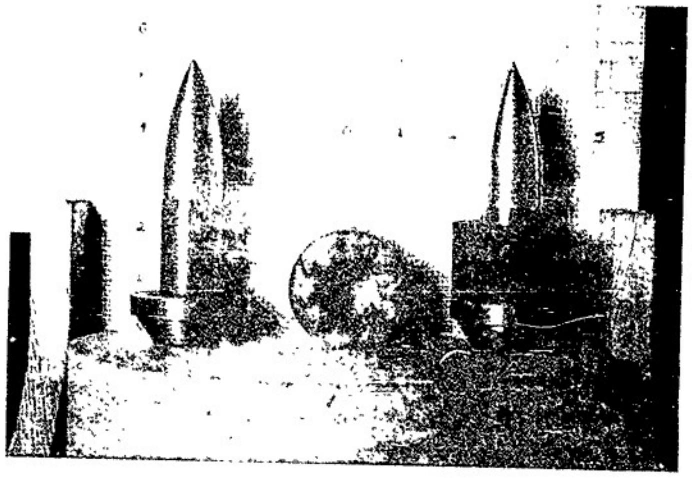


Fig. 13

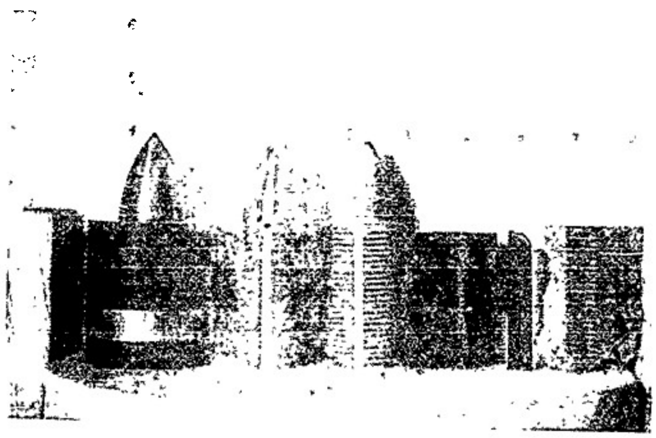


Fig. 14(a)

Fig. 14(b)

The stress analysis for this type of sabot is essentially the same as for the threaded-base sabot. It usually is not necessary to give attention to such matters as the overturning of the sabot segments in the gun, since these are much longer than the segments for the threaded-base sabot. Another essential difference is due to the small modulus of elasticity of plastics ($\underline{E}$ is of the order of 10^6 lb/in.² for plastics, as compared to 30×10^6 lb/in.² for steel). This means that the strain for a given stress is about 30 times as large for plastics as for steel. Hence the stress in the threads holding the sabot to the projectile is concentrated in the threads toward the base of the projectile, rather than distributed over the entire length of the threads. The amount of this stress concentration is difficult to predict, but the use of a safety factor of about 2 has resulted in successful designs of this type.

Since the plastic is exposed to the powder gases, the compressive strength of the plastic should be greater than $\underline{P}$, the maximum powder pressure, in order to avoid crushing at the rear of the sabot. For modern phenolic formaldehyde plastics, the compressive strength is about 40 000 lb/in.² while most modern guns have maximum pressures that are somewhat less than this. (The pressures usually run from 30 000 to 38 000 lb/in.² although for the 20-mm Hispano-Suiza, for example, the maximum pressure is 48 000 lb/in.² and for the 37-mm A.T. gun it is 50 000 lb/in.²).

Attention also should be directed to the fact that most plastics (particularly the laminated type) are not isotropic. This must be considered in the sabot design, so that the high stresses are applied in the direction of maximum strength of the plastic.

The condition for adequate torque transmission from the sabot to the projectile is again given by Eq. (8), where r_2 is equal to $\frac{1}{2}D_p$.

In practical designs of all plastic sabots it has been found necessary to fill the longitudinal slots, either by inserting plastic or metal slips, or by closely fitting the segments and holding them together with an over-all sleeve. Otherwise, there is a tendency toward relative motion between the segments during transmission of torque

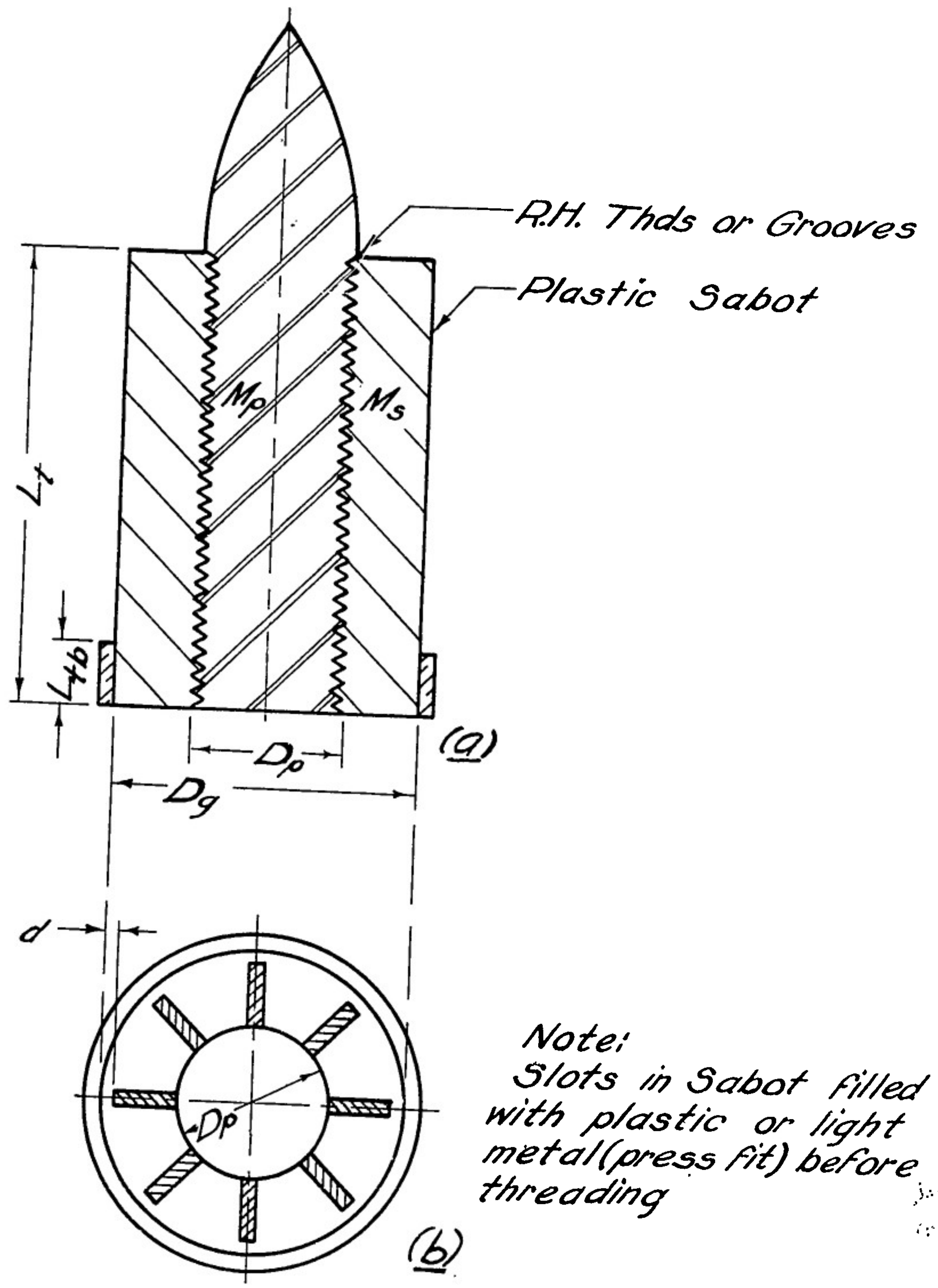


Fig. 15. ALL-PLASTIC SABOT.

which may result in failure in the gun. Filling of the slots, at least for part of the length, is necessary, also, to effect the gas seal.

The release of the sabot is centrifugal, and the stress analysis relevant to this matter is the same as that given for the threaded-base type (Sec. 11). That is, the centrifugal force developed by the plastic sabot must be sufficient to burst the uncut portion of the sabot, and the sabot must also supply the extra force needed to burst the rotating band if it does not burst under its own weight.

It should be mentioned that recently successful all-plastic sabots have been built without the weakening slots, even though the bursting tensile stress as calculated from Eq. (12) is much below the supposed strength of the plastic. The explanation of this ultimately will be found to be similar to that of the same effect encountered in the bourrelets described in Sec. 9 and cannot as yet be given.

Except for the occasional unexplained failures previously noted (which are structural failures and occur in the gun) this type of sabot behaves very well. The sabot segments are released with very little disturbance of the projectile, and the subsequent flight characteristics of the projectile are good.

13. Concluding remarks

A simple analysis relating to the length of a column of a given material that can be fired at an acceleration $\underline{a}$ (with the acceleration of gravity as the unit) may be useful to the sabot designer. Thus if the material considered is a cylinder of diameter $\underline{D}$ (in.), length $\underline{L}$ (in.), density $\underline{\rho}$ (lb/in.^{3}) and if it has a compressive yield point Y_c (lb/in.^{2}) then we must have

$$\frac{\frac{1}{4}\pi D^2 L\rho a}{\frac{1}{4}\pi D^2} < Y_c, \quad \text{or} \quad L\rho a < Y_c,$$

if the base of the column is not to flow. From this relation we see that a column of length $\underline{L}$ can be given an acceleration $\underline{a}$ without flowing, where

$$L < Y_c/\rho a. \tag{33}$$

This is a limiting condition that is useful in projectile and sabot design.

Attention should be drawn to some unsuccessful attempts to use dural for sabots. This material naturally recommends itself to the sabot designer by its high strength-weight ratio. However, this high ratio is not maintained at elevated temperatures. Tests made at the University of New Mexico show that (at least in sections up to the order of 0.125 in. thickness) the shearing strength of dural exposed to the powder gases is only one-fourth the shearing strength it exhibits under static loading at room temperature. The effect is possibly due to two things: (i) ordinary heat conduction into the dural from the hot powder gases, and (ii) a thermitic type of reaction between the dural and the powder gases that apparently liberates large quantities of heat at the surface of the dural. If the dural is insulated from the powder gases, neither effect occurs, and successful insulated sabots of this type have been made. Also, if the dural is in massive sections it is probable that neither of these effects will materially weaken the sabot.

In this connection it is only fair to point out that other designers, notably C. L. Critchfield,[10/] have used dural with some success even when it is exposed directly to the powder gases.

No such anomalous results have been found for steel: the strengths obtained in ordinary static tests seem to be quite applicable to sabot design.

For plastics the situation is not so clear. Thread strengths in the gun seem to be at least as great as observed in static tests, and may be even slightly greater. The compressive strengths given by the plastic manufacturers seem to be quite applicable to sabot design, but, as mentioned before, there is some doubt about the tensile strengths. The subject needs further investigation.

10/ At the Geophysical Laboratory, C.I.W. See C. L. Critchfield and J. McG. Millar, Development of subcaliber projectiles for the Hispano-Suiza gun, NDRC Report A-233 (OSRD No. 2067).

14. Summary

While we have given examples of methods of stress calculation that apply to a number of sabot types, we have not attempted to cover the modifications necessary as design variations are met. It is intended, however, that the examples call attention to the types of stress calculation needed and that these serve more or less as prototypes.

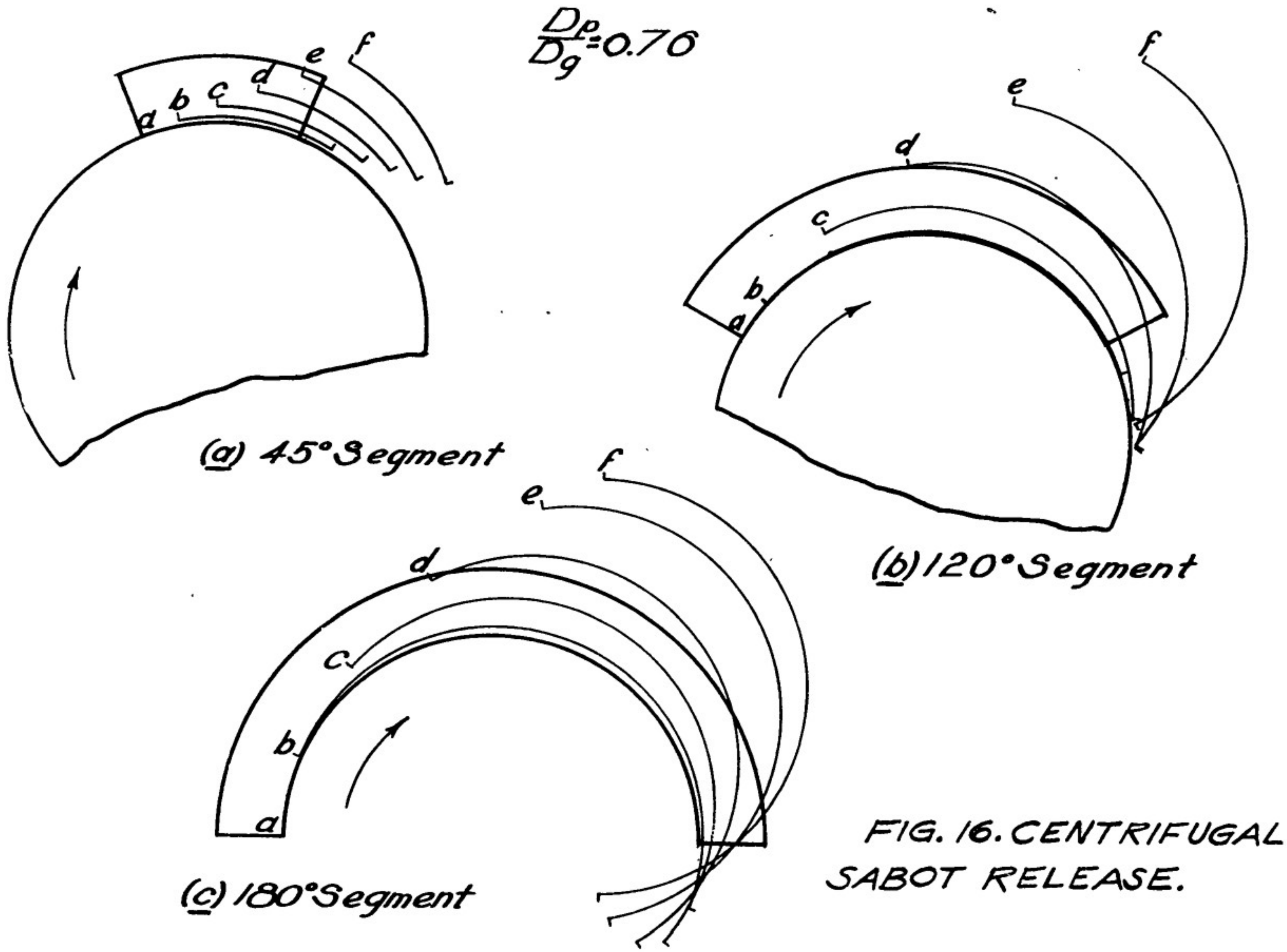
In view of the nature of the problem, it should be emphasized that no amount of theoretical work will give complete insurance that a particular sabot design will be successful. A considerable number of models should be built and gun-tested -- with proper provision for safety of personnel and equipment. A considerable number of unexpected results -- some favorable and some unfavorable -- have occurred during the past work on the problem, and probably others will occur in the future.

