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NATIONAL DEFENSE RESEARCH COMMITTEE

ARMOR AND ORDNANCE REPORT NO. A-233 (OSRD NO. 2067)

DIVISION 1

DEVELOPMENT OF SUBCALIBER PROJECTILES FOR THE HISPANO-SUIZA GUN

by

C. L. Critchfield

and

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DECLASSIFIED - DOD Directive No 5200.9, 27 September 1958

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Approved on November 12, 1943 for submission to the Coordinator of Research

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Preface

The work described in 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.

This work was carried out by the Geophysical Laboratory of the Carnegie Institution of Washington under Contract OEMsr-51.

Conversations with Col. G. M. Ross, British Army; Col. J. M. Berkeley-Miller, British Army; and Col. B. F. Fellers, U.S. Army, showed that in the opinion of these officers the danger to friendly troops would not prevent sabot-projectiles from being of use. The fact that such projectiles would throw off parts at or near the muzzle, and that these parts would fall any place within a triangular area extending some distance in front of the gun and some 8 to 10° on each side of the line of fire, would not prevent their use under conditions such as had obtained in Libya. It was accordingly decided to begin experimental work with two parallel developments, one at the University of New Mexico under Contract OEMsr-668 supervised by E. J. Workman and the other at the Geophysical Laboratory under Contract OEMsr-51 supervised by C. L. Critchfield.

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The NDRC technical reports section
for armor and ordnance edited
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DEVELOPMENT OF SUBCALIBER PROJECTILES FOR THE HISPANO-SUIZA GUN

Abstract

Methods are outlined for the construction of subcaliber projectiles for the Hispano-Suiza gun.using a sabot. Cores both of tungsten-copper "Elkonite," with a density of 14.5 gm/cm^3, and of steel were used. Design drawings and a brief description of the sabot materials and methods of assembly are given. A detailed analysis of the performance of these projectiles is given as a result of firings for yaw, dispersion and muzzle velocity. Successful designs that worked on a centrifugal principle were made, but there was no success with those in which the sabot separates axially. Preliminary firings were made with finned projectiles in a sabot.

1. Preliminary theoretical considerations

Before the experimental development of subcaliber projectiles was begun, a theoretical study of the characteristics and possible advantages of such projectiles was made. Their stability was discussed in an earlier report[1/] in which it was concluded that subcaliber projectiles may be stabilized by spin alone when fired from standard guns if the body of the projectile is suitably shortened. It was found that for a twist of 1/25 no alteration in design is necessary for a shot that has maximum armor penetration. In fact, a considerable advantage can be gained by the use of very dense projectiles and the sabot.

It was stated that for uses other than armor penetration the subcaliber projectile offered little advantage. In particular, it was suggested that the poor ballistic coefficient of the subcaliber projectile made its usefulness in decreasing times of flight doubtful, but the matter is given further consideration in the Appendix of the present report.

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

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2. Problems involved in the firing of subcaliber projectiles

The firing of subcaliber projectiles by use of a sabot presents problems of many kinds. First, such firing must be restricted to guns that are not firing over friendly troops. Second, any compound projectile presents production difficulties that are emphasized for the sabot by the fact that the strength-weight ratio should be high and thus the most suitable materials are also in demand for aircraft.

Underlying the military and production problems is the most general one of making a sabot such that a reasonable efficiency can be obtained with a subcaliber projectile which compares favorably in accuracy, retardation and lack of yaw with standard projectiles. This problem has been studied at the Geophysical Laboratory without careful regard to the military and production aspects. The justification for this approach is that the principles of sabot design must be understood before the other problems become real and, even though the sabot should prove to be impractical for field use, it provides a convenient experimental method of obtaining high velocities. Thus, for example, the desirability of high velocity in armor penetration could be determined with standard guns.

3. Scope of research

Preliminary theoretical considerations presented in an earlier report[2/] have indicated that the performance to be expected from sabot-projectiles would provide a significant improvement in armor penetration only for dense projectiles, for example, tungsten carbide. Accordingly, most of the work on the 20-mm gun reported here has been done with projectiles of density 14.5 gm/cm^3 made of a tungsten-copper alloy, "Elkonite." In such a projectile the stresses are amplified and successful models should be easily adapted to steel projectiles. Tests against plate were made with tungsten carbide.

2/ Reference 1.

[redacted]

The possibility of using steel projectiles has not been neglected, since the flatter trajectory has much to recommend it although armor penetration is not otherwise increased. We have fired the caliber .60 AP projectile from the 20-mm gun at a muzzle velocity of 3700 ft/sec with good results, and also a shortened caliber .50 AP core has been tested at a muzzle velocity of 5200 ft/sec for dispersion and against plate.

Finned projectiles have been tried in centrifugal sabots in order to prepare for the stabilization of elongated subcaliber projectiles in guns of low twist. However, a reliable method of attaching the fins has not been found and except for isolated successes the results are generally negative.

A characteristic development in this work is the "sliding bourrelet" that was invented to reduce yaw and dispersion. The bourrelet of this type is a separate ring that is allowed to slide axially along a conical surface on the sabot-skirt in such a manner that the set-up forces expand the bourrelet against the lands of the gun. The net expansion amounts to a few thousandths of an inch and centers the projectile in the bore more positively than is otherwise feasible. This device has proved particularly useful when the short 11-mm cores were fired in the 20-mm gun, but its usefulness in the case of longer 15-mm (caliber .60) cores is questionable.

4. The 20-mm as a test gun

The advantages of the 20-mm gun as an experimental piece are mainly those of convenience in firing and caring for the gun and of economy of material used for the manufacture of the projectiles. Inasmuch as the chief theoretical virtue of the subcaliber projectile is improved armor penetration, the development of a sabot for the 20-mm must be considered preliminary to future adaptation to larger calibers. Other possible advantages of high velocity, on the other hand, might apply to the 20-mm as well as to larger guns. One satisfactory feature of the choice of the 20-mm as a test gun is that stresses are in general higher and tolerances more critical than in any other cannon so that developments for the 20-mm gun can be adapted readily to larger guns of similar twist of rifling. The sole possibility of difficulty lies in the increased duration of stresses in the larger guns.

For the most part, the projectile fired from the 20-mm gun is subject to more adverse conditions than is one fired from a gun of larger caliber. The maximum pressure and the angular velocity at the muzzle are considerably larger for the smaller caliber and the effect of tolerances, especially in concentricity, is more pronounced. Tolerances are particularly bothersome in composite projectiles that are centered by means of a sabot because both sabot and projectile must be properly centered. The lands of the 20-mm gun form a 7° angle with the axis of the bore; hence, if the center of the projectile is off the center of the bore by 0.001 in., the resulting deflection of the trajectory will be a little over 1 in. in 100 yd. Thus the quality of the machine work must be high in making sabots for 20-mm projectiles that will hit within 3 in. on the average at 200 yd.

There is a notable exception to the general rule that the design of a sabot for the 20-mm shell is more critical than that for larger calibers, and this arises from the short duration of the propelling forces. Even though the maximum pressure is much larger, the length of time of application is less in the smaller guns since it is roughly proportional to the caliber. Therefore, materials that show sufficient strength at small calibers may not be suitable at large calibers if they are incapable of sustaining stress. On the other hand, of course, materials that fail under too rapid loading may be acceptable in large caliber guns but not in small.