III. DESIGN CONSIDERATIONS: THE CENTRIFUGAL RELEASE

15. The ideal case

In all the successful sabot types that we have described, part or all of the sabot is a sleeve around the cylindrical part of the projectile. This is released and escapes from the projectile as a result of centrifugal force, tensile failure being produced in the sleeve material. In actual practice this centrifugal release may not be quite so simple as in the ideal case first to be considered, but it will be of interest to examine it, nevertheless.

We are interested in the relative motion of projectile and released sabot part. Figure 16(a) is a cross section of a projectile and one 45^o sabot (or bourrelet) segment; the whole is to be imagined as initially spinning clockwise. The diameter ratio shown, $D_p/D_g = 0.76$, corresponds to the 75-57 mm combination. The segment is imagined to be suddenly freed of all restraint at its position a. The segment



(a) 45° Segment

(b) 120° Segment

(c) 180° Segment

FIG. 16. CENTRIFUGAL SABOT RELEASE.

then moves through a sequence of positions labeled b, c, and so forth, these positions being determined by a simple graphical construction based upon movement of the center of gravity of the segment at a constant velocity along the tangent at the release position, and upon maintenance of a constant angular velocity of the segment about an axis through its center of gravity perpendicular to the paper.

It is seen in this case that the segment loses contact with the projectile body immediately after release, and is not in contact with it at any later time. This condition applies to all segment widths up to 120° (for the ratio $D_p/D_g = 0.76$), the 120° case being shown in Fig. 16(b).

In Fig. 16(c) we have the same construction for the case of the 180° segment. In this drawing the motion shown is that which would occur if the projectile body were not present. If the projectile is present this motion will be modified, of course, and the inside right-hand corner of the segment will press against the projectile for a short period with considerable force. This is found to have occurred in threaded-base sabots of the type shown in Fig. 12(a), when the sabot has been partially segmented by only two saw cuts spaced 180° apart. The inside corner of recovered segments shows rounding and abrasion, the abrasion resulting from the relative angular motion between projectile and segment which, as can be seen from Fig. 16(c), is quite likely to exist.

To be sure, this lateral force on the projectile does not necessarily result in its deflection. If the other segment is pressing symmetrically on the projectile, there will be no disturbance. However, because of the possible nonsimultaneity of breaking of the restraints, this perfect symmetry may often be lacking, and it seems that the danger of disturbance will be greater for the 180° segments than for segments of 45° or 90°.

16. Practical considerations

The preceding considerations, while academically interesting, are complicated in practice by possible nonsimultaneity of breaking at the weakened sections, by overturning effects due to the muzzle blast or lever action on uncut portions, by centrifugal distortion of the segment itself after release, by elastic rebounds, and so forth.

Nonsimultaneity of release, for the D_p/D_g ratio just discussed, is not likely to result in flight disturbance as long as no unbroken segment persists appreciably whose angle is more than 120°.

In the case of, say, an eight-segment sabot, three or four segments may tend to hang together for a short interval and they then may conceivably exert a lateral push on the projectile. However, owing to the spin of the unbroken section about its own center of gravity, there is a strong centrifugal force tending to straighten out such a string of segments and thus draw the interfering corner away from the projectile.

In the case of the two-segment sabot, nonsimultaneity might be more serious. If the sabot breaks at only one point there probably will be a rather energetic lateral push.

The nonsimultaneity difficulty can be minimized in any case by allowing in the design a considerable margin between the tensile strength and the breaking strength resulting from the centrifugal force.

In the case of a 180° segment of steel, the centrifugal force due to its rotation about its own center of gravity after release, tends to straighten it out. In the 75-57 mm case mentioned, the ends of recovered segments are found to have opened out 1/8 in. or more. This effect probably tends to reduce the deflecting force on the projectile, but, from the markings on the segments, does not eliminate it entirely.

In the case of plastic bourrelets without weakening slots, not enough is known of the detailed sequence of events to permit adequate discussion. The character of the breaks in recovered fragments of the 75-57 mm projectiles strongly suggests that, in some cases at least, the initial tensile failure gives two segments of approximately 180° each. Subsequently the centrifugal force breaks each of these into three parts by a combination of bending and shearing stress. Whether or not there is a deflecting force on the projectile depends on the time lapse between the original failure and the final subdivision into six segments. The excellent performance attained suggests that this time lapse is very small, or that excellent symmetry is maintained.

IV. DESIGN CONSIDERATIONS: STABILITY

17. The stability factor

The fundamental condition for stability of a spinning body is[11/]

$$A^2N^2/4B\mu > 1, \tag{34}$$

where $\underline{A}$ is the moment of inertia with respect to the spin axis, $\underline{B}$ is the moment of inertia with respect to a transverse axis through the center of gravity, $\underline{N}$ is the spin speed in radians per second, and $\underline{\mu}$ is a proportionality factor such that the overturning moment $\underline{M}$ is given by the equation,

$$M = \mu \sin \delta, \tag{35}$$

where $\underline{\delta}$ is the angle of yaw. The left-hand side of Eq. (34) is called the stability factor $\underline{S}$, or

$$S = A^2N^2/4B\mu. \tag{36}$$

11/ Hayes, Elements of ordnance (Wiley, 1938), p. 417.

The quantities A and B are, of course, constants for a given projectile; while μ depends upon velocity, air density and viscosity, as well as upon the dimensions and mass distribution of the projectile and upon δ in Eq. (35) except possibly when δ is very small. A general theoretical approach to the stability problem is seen to be of considerable difficulty. However, it is possible to determine S experimentally by observation of the period of yaw, and after S is known for a given projectile with given velocity and spin, Eq. (36) can be used to obtain S for any other spin at the same velocity.

18. Stability of subcaliber projectiles

In general, sabot-projectiles are fired with lower spin than are similar projectiles fired from guns of their own caliber. This makes the stability question one of critical importance, and places practical limits upon the sabot-projectiles that can be fired from a particular gun. For example, most 57-mm projectiles can be used with sabot in a 75-mm gun with satisfactory stability, but some 37-mm projectiles apparently cannot. It is theoretically possible, of course to make a projectile of the mass of the 37-mm projectile that will be stable when fired from the 75-mm gun, but in most cases it will be at the expense of the ballistic coefficient and penetration.

We may gain a little more insight into the stability problem by the usual substitution in Eq. (36) of $N = 24\pi v_o / n D_g$ and of the relation[12/]

$$\mu = K_m \rho D_p^3 v_o^2,$$

where v_o (ft/sec) is the muzzle velocity, n is the number of calibers per turn of rifling of the gun, D_p (in.) is the diameter of the projectile, D_g (in.) is the diameter of the gun bore, ρ (lb/in³) is the density of air and K_m is the moment coefficient. We then have

$$S = 144\pi^2 A^2 / B K_m \rho n^2 D_g^2 D_p^3, \qquad (37)$$

12/ Reference 11, p. 412.

where S is the stability factor at the muzzle for a given projectile fired from any gun. Since, in general, the stability increases along the trajectory, this equation is sufficient for a discussion of the stability problem. Suppose we now set $K_p = 144\pi^2 A^2/B\rho D_p^3$, which is constant for a given projectile in given air. Then Eq. (37) becomes

$$S = \frac{K_p}{K_m} \cdot \frac{1}{(nD_g)^2}. \qquad (38)$$

This, at first glance, indicates that S is independent of the velocity. However, it must be remembered that the moment coefficient K_m varies with velocity, and in a different manner for different projectiles. Not much information appears to be available regarding K_m at the higher velocities, but judging from the trend for muzzle velocities from 1100 to 2500 ft/sec there is a tendency for K_m to decrease with increasing velocity. This means that we probably are on the conservative side if we assume K_m to be constant and use the value obtained for ordinary velocities.

From Eq. (38) we see, then, that the stability factor of a projectile fired from different guns varies inversely as $(nD_g)^2$, nD_g being the length of one turn of the rifling (at the muzzle, in case of variable pitch).

Let us take as an example the 57-mm APC projectile, M86. In its own gun with $n = 30$ it has an estimated S of 1.68. This projectile has been fitted with a sabot and fired from a 75-mm gun, with $n = 25.6$. From Eq. (38) we may compute the new stability factor as

$$S = 1.68 \left(\frac{30 \times 57}{25.6 \times 75}\right)^2 = 1.33.$$

Measurements carried out for this combination at the New Mexico Proving Ground[13] gave a stability factor of about 1.31 at standard conditions,

13/ "Stability of the 57-mm, M86 projectile saboted in the 75-mm tank gun, M3." Special Report under Contract OEMsr-668, Oct. 26, 1943, available in the files of Division 1, NDRC.

which should be considered good agreement. The ratio 1.33/1.68 is in this case a good approximation because the muzzle velocity in the 57-mm gun is about 2700 ft/sec as compared with 2800 ft/sec in the 75-mm gun. Accordingly, K_m is very nearly the same in the two cases.

Let us take as a second example the 37-mm APC projectile, M51 for which, when fired from its own gun, the stability factor is given as 3.1, with $n = 25$. Suppose we fit this projectile with a sabot in the same 75-mm gun. We then have the new stability factor,

$$S = 3.1\left(\frac{25 \times 37}{25.6 \times 75}\right)^2 = 0.72.$$

It appears that in this combination the projectile is probably unstable. There is the possibility of a compensating change in K_m in this case, however. If the M51 projectile (weighing 1.9 lb) is used in a sabot giving a total mass of 2.7 lb, a velocity of 4700 ft/sec is attainable, as compared to 2900 ft/sec in its own gun. If K_m at 4700 ft/sec is less than 0.72 times its value at 2900 ft/sec, then we may have $S > 1$ and the projectile will be stable. With present information it is impossible to predict whether this may be the case, and the conclusion must depend upon actual tests.

Experience has indicated that values of $\underline{S}$ too near to 1 are not desirable for sabot-projectiles because of small unavoidable disturbance of the flight during the release of the sabot. However, $S = 1.3$ seems to be a fairly safe value.

The result for the 37-mm projectile, M51 does not necessarily mean that no 37-mm projectile can be used with sabot in the 75-mm gun. In fact, the projectile need be modified only to the extent of giving it a value of $S = 5.4$ in its own gun for it to have a value of $S = 1.3$ in the 75-mm gun. A 40-mm projectile has been successfully fired with sabot in the 75-mm gun, though this was a solid shot of 3.2 calibers length that inherently has considerably higher stability than the 37-mm APC projectile, M51.

For another discussion of the stability of subcaliber projectiles, together with other matters, the reader is referred to a report by Critchfield.[14]

19. Nonspin stabilization

It should here be brought out that sabot projectiles offer an excellent opportunity to make use of means other than pure spin for attainment of stability. As far as is known, little advantage has yet been taken of this opportunity.

When fin stabilization is combined with spin stabilization the fins should not be axial but should be placed on the projectile body at an angle corresponding to the angle of rifling in the gun. Interference of the fins with the spin should then be negligible, at least in the early part of the flight. There will be some interference after the velocity has decreased, but there should be by then no difficulty in maintaining stability.

It has been proposed also that stability be increased by use of a hollow tail extending to the rear of the projectile. Critchfield[14/] has discussed this device and has concluded that little improvement in stability is to be expected. However, the conclusion was based upon experimental results of H. P. Hitchcock which indicated that for conventional projectile proportions the position of the center of pressure is practically fixed with respect to the projectile head, and thus is independent of the length of the body. However, it seems somewhat unlikely that this result can apply to a very great range of projectile lengths and further investigation seems indicated before the device is finally abandoned.

These considerations suggest the ultimate possibility of attaining high velocity with a smoothbore gun, using sabot-projectiles. The design of sabots obviously will be much easier for such a gun than for a rifled gun, not to mention advantages inherent in the smoothbore gun itself.

Also to be mentioned is the possibility that departure from conventional projectile proportions may lead to improvement in ballistic

14/ C. L. Critchfield, Stability of subcaliber projectiles, NDRC Report A-88 (OSRD No. 870), Sept. 1942.

coefficient as well as improvement in stability. A large field for research is open here, and it is hoped that facilities may be offered for its exploration.