In general, it appears that a design that permits the required accuracy of fire for the 20-mm gun could be scaled up to larger calibers without difficulty. We have been particularly fortunate in having an excellent machine shop that readily produces the high-grade work that is necessary. Work done in separate pieces by outside shops and assembled later has been markedly inferior. It is patent that a principal requirement for an acceptable sabot is that it can be made by production methods, and it is for such a design that we are striving; but in the experimental stages it is necessary to eliminate disturbing effects in so far as possible.

5. The range at Deephole Point

In October 1942 it was decided that the Geophysical Laboratory should test its own 20-mm sabots and thus expedite the work. A suitable location for a range for the horizontal firing was found at Deephole Point, Prince William County, Virginia. A range there established was used for most of the firings.

6. Propellants and loading

At each firing a number of standard ball projectiles have been used for comparison with the dispersion of the sabot-projectiles. This ammunition is provided already loaded in several lots, two of which are used for testing of guns. One of these lots operates the gun at 88 percent of standard pressure and the other at 120 percent of standard (maximum about 58 000 lb/in.^{2}). In addition, standard rounds are used.

The experimental projectiles are somewhat lighter and therefore require a faster powder. Primed cartridge cases have been provided and are loaded from the magazine of the Geophysical Laboratory. Most of our work has been done with a single-perforated, double-base 75-mm howitzer powder, Lot 4255, having a web of 0.015 in. A graph of mass of powder required to produce a maximum pressure of 48 000 lb/in.^{2} as a function of mass of projectile is shown in Fig. 1. Also shown is the muzzle velocity produced by the charge indicated.[3] Several experimental points plotted as circles show the usefulness of the computations. These graphs apply to a chamber capacity of 2.36 in.^{3}, which is slightly larger than standard but more nearly that allowed in our work.

3/ The calculations on which Fig. 1 is based were made by S. F. Curtiss and R. B. Kershner.

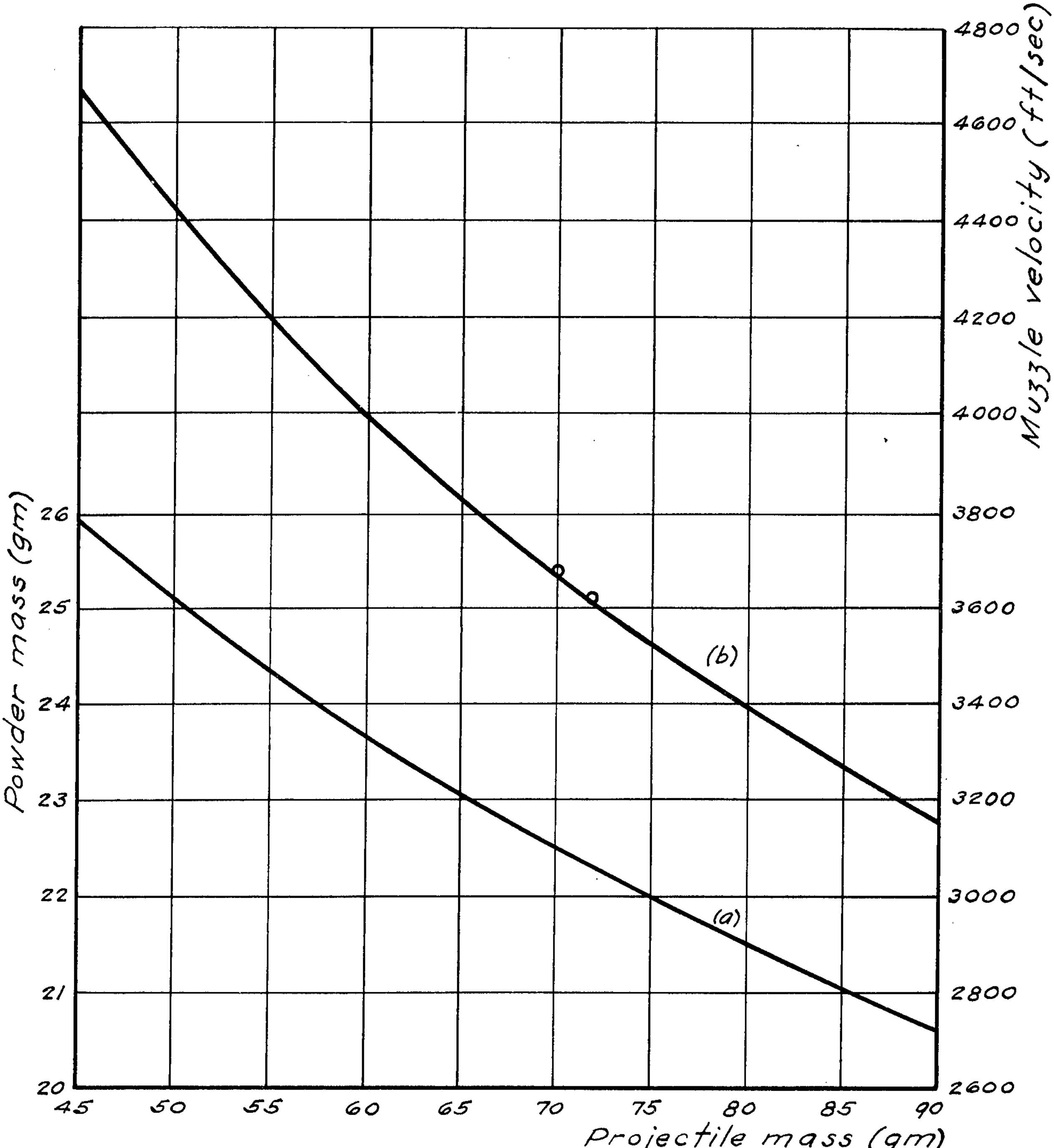

Fig. 1. Loading chart for the 20-mm Hispano-Suiza gun for Lot 4258 FNH M2, 0.015-in. web; maximum pressure, 48000 lb/in.^{2}; chamber volume, 2.36 in^3 Curve(a): mass of powder as a function of mass of projectile. Curve(b): muzzle velocity as a function of projectile mass under the assumption that the charge is that indicated by the point corresponding to the same projectile mass on curve(a).

[redacted]

In addition, a special lot of FNH-M2 powder, HES 3614, was obtained from the Hercules Powder Company. This powder has a 0.023-in. web, a long grain and a very fine single perforation. It was used mainly for the caliber .60 core projectiles.

7. General program

The purpose of the work herein reported is to develop a workable sabot for standard guns operating at standard pressure and adapted to projectiles of standard proportions but of smaller-than-bore diameter. A workable sabot is considered to be one that provides good obturation, transmits spin to the projectile, does not impair the accuracy of the projectile or foul the barrel unduly and remains intact during rough handling, especially during ejection from the chamber after a misfire. In addition to these necessary conditions the sabot must be as light in weight as possible.

The plan of development that has been followed is (i) obtain a workable sabot, as just defined, using duralumin as much as possible and using a steel projectile of simplified design, 14 mm in diameter; (ii) make the sabot as light as possible by removing metal or substituting plastic material or both; (iii) adapt the most promising developments to projectiles made of an alloy of tungsten and copper of standard AP design, 11 mm in diameter, and to finned steel projectiles; and (iv) compare the armor penetration of the products with that of standard AP 20-mm shot. Measurements made in tests include maximum yaw, muzzle velocity, dispersion and the masses of the various parts of the sabot. These measurements are supplemented by observation of the parts of the sabots that are recovered and of the condition of the gun after firing.