V. EXTERIOR BALLISTICS OF SUBCALIBER PROJECTILES

After the subcaliber projectile has discarded its sabot, its trajectory may be calculated by the usual methods, provided valid resistance data are available. The present resistance tables have an experimental basis at velocities below 4000 ft/sec, but the entries above this velocity have been obtained by extrapolation. Until the validity of such hypervelocity entries has been established by test firings, some uncertainty must always exist in regard to conclusions based on the use of the upper registers of the various resistance tables; and this fact must be borne in mind in appraising the value of the discussion given in the present chapter.[15/] However, on theoretical grounds there seems to be no reason to anticipate such anomalous behavior in the hypervelocity region as occurs in the neighborhood of the velocity of sound; and it therefore appears unlikely that errors of any considerable amount will result from use of the hypervelocity portions of the standard resistance tables.

In some cases subcaliber projectiles will happen to have ballistic coefficients somewhat lower than those of conventional projectiles of the same over-all proportions, owing to the presence of threads or grooves incidental to the attachment of the sabots. This effect should be slight, in general.

20. Simplifying assumptions

In order to discuss subcaliber exterior ballistics with a minimum of complication, we shall make the following simplifying assumptions:

15/ It has recently been learned that some experimental retardation data exist in the 4400 to 5000 ft/sec range (O.B. Proc. No. 11388. E.B.D. Report No. 11). These data have not been received in time for consideration in this report.

(i) Attention shall be restricted to ranges so short that the effect of the gravitational field on the motion of the sabot-projectile is negligible. (In the discussion that follows approximate values will be obtained for the ranges in which the vertical component of the motion of various sabot-shells is negligible.)

(ii) If $\underline{M}$ (lb) is the weight of a projectile and $\underline{D}$ (in.) is its diameter, it is assumed that $M = \lambda \cdot D^3$ (Such a relation with $\lambda = 0.6$ holds to a fair degree of approximation for a considerable range of AP projectiles.)

(iii) Let M_p be the mass of a subcaliber projectile and M_o the mass of this projectile plus its sabot. Then if D_p is the diameter of the subcaliber projectile and D_g is the diameter of the gun from which it is fired, it is assumed that

$$M_o = M_p/1.09(D_p/D_g) = 0.93M_p(D_g/D_p). \tag{39}$$

This relation is an empirical one that applies with a fair degree of approximation to a large number of sabot-projectiles designed at the University of New Mexico.

(iv) Let the subcaliber muzzle velocity be v_p (ft/sec) and the standard full-caliber velocity be v_g (ft/sec). Then for all values of $\underline{\lambda}$ we have

$$v_p = 1.04\, v_g(D_g/D_p). \tag{39a}$$

This relation is implied by our assumptions (ii) and (iii) and the constant muzzle energy condition expressed in Eq. (2) of Chapter I.

(v) Attention is confined to the velocity range $1300 \leqq v_p \leqq 6000$.

21. Ballistic coefficient

The ballistic coefficient $\underline{C}$ is defined by the relation

$$C = M/iD^2 \tag{40}$$

where $\underline{i}$ is the form factor, $\underline{M}$ (lb) is the weight and $\underline{D}$ (in.) is the diameter of the projectile. In view of assumption (ii), Eq. (40) implies

$$C = \lambda D/i. \tag{41}$$

Hence, the ballistic coefficients C_1 and C_2 of two projectiles having the same form factors, $i_1 = i_2$, and having diameters D_1 and D_2, respectively, satisfy the relation.

$$C_1/C_2 = D_1/D_2. \tag{42}$$

Subject to our assumptions then, the ballistic coefficient C_1 of a subcaliber projectile fired from a cannon of caliber D_2 is always D_1/D_2 times less than the ballistic coefficient C_2 of a full-caliber shell with the same form factor. Since stability considerations prevent lengthening the subcaliber projectile in order to obtain a more favorable (that is, a smaller) form factor i_1 and may require a shortening and subsequent increase in i_1, it follows that C_1 will always be less than C_2 by a factor <u>at most</u> equal to the ratio D_1/D_2.

22. Distance-velocity relationships

The Gavre table gives $-C\,dv/dt$ as a function of $\underline{v}$, where $\underline{v}$ (ft/sec) is the velocity and $\underline{t}$ (sec) is the time. Let $-C\,dv/dt = F(v)$; then $-C\,dv/ds = F(v)/v$, $\underline{s}$ (ft) being the displacement along the assumed rectilinear trajectory. Let $G(v) = F(v)/v$; then $G(v)$ is obtainable from the Gavre table[16] by dividing each value of $F(v)$ by the corresponding value of $\underline{v}$. Hence, it is possible to plot $G(v)$ against $\underline{v}$; and then to obtain by curve-fitting an approximate analytic expression for $G(v)$ as a function of $\underline{v}$. Proceeding in this manner it is found that for $v \geqq 1300$ ft/sec,

$$G(v) = Av + B, \tag{43}$$

16/ Herrmann, <u>Exterior ballistics, 1935</u>, U.S. Naval Inst., Table I, p. 76.

where $A = 0.00009$ and $B = 0.06$. Since the procedure just outlined can be applied in the case of resistance tables other than the classical Gavre table, we shall carry through the analysis that follows in terms of general literal coefficients $\underline{A}$, $\underline{B}$; and substitute the specific numerical values just mentioned only when we perform calculations based on the Gavre table. The straight-line graph corresponding to Eq. (43) with $A = 0.00009$ and $B = 0.06$ is exhibited in Fig. 17, together with the plotted points $[G(v), v]$ determined by use of the Gavre table.

Solution of the first-order, linear differential equation, Eq. (43), for $\underline{v}$ as a function of $\underline{s}$ gives

$$v = -\frac{B}{A} + K e^{-As/C}. \tag{44}$$

To evaluate the integration parameter $\underline{K}$ we assume that when $s = 0$, $v = 6000$. Whence $K = 6000 + B/A$ and $\underline{v}$ as a function of $\underline{s}$ is given by

$$v = v(s) = \frac{1}{A}\left[G(6000)\cdot e^{-As/C} - B\right], \tag{44a}$$

from which $\underline{s}$ as a function of $\underline{v}$ is obtained in the form

$$s = s(v) = \frac{C}{A}\log_e \frac{G(6000)}{G(v)}, \tag{44b}$$

Our choice of initial conditions insures that the quantity $\underline{s}$ given by Eq. (44b) is the distance that a projectile with ballistic coefficient $\underline{C}$, discharged from a hypothetical gun with muzzle velocity 6000 ft/sec, travels along a rectilinear trajectory $\underline{T}$ in the interval during which its velocity is reduced from 6000 ft/sec to a value $\underline{v}$ such that $1300 \leqq v \leqq 6000$. We shall refer to the point on $\underline{T}$ attained by such a projectile as the point $P(s)$. Evidently if a projectile with ballistic coefficient $\underline{C}$ is fired along $\underline{T}$, in the direction of increasing $\underline{s}$ and with an initial velocity $\underline{v}$, from an actual gun situated at the point $P(s)$ on $\underline{T}$; then the actual trajectory followed by the projectile is identical with the subarc of $\underline{T}$ beginning at the point $P(s)$. Consequently to find the range Δs along the actual trajectory of the projectile out to the point where its velocity has been reduced to a

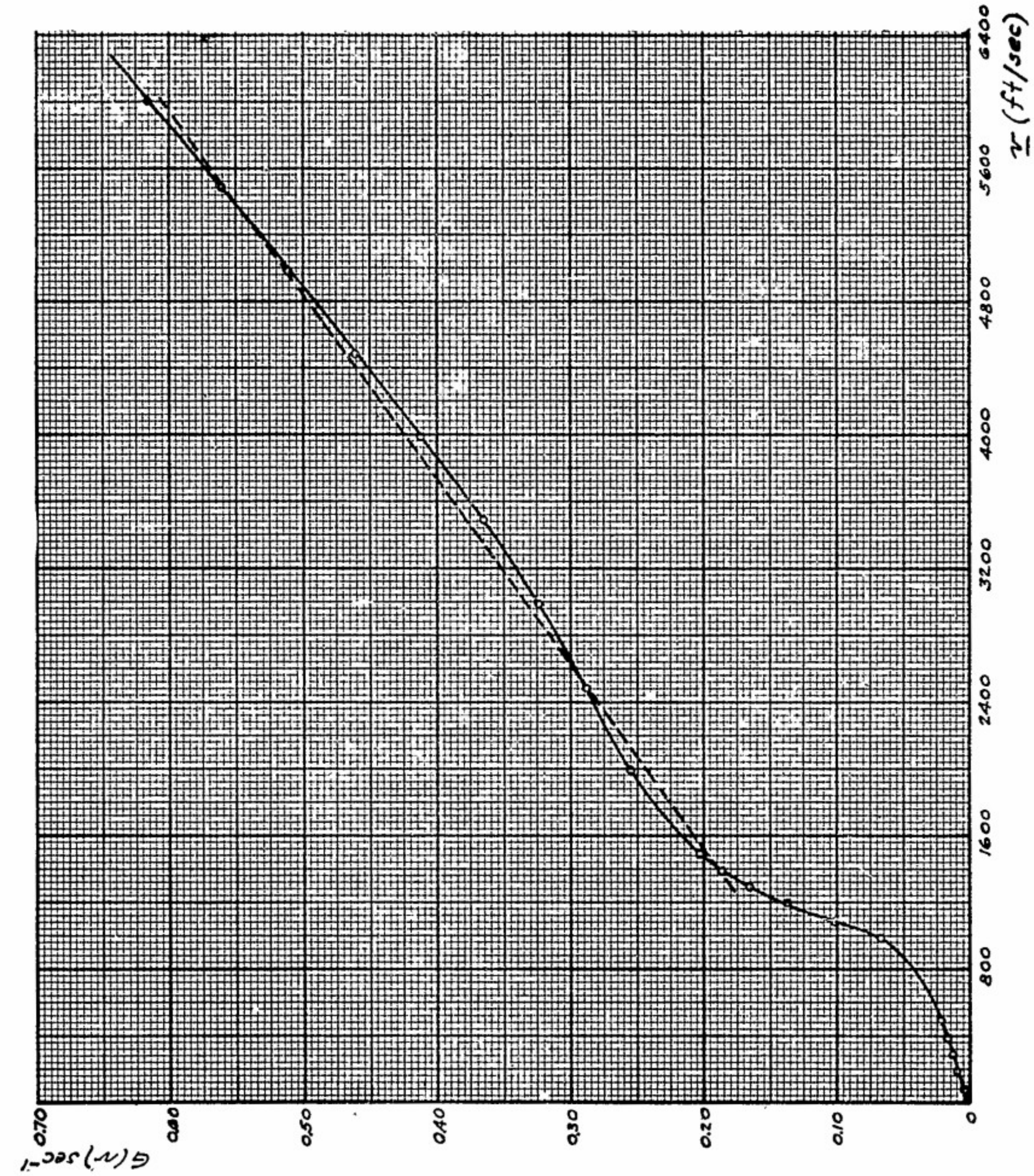


Fig. 17. $G(v)$ as a function of v.

value $v + \Delta v < v$, we need only substitute $v + \Delta v$ for $\underline{v}$ in Eq. (44b) and then subtract $\underline{s}$ from the value $s + \Delta s$ supplied by this equation.

23. Distance-time relationships

Equation (44a) also can be employed to express $\underline{t}$ as a function of $\underline{s}$, for if we replace $\underline{v}$ in Eq. (44a) by its value ds/dt, the resulting differential equation in $\underline{s}$ and $\underline{t}$ can be solved to give

$$t + H = -\frac{A}{B} s - \frac{C}{B} \log_e v(s)$$

where $v(s)$ is the function defined in Eq. (44a). To evaluate the integration parameter $\underline{H}$, we assume that when $s = 0$, $t = 0$; whence

$$t = t(s) = \frac{C}{B} \log_e \frac{v(o)}{v(s)} - \frac{A}{B} s. \qquad (45)$$

Thus our choice of initial conditions is seen to imply that the time $\underline{t}$ given by Eq. (45) is the time required by a projectile with ballistic coefficient $\underline{C}$, discharged from a hypothetical gun with a muzzle velocity of 6000 ft/sec to attain a point on its rectilinear trajectory $\underline{T}$, distant $\underline{s}$ feet from the gun muzzle. Since the fundamental equation, Eq. (44a), is valid only for velocities in the range 1300 to 6000 ft/sec, the derived relation, Eq. (45), holds good only for values of $\underline{s}$ such that $1300 \leqq v \leqq 6000$. If, now, $s + \Delta s > s$ is a value of $\underline{s}$ satisfying the condition just specified, then Eq. (45) gives

$$t + \Delta t = t(s + \Delta s) = \frac{C}{B} \log_e \frac{v(o)}{v(s + \Delta s)} - \frac{A}{B} (s + \Delta s).$$

Hence, if a projectile with ballistic coefficient $\underline{C}$ is fired with an **initial** velocity $v = v(s)$ -- where $1300 \leqq v(s) \leqq 6000$ -- from an actual gun, the time required by the projectile to attain a point on its trajectory distant Δs feet from the gun muzzle is given by

$$\Delta t = \frac{C}{B} \log_e \frac{v(s)}{v(s + \Delta s)} - \frac{A}{B} \Delta s. \qquad (46)$$

At the range Δs, the velocity of the projectile will have dropped from $v = v(s)$ to $v = v(s + \Delta s)$ ft/sec.

Equation (46) gives a convenient method of comparing flight times for short actual ranges, Δs, say up to 2000 yd in length, for projectiles with various muzzle velocities and various ballistic coefficients; always subject to the restriction that throughout the flight the velocity does not fall below 1300 ft/sec.

As a check on the accuracy with which the formulas derived up to this point represent the various elements of a trajectory, we shall employ these formulas to compute the times of flight and the terminal velocities for two typical trajectories:

Case 1: $C = 1$, initial velocity $v = 4200$ ft/sec. (This case corresponds to that of the sabot-projectile 48-57A designed at the University of New Mexico.)