8. Projectiles

Preliminary tests were made on simple cone-headed steel projectiles 14 mm in diameter. The dimensions chosen give an estimated stability factor of 1.30, which is low for practical use but very good for experiments since the yaw of the projectile is amplified more if the stability factor is lower. In Series C[4] these projectiles were made of soft steel, but in Series A it was found that a permanent set held sabot and projectile together and it was necessary to use hard steel and heat-treat it. In Series B a boattail was added to the design. The stability factor for this design is estimated to be 1.8.

Adaptation of subcaliber designs to high-density cores has been approximated by using a tungsten-copper product, "Elkonite."[5] This material has a specific gravity of about 14.0 and a static compressive strength of 75000 to 100000 lb/in.^{2} The design of these projectiles is simply scaled down from the 37-mm AP steel shot without cap. It is, therefore, quite similar to Princeton's E-6. These projectiles were 7/16 in. in diameter, 3 calibers long with a 1.5 caliber tangent ogive and weighed 38.6 gm each. Subseries in which these projectiles are used are given the second letter W, and they are all caliber 20-11 mm.

One other principal type of projectile has been used in the Subseries F. For these the steel core of a caliber .50 ball projectile was used with a 0.40-in. shoulder turned on the rear and fins attached so as to protrude into the slip stream. Without the fins the projectile would be unstable when fired from the 20-mm gun. The area of the fins is chosen to give maximum effect, but quantitative predictions at the high velocities attained -- about 4500 ft/sec -- are impossible. The fins used are helical with the same pitch as the rifling of the gun.

The only general principle adhered to in the design of projectiles is to restrict them to standard types, avoiding annular grooves and unusually low sectional densities.

9. Rotating bands

All rounds with the exception of three made with SAE 1010 steel bands carried copper rotating bands. Several methods of attaching these

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4/ The significance of the letter designations is given in Sec. 9.

5/ Furnished by the General Electric Company.

bands have been tried; some were threaded onto the base from the front with a 32 LH sharp V thread. Three bases, however, were grooved and electroplated with copper to a thickness of $\frac{1}{2}$ mm. A tight bond was not formed between duralumin and copper, but the grooves provided enough purchase to retain the band. Essentially the same construction was obtained mechanically by a method in which a 3/4-mm band was forced into grooves with a die.[6] This method was used in most of the centrifugal series. Another method was to groove the duralumin (about 32 per inch) and then force the copper band into the grooves by means of a die.

10. Sabots

The sabots that have been made are conveniently divided into three classes according to the basic principle of their intended operation.

Series A comprises those sabots that are essentially one piece and cup shaped and from which the projectile proper is released axially. In addition to such sabot-projectiles constructed by us, four sabots of this type (37-mm) were fired for W. A. Forrester[7] at Aberdeen, July 25, 1942, and the results studied by us.

Series B is composed of boattail projectiles mounted on a conical seat in the sabot. Setback presumably distends the sabot which then ejects the projectile upon elastic recovery. Eleven 20-14 mm sabots have been tried in this series; their operation is in most cases all right, but they have a very large dispersion.

Series C includes all sabots that depend upon centrifugal force for their operation. All sabots of the centrifugal type that have been tried are of the same fundamental design. In this design the projectile is seated on a base that carries the rotating band. Rotation is transmitted from base to projectile by friction alone. The sides of the projectile are supported by a segmented sleeve — usually two half-cylinders — that fly off under centrifugal force after leaving the

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[6] This method was devised by J. Jost, of the Geophysical Laboratory.

[7] A patent application has been filed on this device. Description and account of tests are available in the files of Division 1, NDRC.

[redacted]

barrel. Series C contains the only really successful designs developed.

In designating the experimental rounds in this report the series letter is given first, then a number that is different for each principal design and then, perhaps, a lower-case letter indicating variants of the principal design. Series C has been divided into Subseries CW indicating that tungsten-copper is used for the projectile (20-11 mm) and CF indicating that the projectile has four fins. Series A has a Subseries AT in which a tracer charge is supposed to aid separation of sabot and projectile. Thus in Fig. 2 the design numbered CF2b is the second design of a finned projectile in Series C, variant b.

11. Standards of performance

Velocities were sometimes measured with the Aberdeen chronograph and checked in every case with the calculated values.[8] Maximum yaw was estimated from the axes of keyholes made in a set of cards, usually 12 in number, placed 6 ft apart.

Dispersion was measured on a cardboard vertical target placed 200 yd from the muzzle. The gun is mounted on a heavy stone boat by means of a trunnion, and adjustment of aim is accomplished by ½-in. machine screws that move the rear of the mount. Sighting is done through a full-length bore telescope.[9] Play in the gun amounts to about ± 0.1 mil. With this mount, the probable error of a single shot in line and height is about 0.30 mil each using standard ammunition. This represents the capabilities of the mount we are using. Probable errors in line and elevation are estimated in the usual way from the standard deviations of the sample. Let x_i be the line of the ith shot and $\bar{x}$ the average line of n shots; then r_h, the estimated probable error in line, is

$$r_h = 0.674\sqrt{\Sigma(x_i - \bar{x})^2/(n - 1)}.$$

8/ The calculations were made by C. F. Curtiss.

9/ Designed and made by J. L. England.

An analogous formula holds for the probable error r_v of the vertical deviations. Ammunition may be considered acceptable in accuracy if the estimated probable error in line is 0.5 mil or less.[10] Results with 20-11 mm sabots and dense projectiles prove to be just at the boundary of acceptability.

Samples of the dense projectiles were tested for eccentricity.[11] The center of gravity in every case was within 0.001 in. of the geometric center so that dispersion due to eccentricity alone should amount to less than 1 in. or 0.2 mil in line.

12. Series C

(a) Soft steel projectiles. -- Work on centrifugally operated sabots was begun in July 1942. The first model, C1, proved unsatisfactory because of the engraving of the duralumin bourrelet. Since this experience duralumin has been kept from contact with the lands of the gun. The second model, C2, proved acceptable in principle but was much too heavy. The sabot C2 weighed 40 gm whereas a reasonable mass should be more like 10 percent of the mass of AP shot, or 16 gm. Subsequent developments in this series have been directed toward making the sabot lighter. The best all-metal design is C3; the use of plastic was introduced in C5. Representative types are illustrated in Fig. 2.

In making trials of the sabots, types of bases were often interchanged. A detailed report on the firings is given in Table I, but in the following paragraphs we give a brief general description of the variants of each type and their purpose. There are three variants of C2. Variant a had a brass outer sleeve which became deeply engraved. Steel was then substituted for brass in variants b and c. The difference between these two is that in b the outer sleeve was almost completely separated into halves leaving only 0.003 in^2 to be ruptured,

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10/ Information received from R. H. Kent.

11/ These tests were made by the Department of Physics of the University of Virginia.