Employing the Gavre table and numerical integration we find after considerable calculation that at the end of 2 sec, an interval in which the departure of the trajectory from a straight line amounts to 52 ft, the projectile has attained a range Δs of 6001 ft and has a terminal x-velocity of 2175 ft/sec.

From Eq. (44b) with $v = 4200$ ft/sec we find $s = s(v) = 3497$ ft. Hence $s + \Delta s = 3497 + 6001 = 9498$ ft. From Eq. (44a) with $s = s + \Delta s$ we find $v(s + \Delta s) = 2169$ ft/sec. This result differs from the terminal velocity 2175 ft/sec found by a tedious numerical integration by less than 0.3 percent. From Eq. (46) with $v(s) = 4200$ ft/sec, $v(s + \Delta s) = 2169$ ft/sec and $\Delta s = 6001$ ft, we find $\Delta t = 2.014$ sec. This result differs from that found by numerical integration by less than 0.7 percent.

Case 2: $C = 2$, initial velocity $v = 2800$ ft/sec. (This case corresponds to that of the sabot-projectile 28-75D designed at the University of New Mexico.)

By use of the Gavre tables we find that at the end of time $\Delta t = 2.5$ sec, an interval in which the departure from a rectilinear trajectory amounts to 89.9 ft, the projectile has attained a range Δs of 5876 ft and has a terminal velocity of 1975 ft/sec. For the same range Δs, our Eqs. (44b), (44a) and (46) give a terminal velocity of 1994 ft/sec (error less than 1.0 percent) and a time of flight Δt of 2.502 sec (error less than 0.1 percent).

For certain ranges of v there will occasionally be errors somewhat larger than in the examples given, but for applications such as those that follow they will always be negligible.

24. Application to subcaliber projectiles

In order to apply our results to comparison of times of flight over an admissible range Δs of standard and subcaliber projectiles, we first note that

$$\Delta v = v(s + \Delta s) - v(s) = \frac{G(v)}{A} \left[e^{-A\Delta s/C} - 1\right]. \tag{47}$$

Consequently, Eq. (46) may be rewritten as follows:

$$\begin{aligned}\Delta t &= -\frac{A}{B}\Delta s - \frac{C}{B}\log_e \frac{v(s) + \Delta v}{v(s)} \\ &= -\frac{A}{B}\Delta s - \frac{C}{B}\log_e\left[\frac{G(v)\,e^{-A\Delta s/C} - B}{Av}\right].\end{aligned}$$

Hence, for a standard full-caliber projectile with ballistic coefficient C_g fired with velocity v_g from its own gun, the time of flight over an admissible range Δs is given by

$$\Delta t_g = -\frac{A}{B}\Delta s - \frac{C_g}{B}\log_e\left[\frac{G(v_g)\,e^{-A\Delta s/C_g} - B}{Av_g}\right]. \tag{47a}$$

Similarly, for a subcaliber projectile with ballistic coefficient C_p fired with velocity v_p, the time of flight over the same range is given by

$$\Delta t_p = -\frac{A}{B}\Delta s - \frac{C_p}{B}\log_e\left[\frac{G(v_p)\,e^{-A\Delta s/C_p} - B}{Av_p}\right]. \tag{47b}$$

Thus,

$$\Delta t_g - \Delta t_p = \frac{1}{B}\left\{\log_e\left[\frac{G(v_p)\,e^{-A\Delta s/C_p} - B}{Av_p}\right]^{C_p} - \log_e\left[\frac{G(v_g)\,e^{-A\Delta s/C_g} - B}{Av_g}\right]^{C_g}\right\}.$$

Therefore, the time of flight of the subcaliber projectile is less than that of the standard projectile if and only if

$$\left[\frac{G(v_p)\,e^{-A\Delta s/C_p} - B}{Av_p}\right]^{C_p} > \left[\frac{G(v_g)\,e^{-A\Delta s/C_g} - B}{Av_g}\right]^{C_g}. \qquad (48a)$$

Furthermore, from Eqs. (47a) and (47b) we can infer that the ratio of the times of flight of a subcaliber and a full-caliber projectile over the same admissible range Δs is given by

$$\frac{\Delta t_p}{\Delta t_g} = \frac{C_p}{C_g}\,\frac{\log_e\left(\dfrac{G(v_p) - Be^{A\Delta s/C_p}}{Av_p}\right)}{\log_e\left(\dfrac{G(v_g) - Be^{A\Delta s/C_g}}{Av_g}\right)}. \qquad (48b)$$

In case Δs is so small that the square and higher powers of the quantity $A\Delta s/C$ are negligible, a good approximation to the difference $(1 - e^{-A\Delta s/C})$ in Eq. (47) is given by $A\Delta s/C$. In this case the ratio of the times of flight is given by

$$\frac{\Delta t_p}{\Delta t_g} = \frac{C_p}{C_g}\,\frac{\log_e\left(e^{A\Delta s/C_p}\left[1 - \dfrac{\Delta s}{C_p}\,\dfrac{G(v_p)}{v_p}\right]\right)}{\log_e\left(e^{A\Delta s/C_g}\left[1 - \dfrac{\Delta s}{C_g}\,\dfrac{G(v_g)}{v_g}\right]\right)}, \qquad (48c)$$

a formula which does not depend on the value of B.

Equation (48b) -- with Eq. (48c) as a control -- has been used to compute the ratio of the times of flight over various ranges Δs of a 57-mm subcaliber projectile S_p, and a 75-mm full-caliber projectile S_g, under the assumption that $C_p = 2$, $C_g = 2.6$ and $v_g = 2050$ ft/sec. The muzzle velocity of S_p is then determined by Eq. (39a) as $v_p = 2805$ ft/sec. The values chosen for C_g and C_p are based on trajectories computed for 75-mm and 57-mm projectiles by use of a tracer photography technique developed at the New Mexico Proving Ground. The reader will observe that the ratio of C_g to C_p is very nearly equal to the ratio of D_g to D_p. [Compare Eq. (42).]

A graph of the ratio $\Delta t_p/\Delta t_g$ versus Δs is exhibited in Fig. 18. It will be seen from Fig. 18 that for all ranges Δs not exceeding

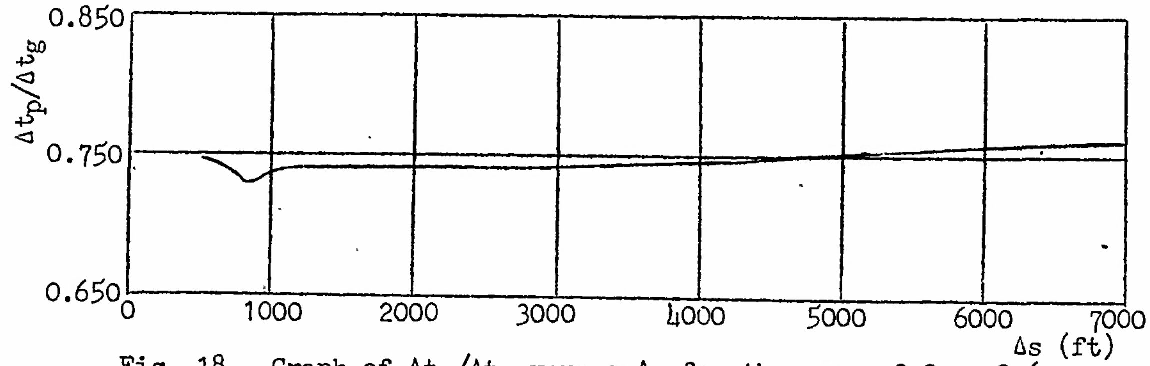


Fig. 18. Graph of $\Delta t_p/\Delta t_g$ versus Δs for the case of $C_g = 2.6$, $v_g = 2050$ ft/sec; $C_p = 2$, $v_p = 2805$ ft/sec.

6000 ft, the time of flight of S_p is only about three-fourths of the time of flight of S_g. The importance of any device permitting such a reduction in flight-time will be emphasized in a later chapter on tactical considerations.

VI. ARMOR PENETRATION OF SABOT-PROJECTILES

In this chapter is derived a relationship whereby the effectiveness of a sabot-projectile against armor can be compared with the effectiveness of the standard projectile from the same gun. Armor penetration, in general, depends on the projectile energy and projectile diameter. The sabot-projectile at first glance suffers in comparison with a standard projectile because of the loss of energy in discarding the sabot. It will be shown, however, that in many cases this is more than offset by the decrease in projectile diameter.

25. Theoretical basis

Various formulas exist that attempt to give a functional form connecting the variables relating to armor penetration. Two of the most widely used are the De Marre and Thompson formulas. The De Marre formula which will be used in this analysis, is

$$e^{0.7} = M_p^{\frac{1}{2}} V/1022\,K D_p^{3/4}. \qquad (49)$$

Here e (in.) is the maximum plate thickness perforated, M_p (lb) is the weight of the projectile, V (ft/sec) is the striking velocity, D_p (in.) is the diameter of the projectile, and K is the "De Marre Coefficient." This formula predicts fairly well the performance of projectiles against plate over limited ranges of V, e and D_p, if K is properly adjusted. The Ballistic Research Group, Princeton University, has shown[17/] that K may vary as much as 18 percent when e/D_p varies from 1 to 4. These results were obtained by using the cores of caliber .30 AP projectiles against homogeneous armor of Brinell hardness 258 to 294. Presumably they would also apply to large caliber uncapped projectiles against homogeneous plate.

26. Application to sabot-projectiles

To make an estimate of the advantage of a sabot-projectile over the standard projectile, both fired from the same gun, it is well first to compare the penetrations of the standard projectile and the full-caliber, subweight projectile. Next, the penetration of the sabot-projectile is compared with that of the full-caliber, subweight projectile of the same total mass.

As is shown in Chap. I, it is possible to maintain constant muzzle energy in any gun for various masses of projectile by properly choosing the powder so as to keep a constant area under the curve of powder pressure versus projectile travel. If this is done, the numerator of Eq. (49) is a constant, since it is proportional to the square root of the muzzle energy. Hence, the penetration at the appropriate muzzle velocity of any full-caliber projectile is the same, regardless of weight. In particular, the muzzle penetration of the standard projectile is the same as the muzzle penetration of any full-caliber projectile of mass $M_g = M_p + M_s$.

17/ The Ballistic Research Group, Princeton University, The ballistic properties of mild steel, NDRC Report A-111 (OSRD No. 1027), Nov. 1942.

Now let us compare the penetration of a subcaliber projectile of mass M_p, fired with a sabot of mass M_s, with that of a full-caliber projectile of mass $M_g = M_p + M_s$. The muzzle velocity will be the same for the two cases. If e_p and e_g are, respectively, the penetrations of the sub- and full-caliber projectiles, while D_p and D_g are their respective diameters, we have

$$\frac{e_p^{0.7}}{e_g^{0.7}} = \frac{M_p^{\frac{1}{2}} D_g^{3/4}}{(M_p + M_s)^{\frac{1}{2}} D_p^{3/4}}$$

which reduces to

$$\frac{e_p}{e_g} = \left(\frac{M_p}{M_p + M_s}\right)^{5/7} \left(\frac{D_g}{D_p}\right)^{15/14}. \qquad (50)$$

In order for there to be any advantage as far as armor penetration goes in using the sabot-projectile, e_p/e_g must exceed 1. The curves of Fig. 19 show e_p/e_g as a function of D_g/D_p for various mass ratios $M_p/(M_p + M_s)$, from Eq. (50). It is seen that for values of $M_p/(M_p + M_s) = 0.6$, and diameter ratio $D_g/D_p = 1.8$, both of which values are readily obtainable in most guns, an improvement at the muzzle of about 30 percent in armor penetration could be expected. Since it has already been shown that the penetration of the full-caliber, subweight projectile of mass $M_s + M_p$ is the same as that of the standard projectile, it follows that this sabot-projectile would have a 30 percent advantage over the standard projectile in armor penetration if their ballistic coefficients were the same.[18/]

It should be emphasized that the values of e_p/e_g obtained from Eq. (50) are values at the muzzle. Subcaliber projectiles have lower

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18/ C. W. Curtis in a personal communication states, "A more exact analytical expression than the De Marre formula is now known. Unfortunately it is not simple and does not give $\underline{e}$ explicitly in terms of the other variables. The De Marre formula... is conservative in that it underrates the penetrating power of nondeforming sabot-projectiles. For the example chosen, the sabot-projectile should have nearer 45 percent than 30 percent advantage."