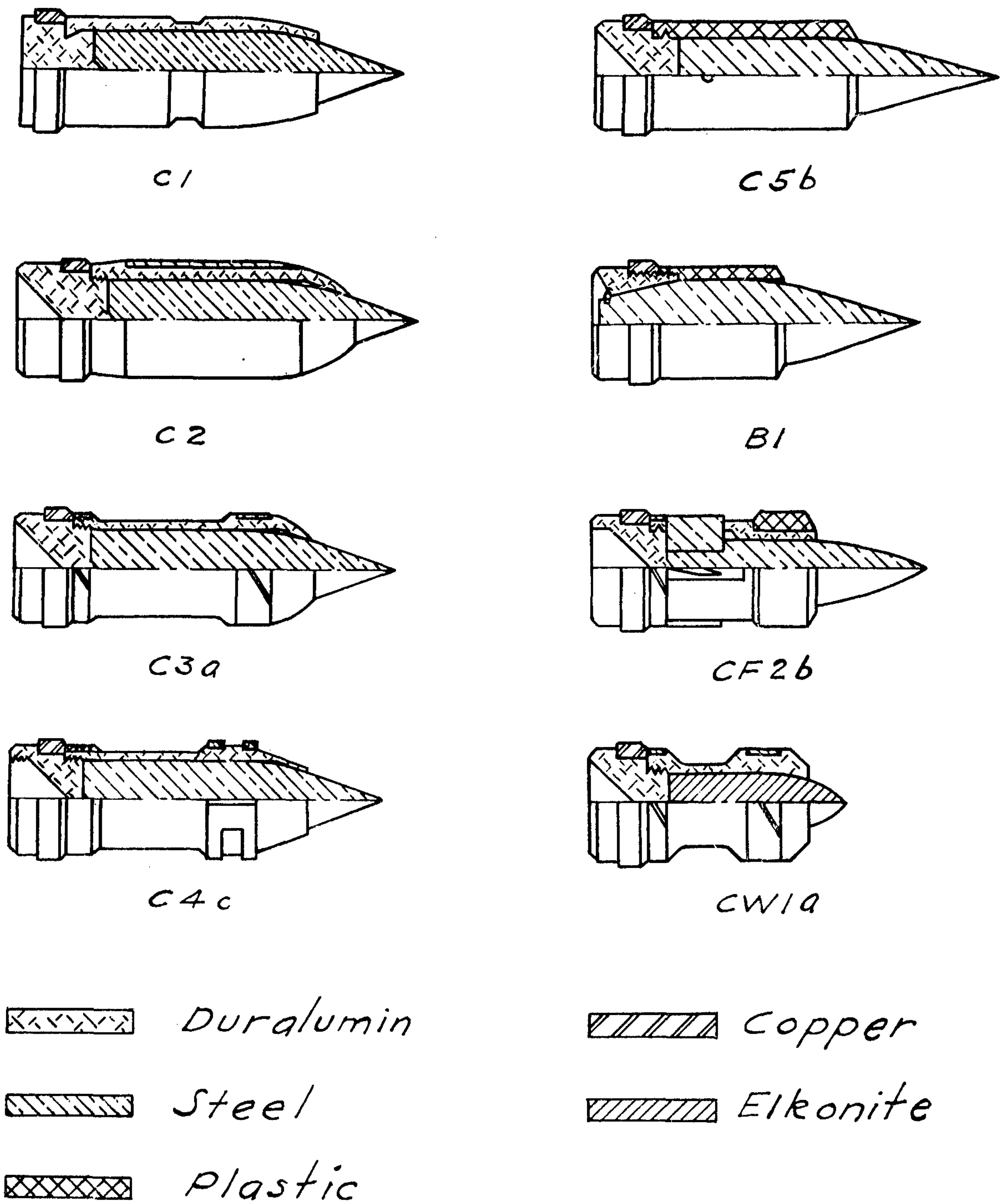

Fig. 2. 20mm sabot-projectiles of Series B and C.

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[redacted]

Fig. 3. Type C2 at 4 ft from the muzzle.

Table I. Data for rounds in Series C, steel projectiles, caliber 20-14 mm.

Number of Rounds	Date (1942)	Type	Mass (gm)			Est. Muz. Velocity (ft/sec)	To Test	Maximum Yaw (deg)
			Proj.	Sabot	Powder			
1	8-20	C1	50	30	20.7	3200	Duralumin bourrelet (split)	80
1	9-14	C2a	50	40	20.7	3100	Brass bourrelet (split)	15
1	9-14	C2b	50	40	20.7	3100	Steel bourrelet (split)	2
1	9-17	C2c	50	40	22.0	3400	Steel (large rupture force)	35
1	11-21	C2b	51	37	20.9	3200	Photographs	
1	11-21	C2b	51	32	22.1	3390	Photographs and plated base	
1	11-21	C4a	50	20	22.6	3670	Photographs and plated base	
1	11-21	C4a	50	23	22.2	3580	Photographs and plated base	
1	11-21	C3b	50	25	22.4	3530	Photographs and cone seat	
1	11-21	C3a	50	26	21.9	3500	Photographs	
1	12-1	C4b	50	24	22.1	3560	Soldered bourrelet	10
1	12-1	C4b	50	24	22.2	3600	Soldered bourrelet	small
1	12-1	C4b	50	24	22.2	3600	Soldered bourrelet	26
1	12-1	CF1	51	36	20.9	3230	Finned projectile	small
1	12-3	C5a	50	20	22.5	3670	Plastic skirt	small
2	12-8	C5b	50	19	22.6	3690	Plastic skirt	5
1	12-8	C3a	51	26	21.9	3500	Base type - J	0
6	12-15	C4c	50	22	22.3	3620	Velocity and dispersions	
12	12-22	C3a	50	26	30.0*	3750	Velocity and dispersions	
1	1-7**	C5c	61	19	29.4*	3500	Performance (caliber .60 core)	11

*Powder: FNH M2, 0.023-in. web, lot HES 3614.

**Jan. 7, 1943.

[redacted]

but in c the sleeve was not so completely separated and 0.025 in^2 had to be ruptured. This latter is about the maximum area of steel that can be broken by the centrifugal forces. Variant b worked very well and is the first completely workable sabot to be made. Figure 3 is a photograph of this taken about 4 ft from the muzzle. Variant c showed a large yaw presumably developed during rupture of the sleeve.

As previously mentioned, type C2 is too heavy to be acceptable, and types C3 and C4 represent attempts to lighten the design. At the same time the steel outer sleeves were fashioned so that no steel need be ruptured. In C3 this was done by sawing the two sleeves at an angle to the elements of the cylinder (see Fig. 2). Variant a as made in our shop worked encouragingly well, so a dozen were obtained from an outside shop and tested for yaw and dispersion. The latter were inferior in construction partly because a softer steel was used for the outer sleeves. A number of these sleeves that have been recovered show appreciable engraving. The mean dispersion at 210 yd proved to be 12 in. as compared with 3 in. for standard ammunition. Although this accuracy is not acceptable, it appeared that there was good reason for adapting this model to heavy cores for further development. This adaptation is designated CW1 and will be discussed subsequently.

One round of variant C3b was made and fired at Aberdeen. It is characterized by a cone seat for restraining the inner sleeve instead of a rear steel sleeve. The device does not prevent the duralumin from springing out, however, and is not satisfactory. The same effect was noted on two 37-mm sabots constructed on that principle and fired on the same day.

Type C4 was designed to put the steel outer sleeve to use not only as a bourrelet but as a lock to hold the duralumin halves together while in the bore. The steel is supported only in bosses that project through the rectangular holes in the duralumin sections. This support proved insufficient and in 10 out of 11 rounds the steel fell off in the gun. In the last nine rounds the outer sleeves were soft-soldered together but without effect except in one round. If the locking device is to be employed, the outer sleeve must evidently be given additional support at the rear, as in C3. At present, the need for locking is not pressing and the design has not been made. Variant a of this type relied on a cone seat alone on the rear as in C3b, but failure was not evident here because the steel sleeves fell to the base and protected the duralumin. Two of variant a were fired at the Michaelsville Range, Aberdeen Proving Ground, then three of b at Deephole. The remaining six were C4c. Variant b used a duralumin ring on the rear in addition to the cone seat; and variant c, a phenolic laminated plastic ring. The design is unsuccessful, the mean dispersion being something like 15 in. at 210 yd.

Type C5 is our first design using laminated plastic, Phenolite-C, in construction of the sabot. Variant a differs from b as shown in Fig. 2 only in having the sabot held to the base by two pins instead of the annular ridge. The operation of this type was apparently successful. Recovered sections of the sabot, however, indicate that charring and possibly failure of the plastic near the base took place. This is not a serious obstacle for use with the 20-11 mm sabot because of the shorter skirt necessary for that application. Inasmuch as the plastic does not have sufficient tensile strength to resist the centrifugal forces, the tendency to fail and char at the base can be overcome in the 20-14 mm sabots by not splitting the skirt all the way to the base.

(b) Finned projectiles. -- The data for the finned projectiles that have been tried appear in Table II. Four were made and tried in a preliminary study of the type. Of these, CF1 is an adaptation of C2a made by slotting the duralumin skirt and mounting four fins on the base of the projectile which would be stable without the fins. The purpose of this round was to detect adverse effects of fins on operation or stability. The fins were damaged by the releasing of the sabot, but the projectile flew straight and with very little yaw.

The 20-11 mm finned projectile used, designated CF2b, is shown in Fig. 2. One each of three variants of the design CF2 have been tried in search of a suitable sabot construction. The skirt in variant a was

Table II. Data on rounds in Series C, finned projectiles, caliber, 11-20 mm.

Number of Rounds	Date (1942-43)	Type	Mass (gm)			Est.Muz. Velocity (ft/sec)	To Test
			Proj.	Sabot	Powder		
1	12-15	CF2a	29	16	25.9	4650	Stability**
1	12-18	CF2b	29	22	25.0	4400	Velocity and stability
1	12-22	CF2c	29	18	30.0*		Velocity and stability (plastic sabot)
1	2-2	CF3a	24	22	25.7	4600	Yaw
1	2-4	CF3b	24	22	25.7	4600	Yaw
2	2-12	CF4b	25	17	26.8	5010	Yaw and velocity
2	3-2	CF4c	25	21	25.8	4600	Yaw (AP)
1	3-4	CF4d	25	21	25.8	4600	Yaw (AP)
1	3-9	CF4d	25	21	25.8	4600	0.003 push fit
1	3-11	CF4e	25	21	25.8	4600	Threaded fins
1	3-17	CF4f	25	21	25.1	4500	Yaw (ball)
1	3-17	CF4e	25	21	25.1	4500	Yaw (AP)
8	3-30	CF4f	25	21	25.1	4500	Dispersion

*Powder FNH M2, 0.023-in. web, lot HES 3614.

**Maximum yaw, 68°.

made mostly of plastic bushed at the nose with duralumin and evidently failed in the gun because the yaw was 68°. The skirt in variant c was all plastic, quartered instead of halved, and equipped with a split steel ring at the base. It did not fail in the bore, but the projectile was about 1° off line. Variant b is the only promising one of the three, and it was $\frac{1}{2}$° off line though evidently stable. The maximum yaw developed was 25° and instrumental velocity[12/] was 4200 ft/sec. The bullet just nicked the last velocity frame; no contact was made so no muzzle velocity was obtained. The fins in all these models were handmade of steel and were therefore not particularly well balanced.

12/ Velocity as measured at the chronograph, not corrected back to the muzzle.

[redacted]

Nineteen additional rounds of finned projectiles were fired. Of these, 15 were either attempts to mount fins on hardened AP cores or to find a method by which this could be done. All these were failures. Two rounds were fired with plastic skirts that were not completely separated behind the protruding fins. The fins were badly torn during release of the sabot.

The only successful rounds were the first two fired in this series (CF3a and CF3b). The cross-sectional drawing is shown in Fig. 4. The core is soft steel (caliber .50 ball ammunition) and the base has a center that projects into a corresponding center hole in the projectile. The fins were made of duralumin canted at 7° to an element of the surface, and were forced onto the $\frac{1}{4}$-in. cylinder that had been turned on the rear of the ball. These fins stayed on, apparently because of a riveting action under setback. It is not possible to say from the two successful rounds that finned projectiles are practicable.

Inasmuch as four fins were used and the sabot quartered, it was impossible to keep the duralumin skirts from bearing on the lands. This is a fundamental objection to the design. Fins might be useful, however, if a two-section sabot, such as the Budd Wheel Company has designed,[13/] is practicable. As is pointed out in the Appendix, fins on rotating 3-in. projectiles might permit their being fired from 4.7-in. or 5-in. guns with a very significant reduction in time of flight even at ranges of 20000 to 30000 yd.

(c) Heavy-alloy projectiles. -- A summary of the characteristics of design for heavy-alloy projectiles is given in Table III and detailed firing data are given in Table IV. The first of the tungsten-copper projectiles tried were of the type CW1. The variants are a, duralumin skirt with two steel (split) rings as shown in Fig. 2; b, the same as a with 2 gm of duralumin cut out from under the forward ring (inside); c phenolite skirt with one steel ring forward; d, all-phenolite skirt;

13/ Drawings in the files of Division 1, NDRC.

[redacted]

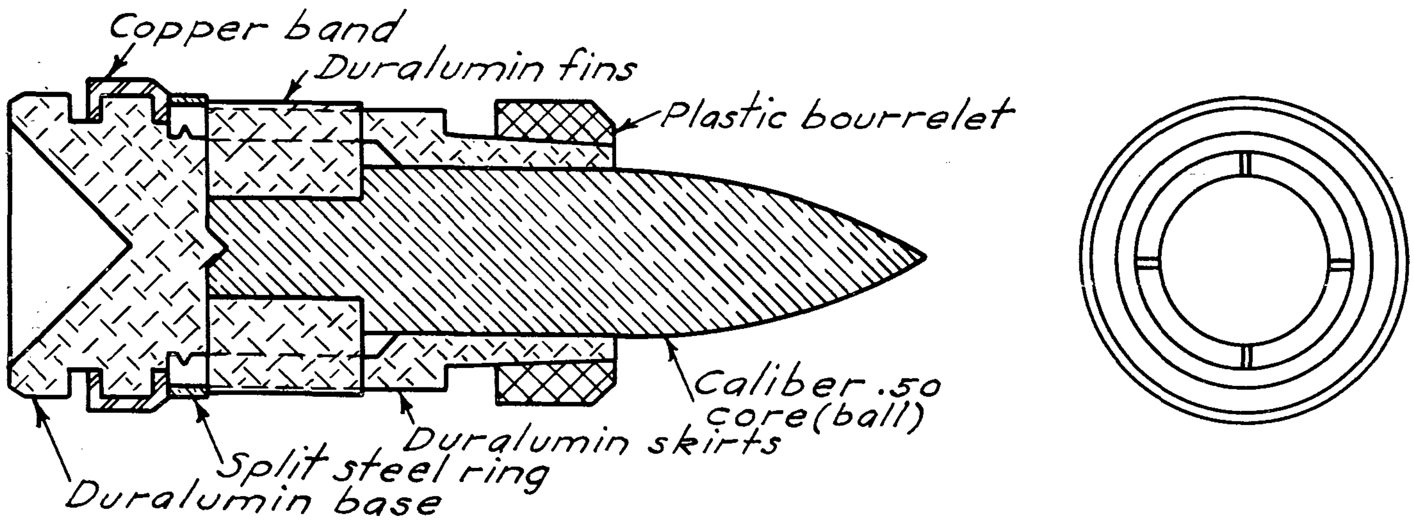

Fig. 4. The 20—11 mm finned projectile CF3b.