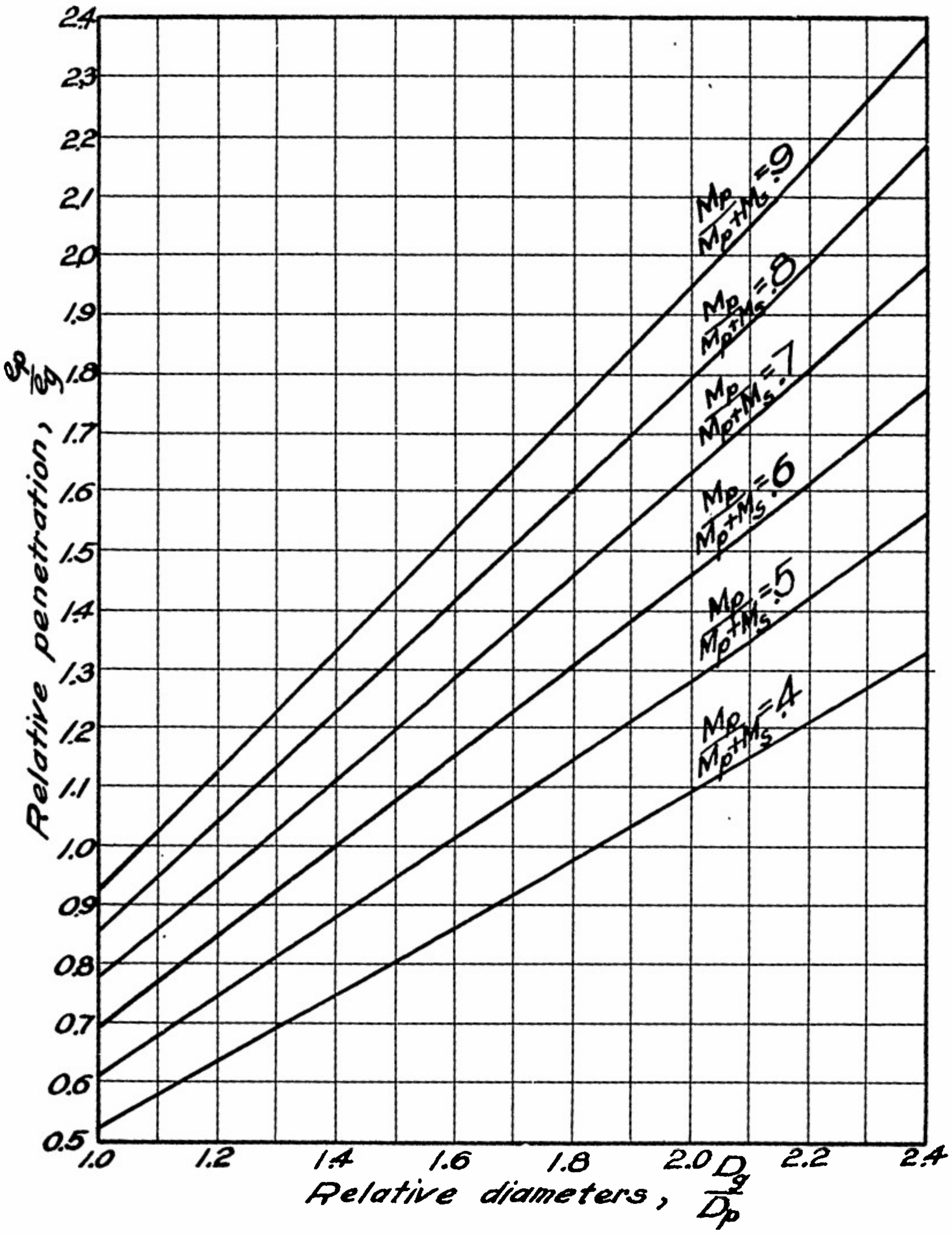

Fig. 19. Relative penetrations of subcaliber projectiles as a function of ratio of diameters of full- and subcaliber for various ratios of weights of sub-to full-caliber projectiles.

ballistic coefficients than full-caliber projectiles (assuming the same density and form factor), and therefore the advantage in armor penetration becomes smaller as the range is increased. Even so, according to this analysis, significant improvement in the armor-piercing characteristics of a given gun may be expected over tactically useful ranges when properly designed subcaliber projectiles are employed.

If a similar analysis is carried through on the basis of the Thompson formula, similar conclusions are drawn, and the advantage of the subcaliber is found to be somewhat greater than that shown by the De Marre formula.

In connection with this discussion of armor penetration it will be of interest to read Critchfield's treatment of the subject.[19/]

27. The "shatter" effect

The validity of the preceding analysis is very seriously marred by the fact that very little is known of the validity of the De Marre or Thompson formulas at the high velocities which sabot-projectiles make possible. The little that is known seems to show that the analysis is not valid, mainly due to the onset of the phenomenon of "shatter," which has been described by the Ballistics Research Group, Princeton University[20/] and in various British reports.[21/]

19/ See reference 14.

20/ Information obtained in personal conferences: probably to appear in a forthcoming report.

21/ (a) O.B. Proc. No. 13634, Aug. 25, 1941;
(b) O.B. Proc. No. 13965, Sept. 15, 1941 (OSRD No. WA-56-6);
(c) OSRD No. W-92-31, a fragment otherwise unidentified;
(d) O.B. Proc. No. 15476, Dec. 19, 1941 (OSRD No. W-112-7);
(e) O.B. Proc. No. 15876, Jan. 19, 1942 (OSRD No. W-143-32);
(f) O.B. Proc. No. 16607, Mar. 11, 1942 (OSRD No. W-168-13);
(g) O.B. Proc. No. 17179, April 22, 1942;
(h) O.B. Proc. No. 18532, July 15, 1942;
(i) O.B. Proc. No. 19074, Aug. 21, 1942 (OSRD No. W-172-8);
and others, no doubt, which have not come to our attention.

A typical occurrence of the shatter effect may be described as follows. With a given armor plate and given projectile, we start with low velocities and gradually increase the velocity until perforations of the plate are obtained. If the velocity is further increased, perforations are still obtained until a critical velocity is reached where the projectile shatters on the plate, and does not perforate. A further increase of velocity to a sufficiently high value will again produce perforations of the plate. However, the holes are now of quite a different character from the normal perforations. Normally, the perforations are smooth, round holes of approximately projectile diameter, possibly with petalling at the front and back of the plate. They look as if they might have been drilled and polished. The projectile body does not break up or deform appreciably, and in some cases (for an uncapped projectile) the projectile looks almost as if it had never been fired. Shatter penetrations are quite different. The holes are larger than the projectile and are quite ragged. The projectile body is badly deformed or broken, and the part that reaches the other side of the plate generally consists of small fragments.

The foregoing description of the process gives rise to four possible results -- namely, normal failure, normal perforations, shatter failure and shatter perforations, in the order of increasing projectile velocity. Sometimes one or more of these four results may not be found.

In Fig. 20 we have a schematic graphical representation due to Milne[22/] of these facts for a given projectile (a solid shot without AP cap) fired at varying velocities v against homogeneous armor of varying thicknesses e. For this projectile we plot velocity versus maximum penetration thickness from the De Marre formula and label the curve, "De Marre perforation." There also is shown a curve labeled "Shatter limit" above which the projectile shatters, and another curve

22/ E. A. Milne, "The performance of shot against plate," British E.B.D. Report No. 20(A.C. 1421) Nov. 24,1941; Reviewed in O.B. Proc. 14981.

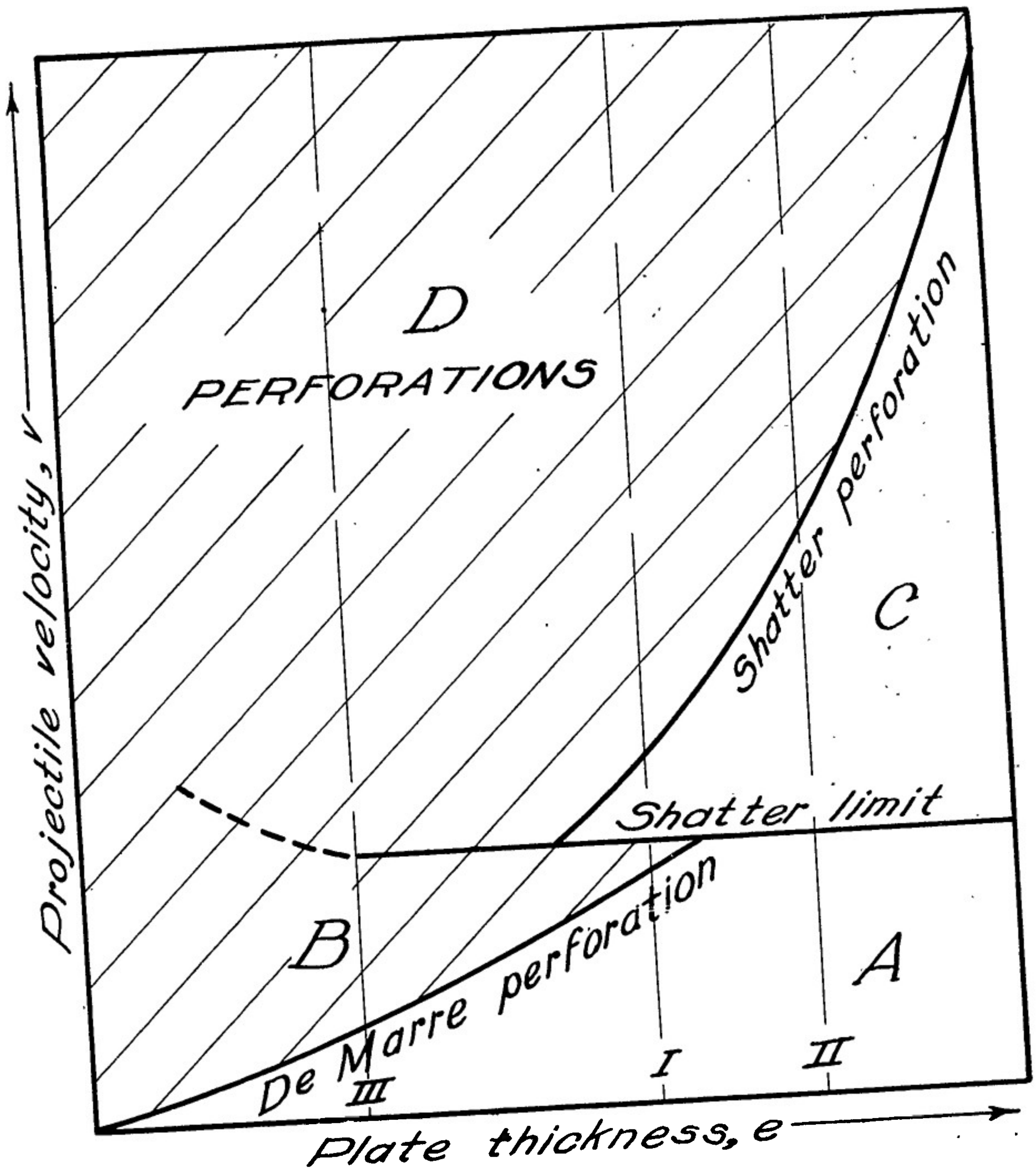

Fig. 20. Armor penetration as a function of plate thickness and projectile velocity.

labeled "Shatter perforation" above which there is perforation in spite of shatter. In the hatched area B and D labeled "Perforations" the projectile perforates the plate. In the unhatched area, the projectile is defeated by the plate. The De Marre formula holds fairly well for perforations up to the shatter line, where it fails, and a higher velocity is needed to perforate the plate than is predicted by the De Marre formula. The velocity traverse labeled I includes the region A (normal failures), the region B (normal perforations), the region C (shatter failures) and the region D (shatter perforations). On the other hand, velocity traverse II does not include the region of normal perforations at all, and velocity traverse III does not include shatter failures.

The preceding discussion results from the research of the Ballistics Research Group, Princeton University, using uncapped projectiles against homogeneous armor.[23/] Experimental results available seem to show definitely that capped projectiles show less tendency to shatter than uncapped projectiles.[24/]

The velocities at which shatter sets in depend on a number of variables, some of which are the ratio e/D_p, the type of armor attacked (homogeneous or face-hardened), the type of projectile attacking (capped or uncapped), the shape of the head of the attacking projectile and the heat treatment which the projectile and armor has received. Thus the British have had trouble with shatter in the 2-pdr. gun (the equivalent of the American 37-mm gun) at velocities as low as 2500 ft/sec, while subsequent improvement in the heat treatment of its projectile and in the shape of the nose has raised this limiting velocity by about 500 ft/sec.[25/]

These remarks concerning shatter apply to steel AP shot or AP shell. A somewhat better situation exists if tungsten carbide

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23/ Reference 17, and a forthcoming report.

24/ O.B. Proc. No. 13965.

25/ O.B. Proc. No. 19074.

projectiles, or projectiles with tungsten carbide cores, are considered. Here two advantages are obtained. The first is that, with a given mass, the tungsten carbide core may have a smaller diameter than a steel core, owing to its higher density. At a given velocity, then, according to the De Marre formula, the tungsten carbide core should have the greater perforating ability. The second advantage is that the tungsten carbide core is less subject to shatter than is the steel core. C. W. Curtis in a personal communication states, "At small obliquities the nose of the tungsten carbide bullet tends to stay intact while the back end breaks, and the perforating power is changed but little. Just the opposite is true of a steel bullet. As pointed out by Leeder the advantage of tungsten carbide may be lost at high obliquities where it breaks up badly throughout."

Unfortunately there are objections to the use of this type of projectile. The first is that tungsten is quite scarce, and facilities are limited (at present) for making what tungsten is available into tungsten carbide. The second is that the tungsten carbide bullet is not particularly effective against spaced armor, since one or both of the spaced plates must be attacked at high obliquity. The third is that the tungsten carbide projectile cannot be made to carry a charge of high explosive.

VII. TACTICAL CONSIDERATIONS

The tactical advantages of high-velocity sabot-projectiles may be conveniently grouped under six heads:

(i) Decreased time of flight to the target.
(ii) Flatter trajectory.
(iii) Increased range.
(iv) Higher terminal velocity.
(v) Reduction of gun recoil.
(vi) Versatility of gun performance.

The first four of these advantages are common, of course, to all high-velocity projectiles, but the fifth is limited to light-weight projectiles, and the sixth, as associated with high-velocity performance, is to a considerable extent peculiar to the sabot-projectile. Any one design may not realize all the advantages to the fullest extent, but it is nevertheless believed that very real gains may be attained by employment of sabot-projectiles for high-velocity work.

28. Decreased time of flight

Since, during its time of travel from the gun to the target, a projectile is subjected to the exterior influences of gravity, wind and earth motion, a shortening of the time of flight will decrease the total effect of these disturbing influences. The reduction in effect of wind and earth motion may be relatively unimportant. The decrease in gravitational effect, however, results in flatter trajectories with the advantages to be discussed in Sec. 29.

A decrease in time of flight to the target has the immediate advantage that, in the case of movable targets, the dodge area is decreased. The total dodge area in the case of ground targets is approximately proportional to the square of the time of flight, but the effective hitting probability is more nearly inversely proportional to the first power of the time of flight, at least for moderate ranges. In antiaircraft fire the dodge volume is proportional to the cube of the time of flight and the hitting probability varies about as the inverse square. (In case of very severe dodging the probability, according to Weaver,[26/] may vary inversely as a higher power — as high as 6.) In the use of tracer fire the shorter time between firing and arrival at the target permits the gunner to correct his aim more readily, and should considerably increase the effectiveness of his fire.

26/ W. Weaver, "The way muzzle velocity affects the probability of hitting aircraft by AA fire," Section D-2 (Fire Control) NDRC, Apr. 1, 1942.

The important tactical advantage is evident: more hits per round expended means an increase in effective fire power and a decrease in supply problems.

29. Flatter trajectory

The flat trajectory of high-velocity weapons is a consequence of the **shorter time of** flight. The angle of descent at the target is less than with a low-velocity projectile, and therefore the hitting space (the distance along the trajectory within which the ordinate is less than the height of the target) is greater. The range, therefore, need be estimated less accurately, and changes in range caused by movement of the target are less effective in producing misses. In tank battles, particularly, there is with high velocity greater probability that the engagement may be fought within the "danger range," the range within which the height of the target is greater than the maximum ordinate of the trajectory. With the target in the danger zone, the range setting need not be changed to produce hits as the range closes and the training will be limited to azimuthal changes and lead. Firing will be more nearly that of open sights and will produce a larger percentage of hits.

30. Increased range

The sabot-projectile is ordinarily considered as a possible means of obtaining higher velocity over a short range. If the possibility of using sabot-projectiles in guns of large caliber is considered, we find that there is a possibility of increasing the total range of the gun. This would be of importance in naval and coast defense weapons.

An examination of one such application has been carried out in the New Mexico Laboratory.[27/] The combination considered was the

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27/ L. LaPaz and H. F. Dunlap, "Application of the sabot principle to large caliber guns," Memorandum (June 1943), available in the files of Division 1, NDRC.

10-in. projectile Mk. IV weighing 510 lb mounted in a sabot for the 16-in. gun, M1919. The normal muzzle velocity of the 16-in. gun is 2700 ft/sec with a 2340-lb projectile. Two sets of calculations were made, with sabots weighing 307 and 200 lb. The anticipated muzzle velocities (based on constant muzzle energy) were 4500 and 4900 ft/sec, respectively. The elements of the trajectories for the two sabot-projectiles were:

Muzzle velocity (ft/sec)	4500	4900
Angle of departure (deg.)	30	30
Ballistic coefficient	9	9
Summital height (yd)	12397	13970
Summital velocity (ft/sec)	1866	1951
Terminal velocity (ft/sec)	1519	1567
Angle of descent (deg.)	50.76	51.7
Total range (yd)	60900	67623
Time of flight (sec)	95.9	101.8

According to Hayes,[28/] the maximum range of the 16-in. projectile, Mk II at optimum elevation is 49140 yd. If the 16-in. projectile, Mk V is assumed to have a similar range, the sabot-projectile considered would outrange the 16-in. by 12000 to 18000 yd even at 30° elevation.

The advantage of permitting one fleet to shell an opposing fleet while still completely out of enemy range is obvious. Similar situations will hold in encounters between fleets and land-based defense guns or with siege artillery and fixed defenses on land. There is the further possibility of extending the covering power of naval vessels engaged in supporting landing forces.

31. Higher terminal velocity

As is shown in greater detail in Chap. VI, the effectiveness of an armor-piercing shell is determined by its velocity, with due regard to the limitation imposed by the shatter phenomenon. Under

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28/ T. J. Hayes, Elements of ordnance (Wiley, 1938), p. 286.

short range conditions, maximum effectiveness results if the muzzle velocity is in the neighborhood of the shatter limit. For longer ranges, still higher muzzle velocities are desirable in order that the most effective terminal velocities may be attained. While the smaller subcaliber projectiles are usually fired at such short ranges that hypervelocities may persist up to the target and result in the shatter effect even in projectiles that have been given special heat treatment designed to raise the shatter limit, it should be noted that in the case of large caliber sabot-projectiles fired over such ranges as those considered in the numerical examples of Sec. 30 the impacts against the target occur at velocities too low for the shatter phenomenon to develop even in projectile material which has not been subjected to this special heat treatment.

32. Reduction of gun recoil

With constant muzzle energy, if the inertia of the powder gas is neglected, the ratio of the recoil momentum of a gun after firing a sub-weight projectile of weight M_1 to its recoil momentum after firing its standard projectile of weight M_2 is $(M_1/M_2)^{\frac{1}{2}}$. This fact is of some importance in that it may permit greater accuracy of fire, particularly in the case of a light gun and mount. This is illustrated in the case of the 105-mm howitzer, M3, for which sabot-projectiles are now being developed at the New Mexico Proving Ground. Recoil, rather than barrel strength, seems to be the limiting factor in this gun, and the Charge 3, giving a 33-lb shell a velocity of 780 ft/sec, seems to be the largest usable.

A 57-mm sabot-projectile with a total weight of 10.5 lb has been fired from this gun at the New Mexico Proving Ground. If powder gas inertia is neglected, this projectile gives the Charge 3 recoil when fired at 2460 ft/sec. The projectile energy for the case of the sabot-projectile (taking the projectile as weighing 7.2 lb) is about 2.2 times that of the standard projectile with Charge 3. In fact, it is 1.2 times that of the standard projectile with Charge 5. In practice, this advantage in recoil is not fully realized, since the sabot-projectile uses a heavier powder charge than the standard Charge 3, and the powder-gas inertia therefore contributes more to the recoil. Nevertheless, use of the sabot-projectile in this gun should make it a powerful armor-piercing weapon, while retaining the accuracy of fire possible with the lighter standard charges.

33. Versatility of gun performance

The use of sabot-projectiles in a gun does not preclude the use of the gun's standard ammunition as well. Many successful sabot designs are possible that require no alteration in the gun or powder chamber.

In howitzer and mortar fire the use of variable charges is the rule. In naval gun fire the charge is often varied. Most guns are also capable of firing either high explosive, armor-piercing or chemical shell, or shrapnel. The sabot-projectile adds another type of projectile with its own uses. In this case, the feature of the projectile is a high muzzle velocity, and a new factor is added of obvious tactical and strategical advantage. Problems of ordnance manufacture and ammunition supply would be greatly aggravated by the necessity, if it existed, of supplying different guns to fire high explosive, smoke and armor-piercing shell. The sabot-projectile may constitute another step in the problem of reducing the complications of supply.

To cite a particular example, the authors have developed a 75-57 mm combination designed solely to provide the 75-mm tank gun with a high-velocity shell capable of duplicating the known performance of the British 6-pdr., or the American 57-mm gun. The 75-mm tank gun normally fires a 14.9-lb projectile with a velocity of about 2000 ft/sec. The 57-mm projectile, M86 weighing 7 lb, may be fired from the 75-mm gun at 2800 ft/sec, which exceeds slightly the muzzle velocity of the 57-mm gun. The 75-mm is then able to assume the antitank role of the towed 6-pdr. while retaining its high explosive shell for counterbattery and antipersonnel work. Photographs of such 75-57 mm combinations are shown in Figs. 7(b), 7(c) and 12, while drawings and performance data are given in Chap. VIII.

Similarly, calculations for the 105-mm howitzer, M3 used as an infantry support weapon and in tank-destroyers, show that both the 57-mm and the 75-mm projectiles can be fired from this gun with resultant muzzle velocities of 2800 and 2100 ft/sec. Thus the 105-mm gun can assume the roles of either the 57-mm or the 75-mm guns and still retain use of its standard projectiles for its former roles. Preliminary work on the development of 105-mm sabots for these projectiles bears out these predictions. In fact, the 57-mm projectile, M86, has been fired from the 105-mm howitzer at more than 2700 ft/sec, and the 3-in. projectile, M42A1 at more than 2100 ft/sec.

34. Hypervelocity use

One matter, not mentioned in the tactical advantages listed at the first of this chapter should be given some discussion; that is, the use of the sabot in the "hypervelocity" field.

The hypervelocity range currently is considered to start at about 3500 ft/sec. Unfortunately, this range of velocities is relatively unexplored. The nature of the drag coefficient, the overturning moment and the terminal ballistics are all scantily known. Thus the advantages of the hypervelocity weapon are still in doubt. Nevertheless, sufficient interest has been shown in the research on the tapered-bore gun to indicate that there are possibilities in this field. The sabot-projectile presents an immodiate method for exploring the hypervelocity region with relatively little expense and research.

It is our opinion that the sabot-projectile offers a much simpler method of attaining hypervelocities than any other proposed weapon. There is little doubt that the performance of the famed German long-range gun that shelled Paris in the 1914-1918 war could have been much more easily attained by using a sabot-projectile in a 16-in.

railway gun with a steeper pitch of rifling. The performance of the tapered-bore gun can certainly be duplicated in several existing service weapons without any change whatever in the gun.

35. Disadvantages

Balanced against the advantages of high velocity and gun versatility we have the obvious disadvantage that the sabot-projectile offers a hazard to friendly personnel in the region ahead of the gun. The sabot and bourrelet fragments are dispersed in a cone whose apex angle is roughly twice the rifling angle of the gun -- about 14° for $n = 25$ calibers per turn. The range of the fragments is small, of course, though no extensive investigation has been made of the matter. The fragments ricochet from the ground, and there is some danger at angles considerably greater than the angle of the primary dispersion cone. It may be remarked that these fragments likewise constitute a hazard to any enemy personnel who may happen to be in the space ahead of the gun.

An objection may arise, in the case of separately loaded guns, because of the necessity for using powder charges of different kinds and sizes. In the case of howitzers this is probably not too serious, as the crews are accustomed to using a variety of charges. The difficulty does not arise with fixed ammunition.

The sabot-projectile necessarily is not capable of carrying as large a bursting charge as the full-caliber projectile from a given gun. Where this consideration is primary, the full-caliber projectile is naturally to be chosen. The sabot-projectile offers a means of attaining higher than standard muzzle velocity with a given gun, with all the advantages attendant on high muzzle velocity.

VIII. EXAMPLES OF PERFORMANCE DATA

Work at the University of New Mexico has included design and testing of a large number of sabot-projectiles -- approximately 230 projectiles for the 20-mm Hispano-Suiza; 690 for the 6-pdr. Navy gun, Mk VII; 330 for the 75-mm tank gun, M3; and to date (Nov. 26, 1943) approximately 80 for the 105-mm howitzer, M3 -- some 1300 rounds in all. Some 140 distinct designs were involved, several of which went through a number of minor modifications.

A series of progress reports made to Division 1 contained a complete record of these designs and tests, including a large number that for one reason or another were unsatisfactory, and it is felt that this report would be unduly burdened if they were all included here. Accordingly, three examples have been chosen, and an assembly drawing and performance data are presented for each.

36. Description of tests

The pressure measurements, where shown, were made with a copper crusher gage using 5/32-in. copper balls. Considerable difficulty was experienced with them and a large number of readings are much too low. The highest pressures shown for a given projectile and powder charge are probably the true crusher gage pressures within a few percent.

Velocity measurements were made with a simple resistance-capacitance circuit and two wire grids. The first grid was 60 ft from the muzzle and the second was 45 ft beyond the first. Breaking of the first grid by the projectile disconnected a battery from the R-C circuit; the condenser then discharged through the resistance until the R-C circuit was broken by the breaking of the second grid. The charge that remained in the condenser was then measured by a ballistic galvanometer. The instrument was calibrated with falling weights. The principal source of error was in reading the swing of the rather short-period ballistic galvanometer. The accuracy of the velocities shown is of the order of ±2 percent.

Flight characteristics were determined by a series of eight or nine yaw cards distributed along the first 1300 ft of the trajectory. These were of red rosin building paper and exerted practically negligible forces upon the projectile. The flights described as "V. Good" exhibited yaws of less than 1°; "Good," between 2° and 5°; "Fair," between 6° and 10°; "Poor," greater than 10°.

The accuracy tests were made against plywood target boards at 1000-yd range. Velocity or yaw observations were ordinarily not made in the accuracy tests.

The powder charge used in each case was based upon calculations made by J. O. Hirschfelder and his associates of the Geophysical Laboratory.

37. Results with design 48-57A

This is a cantilever design for the 6-pdr. gun, Mk VII. A photograph of the projectile appears in Fig. 9(b), and an assembly drawing appears in Fig. 21. Table II gives the results of tests.

No significant accuracy tests were possible with the gun available, owing to excessive play of the barrel in the mount. Such tests as were attempted gave the impression that the accuracy with the 48-57A was at least as good as with the standard shot, 6-pdr. Mk III, Mod 4.

38. Results with design 25-75A

This projectile is a 75-57 mm disk-sabot combination, using the 57-mm APC shell, M86. It is shown in the photographs of Figs. 7(b) and 7(c), and in the assembly drawing of Fig. 22. The tests were all made with the 75-mm tank gun, M3 in a 76-mm elevating mount. This assembly was set in a structural steel frame, which was in turn mounted on a massive concrete base, with a pivot provided for horizontal traverse.