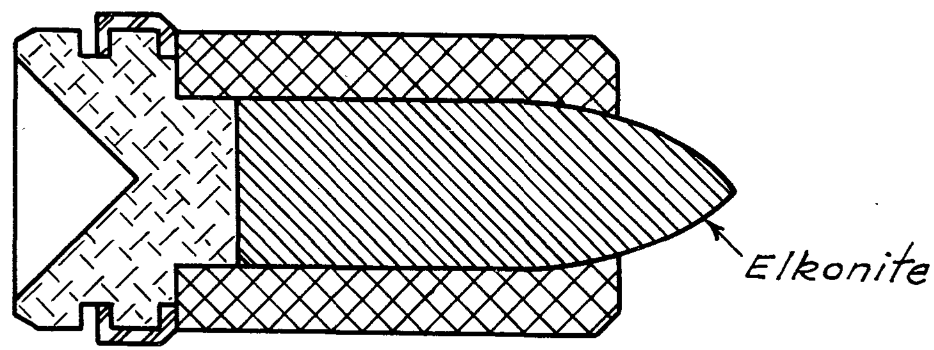

Fig. 5. Solid sabot CW1e.

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 [redacted]

e, simple all-plastic skirt, split two-thirds the way down from the forward end, no sliding bourrelet (Fig. 5); f, like e but with shorter core and masonite skirt cut perpendicular to grain; g, same as f with standard core and masonite cut parallel to grain; and h, same as e except that the projectile is 4 calibers long and was designed to test overload on the base. Variants a and d gave the best results in the early firing. The steel ring in c evidently fell off as a maximum yaw of 38° was developed. This was fortunate from one point of view, however, as the hole made by the projectile showed that there was no appreciable mushrooming of the tungsten-copper projectile. The purpose of tests with Elkonite is to find a design that works for high-density cores in general; there is no evidence that this material is particularly good as armor-piercing cores. The recovered bases show that the duralumin takes a permanent set during acceleration.

In all, 114 of the 20-11 mm Elkonite projectiles have been fired at Deephole Point or into a recovery box. Dispersion data on 90 of these in groups of 9 were obtained and, of the remaining number, 14 were tested for maximum yaw and general performance of the several designs. Two rounds were tested for velocity, 5 were to prove certain plastics and 1 to prove the base design.

The working drawing for sabot CW3a and CW3b is presented in Fig. 6. The base is made of duralumin 17-ST and the rotating band is crimped over the 0.135-in. ridge.[14/] It is imperative that the propellent gases do not leak through between the band and the duralumin because of the tendency of the latter to excessive erosion. The assembly is shown in Fig. 7. These bases are found between 100 and 250 yd from the muzzle of the gun when fired horizontally. Rotation is transmitted from band to base and from base to projectile by frictional force alone. This design has been fired at 56000 lb/in.^{2} against a 50.7-gm (11-mm) projectile without shearing. The calculated maximum compression between base and projectile

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14/ This method of mounting rotating bands was devised by J. Jost of the Geophysical Laboratory Shop.

[redacted]

Table III. Summary of the characteristics of design for heavy-alloy projectiles.

	A. Designs on which dispersion tests were made
CW1e	Straight plastic skirt, no sliding bourrelet (Fig. 5).
CW3a	Sliding bourrelet design* $3^\circ \times 0.15$-in. (Fig. 7).
CW3b	Sliding bourrelet design $4^\circ \times 0.15$-in.
CW2a	Sliding bourrelet design $3^\circ \times 0.10$-in.
CW2b	Sliding bourrelet design $3^\circ \times 0.13$-in.
CW2c	Sliding bourrelet design $3^\circ \times 0.16$-in.
CW4b	Duralumin 17-ST skirts, sliding bourrelet made of linen rod, $3^\circ \times 0.13$-in.
CW5	Tungsten carbide core of German 28/20 Gerlich used in elongated design built on CW3b sabot. The core is 3.7 calibers long instead of 3 calibers.
CW6	Sliding bourrelet next to core $3^\circ \times 0.15$-in. (Fig. 8)
	B. Designs for other tests, such as preliminary work and tests of material
CW1a	Duralumin skirt with two split steel rings (Fig. 2).
CW1b	Same as CW1a with 2 gm of duralumin cut out from under the forward ring on the inside.
CW1c	Phenolite skirt with one steel ring forward.
CW1d	All phenolite skirt.
CW1f	Like 1e but with shorter core and masonite sabot cut perpendicular to grain.
CW1g	Same as 1f with standard core and masonite cut parallel to grain.
CW1h	Same as 1e except projectile was 4 calibers long.
CW2d	Sliding bourrelet design $3^\circ \times 0.20$-in.
CW4a	Like 4b except bourrelet was made of flat stock.

*The first figure indicates the semivertical angle of the cone and the second the distance that the bourrelet moves.

Table IV. Data on firing of heavy-alloy projectiles, caliber, 20-11 mm.

Number of Rounds	Date (1942-43)	Type	Mass (gm) Projectile	Mass (gm) Sabot	Mass (gm) Powder	Estimated Muzzle Velocity (ft/sec)	Maximum Yaw (deg)	Dispersion (mils at 200 yd) Horiz.	Dispersion (mils at 200 yd) Vert.	To Test
1	12-31	CW1a	38	25	23.4	3800	11			Elkonite and performance
1	12-31	CW1b	38	22	23.7	4000	18			Elkonite and performance
1	12-31	CW1c	38	19	24.2	4150	38			Elkonite and performance
1	12-31	CW1d	33	17	24.4	4200	11			Elkonite and performance
1	2-2	CW2a	38	18	24.3	4140	5			Yaw
2	2-2	CW2a	38	18	24.3	4110	Test halted			Dispersion
1	2-3	CW1f	34	17	24.9	4360				"Masonite"
1	2-3	CW1g	39	18	24.1	4130				"Masonite"
9	2-4	CW2a	38	18	23.3	3900		0.50	0.42	Dispersion
2	2-12	CW1e	38	18	24.3	4150*				
1	2-12	CW2e	38	18	24.3	4150	7			Yaw
1	2-12	CW2b	38	18	24.3	4150				Targeting
1	2-15	CW1h	50	18	24.3	3980				Overload on base
9	2-16	CW2c	38	18	24.3	4150		.51	.37	Dispersion
9	2-16	CW1e	38	18	24.3	4150		.64	.43	Dispersion
9	2-18	CW2a	38	18	24.3	4150		.93	.88	Dispersion
9	2-18	CW2b	38	18	24.3	4150		.50	.70	Dispersion
1	2-24	CW2d	38	18	24.3	4150	7			Yaw**
1	2-24	CW2e	38	21	23.9	4040	5			Asbestos
1	3-2	CW4a	38	19	24.1	4120	13			Yaw
4	3-2	CW4a	38	19	24.1	4120		Large		Dispersion
1	3-4	CW4b	38	19	24.1	4120	5			Yaw
1	3-4	CW3b	38	18	24.3	4150	0			Yaw
1	3-4	CW3a	38	18	24.3	4150				Yaw
1	3-4	CW2c	38	18	24.3	4150	0			Yaw
9	3-4	CW3a	38	18	24.3	4150		.56	.47	Dispersion
9	3-4	CW3b	38	18	24.3	4150		.25	.60	Dispersion
1	3-9	CW3a	38	18	23.5	3930***				
1	3-9	CW1e	38	18	24.3	4150	10			Yaw
9	3-11	CW3b	38	18	23.1	3900		.45	.57	Dispersion
5	3-11	CW4b	38	19	24.1	4120		.84	1.40	Dispersion
7	4-1	CW5	47	20	22.9					Dispersion
1	4-13	CW5	47	20	22.9					Stability factor
1	4-13	CW2c	50	19						Performance, Mallory 1000
1	6-1	CW6	39	18	24.1	4130	7			Yaw
8	6-1	CW6	39	18	24.1	4130		.55	0.55	Dispersion