Velocity and flight results are shown in Table III, while the result of an accuracy test is shown in Table IV. The projectiles of Table IV are designated as 25-75 A', which indicates that the attachment of the windshields and AP caps was reinforced by brazing. This

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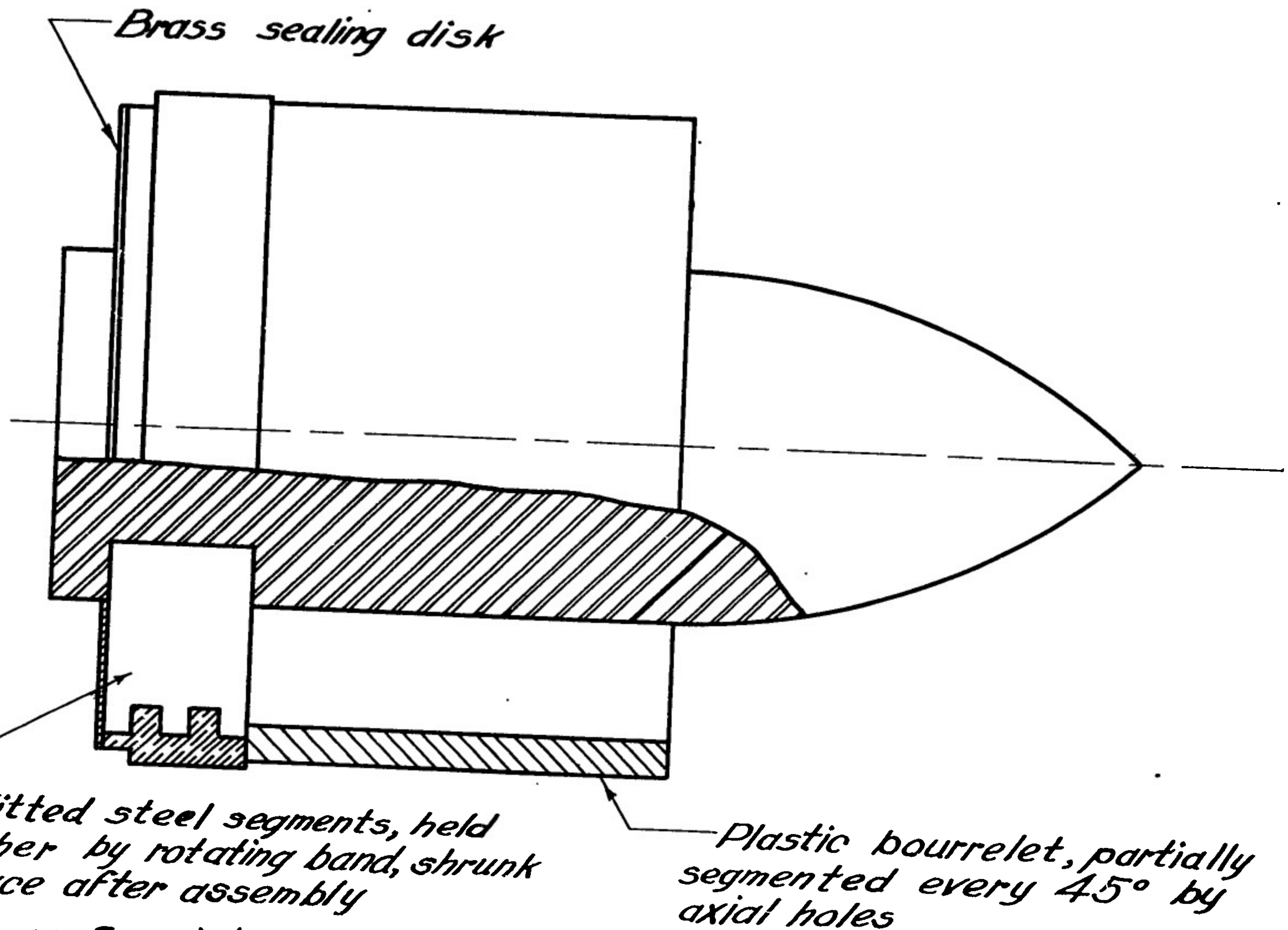

Fig. 21. Special projectile mounted in 57-mm cantilever sabot. Model 48-57A; projectile weight, 0.86 lb; total weight, 1.54 lb.

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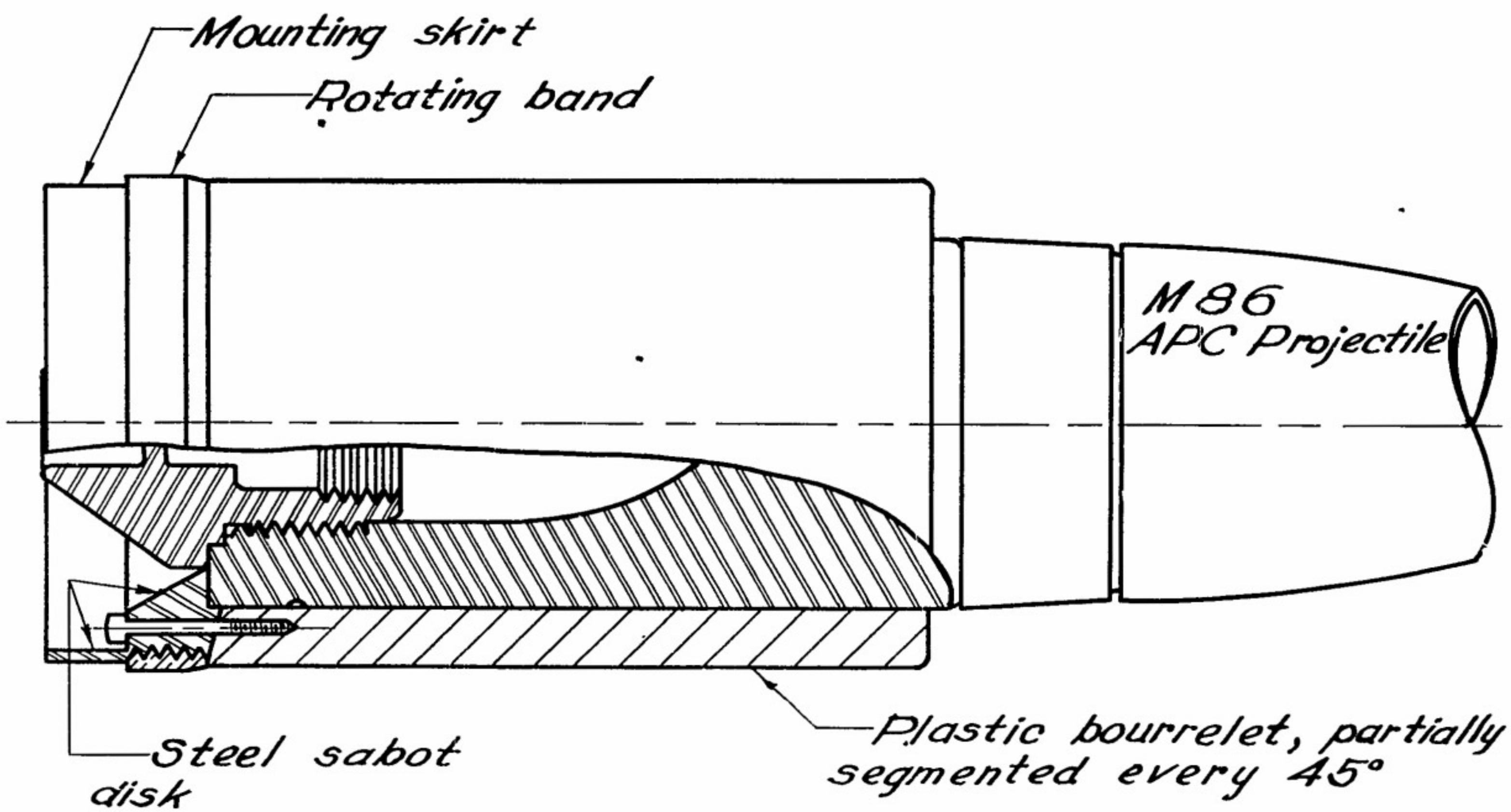

Fig. 22. 57-mm projectile, M 86 mounted in 75-mm disk sabot. Model 25-75 A; projectile weight 7.01 total weight 8.25 lb.

Table II. Velocity and flight determinations for design 48-57A.

Serial No.	Date Fired (1942-43)	Proj. Weight (gm)	Total Weight (gm)	Powder Charge* (gm)	Velocity (ft/sec)	Pressure (lb/in²)	Flight	Remarks
---	11-27	---	686	570	4480	37000		Dilecto C bourrelet
112	12- 7	---	704	560	4700	44000	Poor	Dilecto C bourrelet
138	12-23	399.5	702	550	4440	39000	V. Good	Dilecto C bourrelet
145	12-23	400	701	550	4440	41000	Good	Dilecto C bourrelet
144	1-12	399.5	702	530	---	---	V. Good	Dilecto C bourrelet
148	1-12	400	702	530	---	---	Fair	Dilecto C bourrelet
142	1-12	399.5	702	530	---	---	V. Good	Dilecto C bourrelet
218	1-13	398.5	697	530	---	---	Good	Masonite bourrelet
215	1-13	398	694	530	---	---	Fair	Masonite bourrelet
213	1-13	397	693	530	---	---	Fair	Masonite bourrelet
118	1-13	398.5	702	530	---	---	Fair	Dilecto C bourrelet
225	2- 1	399	707.5	530	---	28000	Good	Helmet scrap bourrelet
336	2- 2	395.5	701	530	---	28000	V. Good	Helmet scrap bourrelet
337	2- 2	397	702	550	---	37000	Fair	Helmet scrap bourrelet
338	2- 2	396.5	695	550	---	33000	Good	Helmet scrap bourrelet
339	2- 2	397	700.5	550	---	29000	Good	Helmet scrap bourrelet
123	2-10	389	690	530	4360	32500	---	Dilecto C bourrelet
363	2-23	396	692	530	---	22500	---	Dilecto C bourrelet
369	3- 9	398.5	697.5	530	4200	32500	V. Good	Dilecto C bourrelet
346	3- 9	399.5	697.5	530	---	---	Good	Dilecto C bourrelet
347	3-10	398.5	697	530	---	24500	Good	Dilecto C bourrelet
373	3-17	398.5	700.5	530	4210	33500	Good	Bakelite BM3510 bourrelet
128	3-17	387	692	530	4210	34000	V. Good	Bakelite XN15000 bourrelet
136	3-17	388	689	530	4210	37500	Good	Lignilite bourrelet
344	3- 4	400	696.5	530	---	40000	Fair	Lignilite bourrelet

*Powder used in all tests FNH, Lot 4281 for 37-mm gun, M2 (Hercules).

Table III. Velocity and flight determinations* for design 25-75A.

Serial No.	Date Fired (1943)	Proj. Weight (lb)	Total Weight (lb)	Velocity (ft/sec)	Pressure (lb/in.²)	Flight	Remarks
59	5-10	7.00	8.31	2740	32 000	Poor	
61	5-11	7.00	8.31	2780	31 000	Good	
62	5-11	7.00	8.25	2820	31 500	--	
60	5-12	6.81	8.13	2870	30 000	--	No windshield
72	5-13	7.00	8.37	2870	32 500	Good	Brazed Caps 25-75A'
84	5-18	7.00	8.25	2820	32 500	Tumbled	Brazed Caps 25-75A'
83	5-18	7.00	8.25	--	--	Good	Brazed Caps 25-75A'
287	7- 7	7.00	8.09	--	--	Poor	Non-slotted bourrelet
289	7- 9	7.00	8.22	--	--	Good	8 slots in bourrelet from outside in

*Powder charge in all tests, 930 grams of FNH, Lot 4254 for 37-mm gun, M2 (Hercules).

Table IV. Accuracy test of design 25-75A' at 1000 yd on June 3, 1943.

Gun	75-mm, M3	Powder	FNH, Lot 4254 for 37-mm gun, M2 (Hercules)
Mount	76-mm, M34A1	Charge	930 gm
Cases	M18131 (steel)	Muzzle velocity	2820 ft/sec
		Range to ground	1100 yd
Primers	M31A2	Powder temp.	60° to 65°F

Round	Point of Impact, Measured from Center of Target (in.)		Dispersion (in.)		Serial No.	Quadrant Angle of Departure (mils)
	Horiz.	Vertical	Horiz.	Vertical		
3	45.0	-4.0	22.5	-3.8	148	8.5
4	45.0	-11.0	22.5	-10.8	147	8.5
5	34.0	-3.5	11.5	-3.3	146	8.5
6	14.5	1.5	-8.0	1.7	145	8.5
7	31.5	4.5	9.0	4.7	144	8.5
8	18.5	10.5	-4.0	10.7	143	8.5
9	11.0	9.5	-11.5	9.7	142	8.4
10	32.5	-13.5	10.0	-13.3	141	8.3
11	5.5	-9.0	-17.0	-8.8	140	8.4
12	-12.5	13.5	-35.0	13.7	139	8.4
Total	225.0	- 1.5	151.0	81.5		
Mean	22.5	- 0.2	15.1	8.2		
	True mean (in.)*		15.9	8.6		
	(min)		1.50	0.82		
	Probable error (in.)		13.5	7.3		
	50-percent zone (in.)		27.0	14.6		
	(min)		2.53	1.40		

*Corrected to take into account the number of shots on which the determination is based. See, for example, E. E. Herrmann, Exterior ballistics, 1935, U.S. Naval Inst.

was done because some early samples of the M86 shell gave trouble because of insecure caps. All of the 25-75A tests were made with a flat base plug in the shell. The high-explosive cavity was loaded with lead and sand. Sabots were made of Crescent tool steel, and bourrelets of Dilecto C laminated phenolic tubing or Celeron macerated fabric phenolic.

Tables VIII and IX give for comparison the results of accuracy tests with the 75-mm gun, using the standard 75-mm APC shell, M61. The accuracy with the 25-75A' is slightly less than with the standard projectile, but the difference is hardly large enough to be significant.

39. Results with design 28-75D

This is a threaded-base design for firing the 57-mm APC shell, M86 in the 75-mm gun. Photographs appear in Fig. 12(a) to 12(f), and an assembly drawing appears in Fig. 23. The tests of Tables V and VI were made at the New Mexico Proving Ground with the gun described in Sec. 38. The tests of Tables VII and VIII were made at Aberdeen Proving Ground.29/

As is noted in the "Remarks" column of Table V, a considerable number of variations of bourrelet material and design were tried, with practically uniform success. These materials included laminated phenolic tubing, grades C and XX, Celeron macerated fabric phenolic, and bourrelets molded from several phenolic molding powders by Arthur D. Little, Inc. All the projectiles used in the accuracy tests of Tables VI and VII had bourrelets of Dilecto C.

Some of the projectiles of these tests, as is indicated under "Remarks," were fired with a dummy base fuze. The projectile weight is slightly larger in these cases than with the flat base plug.

The results of the accuracy tests of Tables VI and VII are to be compared with the results of Tables VIII and IX for the standard round with the 75-mm shell, M61.

29/ The results of the firings at Aberdeen are given in Firing Records M24862 and M25496 on Ordnance Program No. 5962.

Table V. Velocity and flight determinations for design 28-75D.

Serial No.	Date (1943)	Proj. Wt. (lb)	Total Wt. (lb)	Powder Charge* (gm)	Velocity (ft/sec)	Pressure (lb/in²)	Flight	Remarks
85	5-19	7.00	8.5	930	2820	34 000	V. Good	Brass rotating band
86	5-19	7.00	8.5	930	2820	36 000	V. Good	Copper rotating band
344	7-29	7.31	8.69	930	—	30 000	V. Good	Base fuze
358	8-31	7.00	8.25	930	—	—	Some Yaw	G.E. XX tubing bourrelet
359	8-31	7.00	8.25	930	—	—	Good	G.E. XX tubing bourrelet
177	10-21	7.03	8.41	930	2860	—	—	No windshield; Dilecto C bourrelet; base fuze
184	11-13	7.22	8.59	930	2870	—	—	Brazed cap; Dilecto C bourrelet; base fuze
195	6-21	7.13	8.5	930	2770	—	—	No cap; Dilecto C bourrelet; base fuze
196	6-21	7.22	8.59	670	2250	—	Good	Brazed cap; Dilecto C bourrelet; base fuze
198	6-21	7.31	8.69	600	2070	—	Good	Brazed cap; Dilecto C bourrelet; base fuze
213	10-7	7.31	8.69	930	—	—	Good	Brazed cap; Celeron bourrelet; base fuze
216	10-7	7.31	8.69	930	—	—	Good	Brazed cap; Celeron bourrelet; base fuze
218	10-21	7.22	8.59	530	1950	—	Good	Brazed cap; Celeron bourrelet; base fuze
334	7-23	7.00	8.34	930	—	—	V. Good	Bourrelet diameter, 2.940 in.
335	7-23	7.00	8.34	930	—	—	Some Yaw	Bourrelet diameter, 2.935 in.
336	7-23	7.00	8.34	930	—	—	Considerable Yaw	Bourrelet diameter, 2.930 in.
337	7-23	7.00	8.34	930	—	—	V. Good	Bourrelet diameter, 2.925 in.
364	11-9	7.00	8.31	930	—	—	V. Good	Base plug; molded bourrelet cemented on
372	11-9	7.00	8.25	930	—	—	V. Good	Base plug; molded bourrelet cemented on
373	11-9	7.00	8.25	930	—	—	V. Good	Base plug; molded bourrelet cemented on
386	11-2	7.13	8.50	930	—	—	V. Good	Base fuze; molded bourrelet; slots full depth
387	11-2	7.13	8.50	930	—	—	V. Good	Base fuze; molded bourrelet; slots full depth
388	11-2	7.13	8.53	930	—	—	V. Good	Base fuze; molded bourrelet; slots full depth
390	11-3	7.13	8.50	930	—	—	V. Good	Base fuze; molded bourrelet; slots half depth
391	11-3	7.13	8.50	930	—	—	V. Good	Base fuze; molded bourrelet; slots half depth
392	11-3	7.13	8.50	930	—	—	V. Good	Base fuze; molded bourrelet; slots half depth
395	11-4	7.16	8.53	930		—	V. Good	Base fuze; molded bourrelet; no slots
396	11-4	7.16	8.53	930	—	—	V. Good	Base fuze; molded bourrelet; no slots
397	11-4	7.16	8.53	930	—	—	Good	Base fuze, molded bourrelet; axial release
399	11-8	7.13	8.50	930	—	—	Good	Base fuze; molded bourrelet
400	11-8	7.13	8.50	930	—	—	Good	Base fuze; molded bourrelet

* Powder used in all tests FNH, Lot 4254 for 37-mm gun, M2 (Hercules).

Table VI. Accuracy test of design 28-75D at 1000 yd on vertical target; May 26, 1943.

Gun	75-mm, M3	Charge	930 gm (5 gm lead foil)
Mount	76-mm, M34A1		
Cases	M18B1 (steel)	Muzzle velocity	2820 ft/sec
Primers	M31A2	Angle of Departure	8.5 mils
Powder	FNH, Lot 4254, for 37-mm gun, M2 (Hercules)	Range to ground	1100 yd
		Powder temperature	60° to 70°F

Round	Coordinates of Point of Impact, Measured from Center of Target (in.)		Dispersion (in.)	
	Horizontal	Vertical	Horizontal	Vertical
5	7.0	14.0	0	2.5
6	13.0	16.0	6.0	4.5
7	36.0	20.0	29.0	8.5
8	13.5	24.5	6.5	13.0
9	-14.0	10.0	-21.0	-1.5
10	8.5	20.0	1.5	0.5
11	5.0	12.5	-2.0	1.0
12	10.5	-2.0	3.5	-13.5
13	18.0	21.0	11.0	9.5
14	-4.5	15.5	-11.5	4.0
15	16.0	9.0	9.0	-2.5
16	1.5	-4.5	-5.5	-16.0
17	13.0	3.0	6.0	-8.5
18	9.5	-4.5	2.5	-16.0
19	-13.5	11.5	-20.5	0
20	-32.0	40.0	-39.0	28.5
21	10.5	4.5	3.5	-7.0
22	28.0	-3.0	21.0	-14.5
Total	126.0	207.5	199.0	159.5
Mean	7.0	11.5	11.1	8.9
		True mean (in.)	11.4	9.2
		(min)	1.08	0.90
		Probable error (in.)	9.6	7.8
		50-percent zone (in.)	19.2	15.6
		(min)	1.80	1.48

Table VII. Accuracy test of design 28-75D at 800 yd on vertical target; Aberdeen Proving Ground* July 15, 1943.

Gun	75-mm, M3	Charge	32.50 oz.
Mount	75-mm tank mount in 155-mm howitzer carriage, M1918	Muzzle Velocity	2800 ft/sec (average for only 3 rounds)
Cases	M18		
Primer	Perc. M31A2		
Powder	FNH, Lot 4254 for 37-mm gun, M3, M5, M6 (Hercules)	Projectile	M86 with brazed caps

Coordinates of Point of Impact, Measured from Center of Target (in.)			Dispersion (in.)	
	Horizontal	Vertical	Horizontal	Vertical
	-13.5	-2.2	11.5	1.6
	-9.5	9.9	7.5	10.5
	7.4	5.5	5.4	7.1
	-8.6	-1.4	6.6	0.8
	0.0	12.8	2.0	3.4
	-4.2	-10.0	2.2	9.4
	0	-10.5	2.0	9.9
	5.3	-3.5	7.3	2.9
	7.5	-6.2	9.9	5.6
	9.9	0	11.9	0
Total	-20.5	-5.6	55.9	61.2
Mean	-2.0	-0.6	5.6	6.1
		True mean (in.)	5.9	6.4
		(min)	0.71	0.76

*These data were obtained by measurement of a photograph of the target for rounds No. 1933 to 1942. (Aberdeen Proving Ground Photograph No. 88216 with Firing Record No. M24862 on Ordnance Program No. 5962.)

Table VIII. Accuracy test of 75-mm projectiles, M61, at 800 yd on a vertical target; Aberdeen Proving Ground;* July 15, 1943.

Gun	75-mm, M3
Mount	75-mm tank mount in 155-mm howitzer carriage, M1918
Cases	M18
Primer	Perc. M1B1A1
Powder	Not specified } Complete round ammunition Lot KOP 6951-87
Charge	Not specified } Complete round ammunition Lot KOP 6951-87
Muzzle velocity	2059 ft/sec (average)
Projectile	M61 (weight, 14.9 lb)

Coordinates of Point of Impact Measured from Center of Target (in.)		Dispersion (in.)	
Horizontal	Vertical	Horizontal	Vertical
-23.8	-2.4	23.4	1.0
-8.3	6.2	7.9	7.6
-4.7	3.3	4.3	4.7
-5.1	1.6	4.7	3.0
-2.4	0	2.0	1.4
2.5	-0.8	2.9	0.6
4.3	-5.3	4.7	3.9
6.1	7.7	6.5	9.1
6.9	-23.9	7.3	22.5
23.2	0	23.6	1.4
Total -3.8	-13.6	87.3	55.2
Mean -0.4	-1.4	8.7	5.5
	True mean (in.)	9.2	5.8
	(min)	1.10	0.69

*These data were obtained by measurement of a photograph of the target for rounds No. 1922 to 1931. (Aberdeen Proving Ground Photograph No. 88216 with Firing Record No. M24862 on Ordnance Program No. 5962.)

Table IX. Accuracy test of 75-mm projectiles, M61 at 1000 yd on vertical target, June 4, 1943.

Gun	75-mm, M3	Charge	Standard fixed round
Mount	76-mm, M34A1	Muzzle velocity	2050 ft/sec
Projectile	75-mm, M61	Powder Temp.	60° to 70°F

Round	Coordinates of Point of Impact, Measured from Center of Target (in.)		Dispersion (in.)	
	Horizontal	Vertical	Horizontal	Vertical
3	4.0	-32.5	8.75	-4.0
4	2.5	-44.0	10.25	7.5
5	5.0	-43.0	7.75	6.5
6	8.5	-39.0	4.25	2.5
7	16.0	-38.5	-3.25	2.0
8	18.0	-34.5	-5.25	-2.0
9	24.0	-42.0	-11.25	5.5
10	22.5	-31.0	-9.75	-5.5
11	18.5	-29.0	-5.75	-7.5
12	8.5	-31.5	4.25	-5.0
Total	127.5	-365.0	70.50	48.0
Mean	12.75	-36.5	7.05	4.8
		True mean (in.)	7.4	5.1
		(min)	0.70	0.50
		50-percent zone (in.)	12.5	8.6
		(min)	1.74	0.85

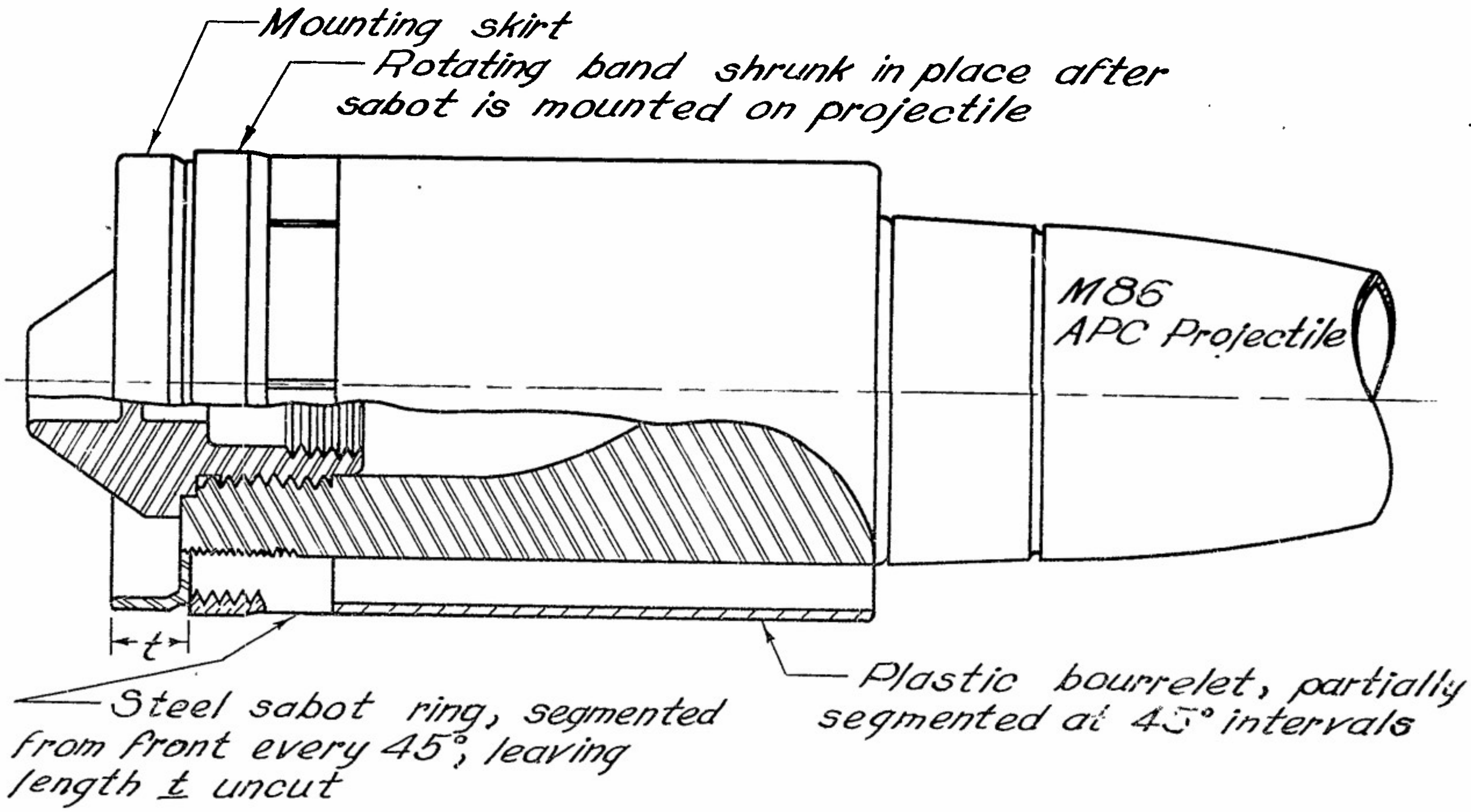

Fig. 23. 57-mm projectile, M86 mounted in 75-mm threaded-base sabot. Model 28-75D; projectile weight, 7.0 lb; total weight, 8.4 lb.