*Measured velocity, 4090 ft/sec. **This projectile broke. ***Measured.

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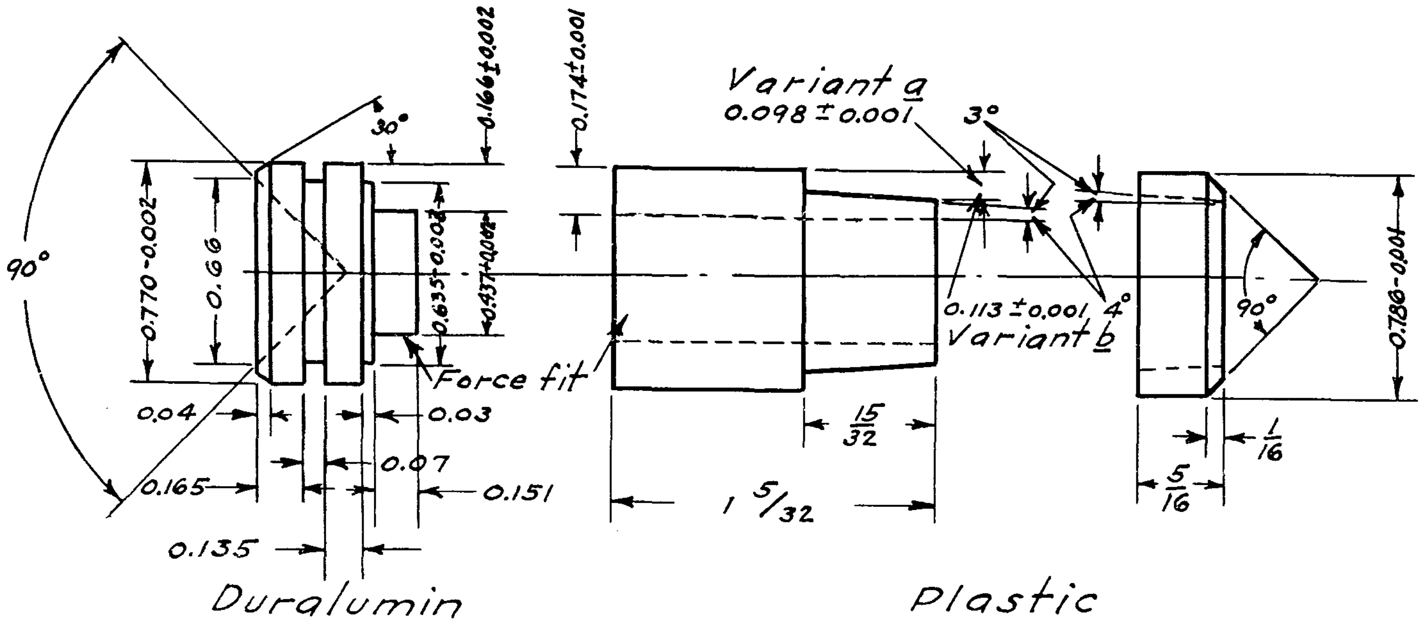

Fig. 6. Working drawings for sabots CW3a and CW3b. Dimensions in inches.

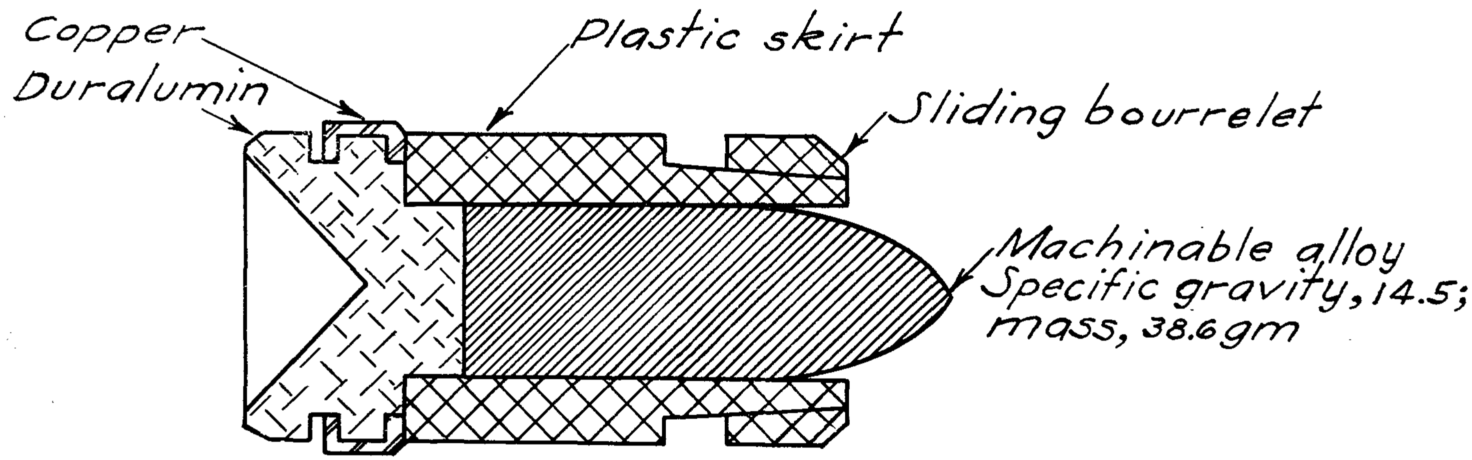

Fig. 7. Sabot assembly for types CW3a and CW3b.

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is 136000 lb/in^2, and the base shows a 2-mm permanent set. All bases fired at a maximum pressure of 48000 lb/in^2 show about 1-mm set and those fired at 44000 lb/in^2 show a slight one. A completed base with rotating band weighs 10 gm.

Onto the base is fitted a cylindrical skirt that has been sawed on one diameter for about two-thirds its length to encourage symmetrical separation. This skirt is made of a canvas-base plastic except in the case of CW4 and is supposed to be shed by centrifugal action at the muzzle. The pieces leave the gun at 7° to the line of fire and are found as far as 200 ft from the muzzle. The forward end of the large piece shown in Fig. 6 is the split section. The smaller ring fits onto the larger piece on the conical surface so that the forward surfaces are flush and the projectile is held firmly. The smaller ring is not split and is expected to remain in one piece during propulsion. Expansion of this ring as it slides down to the shoulder on the larger piece is intended to center the projectile firmly and thus reduce yaw and dispersion. The effectiveness of the device in this respect depends upon the quality of the machine work, the angle of the cone and the axial distance that the bourrelet moves. Several axial distances in addition to those shown in Fig. 6 have been tried with semivertical angles of 3° and 4°. The best results were obtained with 3° and 0.16-in. slide and with 4° and 0.15-in. slide. These are designated 3$^\circ \times$ 0.16 in. and 4$^\circ \times$ 0.15 in., respectively. A 3$^\circ \times$ 0.20-in. combination was tried but the yaw proved large indicating that the ring split in the gun. The difference between the CW3 series and the CW2 series is that in the CW2 the plastic skirt is threaded onto the base instead of being a force fit.

Another type, CW4, has a sliding bourrelet but the larger skirts are made of duralumin 17-ST. In variant a of CW4 the bourrelet was made of sheet plastic and in variant b it was made from linen-base rod.

Still another type, CW6 (Fig. 8) has the sliding bourrelet on the inside next to the core. The principle is the same as with the other

[redacted]

types except that instead of the ring expanding, the skirt is expanded by the ring against the lands thereby centering the projectile. The main advantage of this type is the absence of grooves on the outside of the skirt. The assembly drawing is shown in Fig. 9.

Masonite and asbestos-base phenolic were tried as material for the skirts, but both are unacceptable at these high pressures. Unfortunately, enough plastic stock of a single specification was not available, and we had to use tubes and rods of a variety of sizes and degrees of cure. The best material when all aspects are considered was $3/8 \times 7/8$-in. canvas-base phenolic tube (Phenolite 45-C). In addition to the variation in materials, the quality of work was not the same for all since several machine shops were used to produce the sabots. The results on yaw and dispersion are thus fairly representative of the general design of sabot considered.

The usual test procedure was to fire one or two sabots of a certain design through yaw cards to note how much yaw was developed and how the design worked in general. Then nine rounds were fired at the vertical target at 200 yd. Dispersion is caused by large yaw as well as by other factors, and it was deemed advisable to judge a design from its dispersion rather than by measuring the yaw on a similar number of rounds.

Reproductions of the targets for each of the dispersion tests as well as for tests of standard rounds are given in Fig. 10. A circle about the center of the pattern containing half the shots is drawn in each case. It will be noted that the accuracy of the gun with standard ammunition becomes worse with time. The reason for this trend is not clear but may be partly due to freeing of the mount in the spring thaws.

A considerable difference in the dispersion as measured by different tubes is also evident. Thus on February 4 (Table IV) the probable error in dispersion of type CW2a was 0.50 mils horizontal, 0.42 mils vertical whereas on February 18 the same type gave almost double the dispersion. The explanation for this result may lie in the

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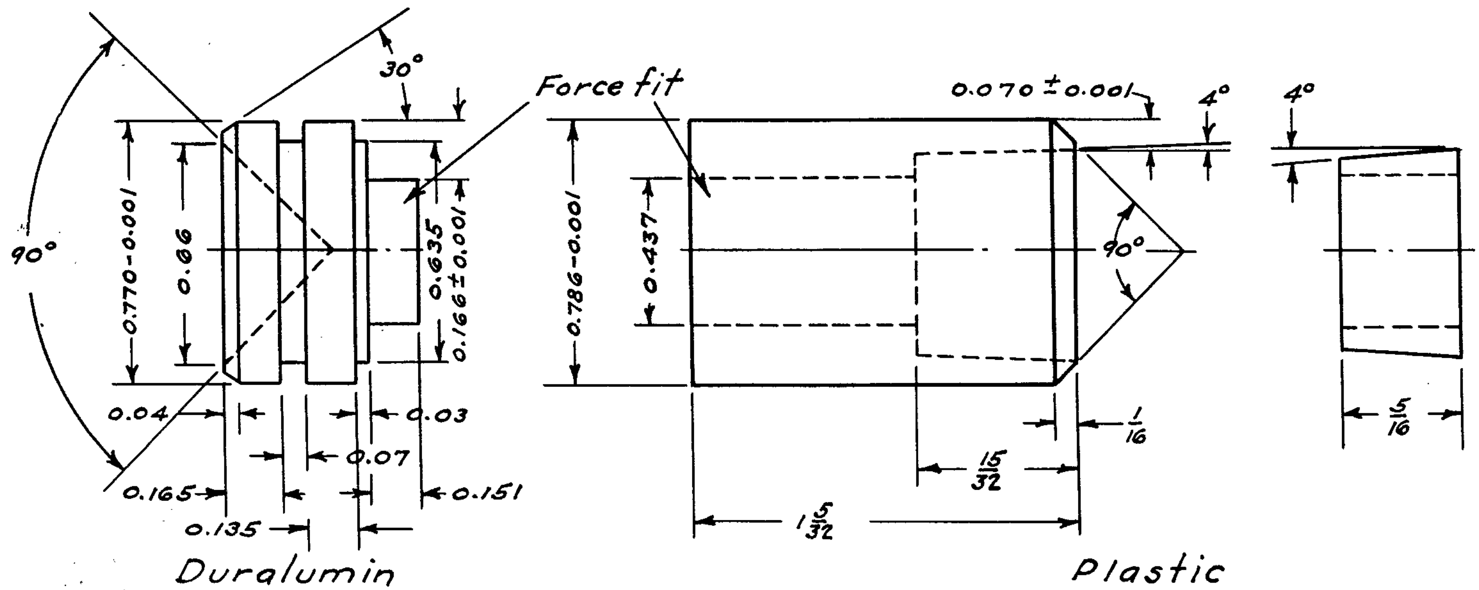

Fig. 8. Working drawings for sabot CW6. Dimensions in inches.

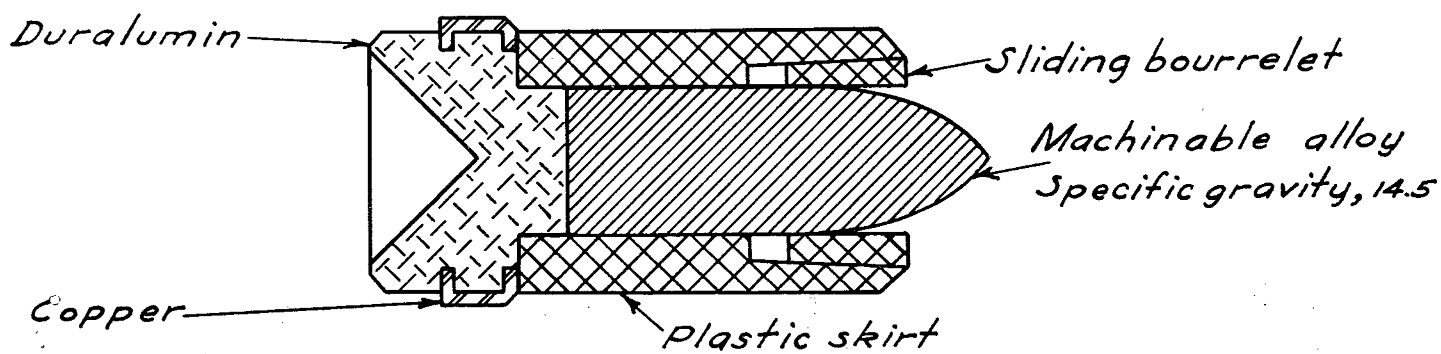

Fig. 9. Sabot assembly for the 20-11 mm type CW6.

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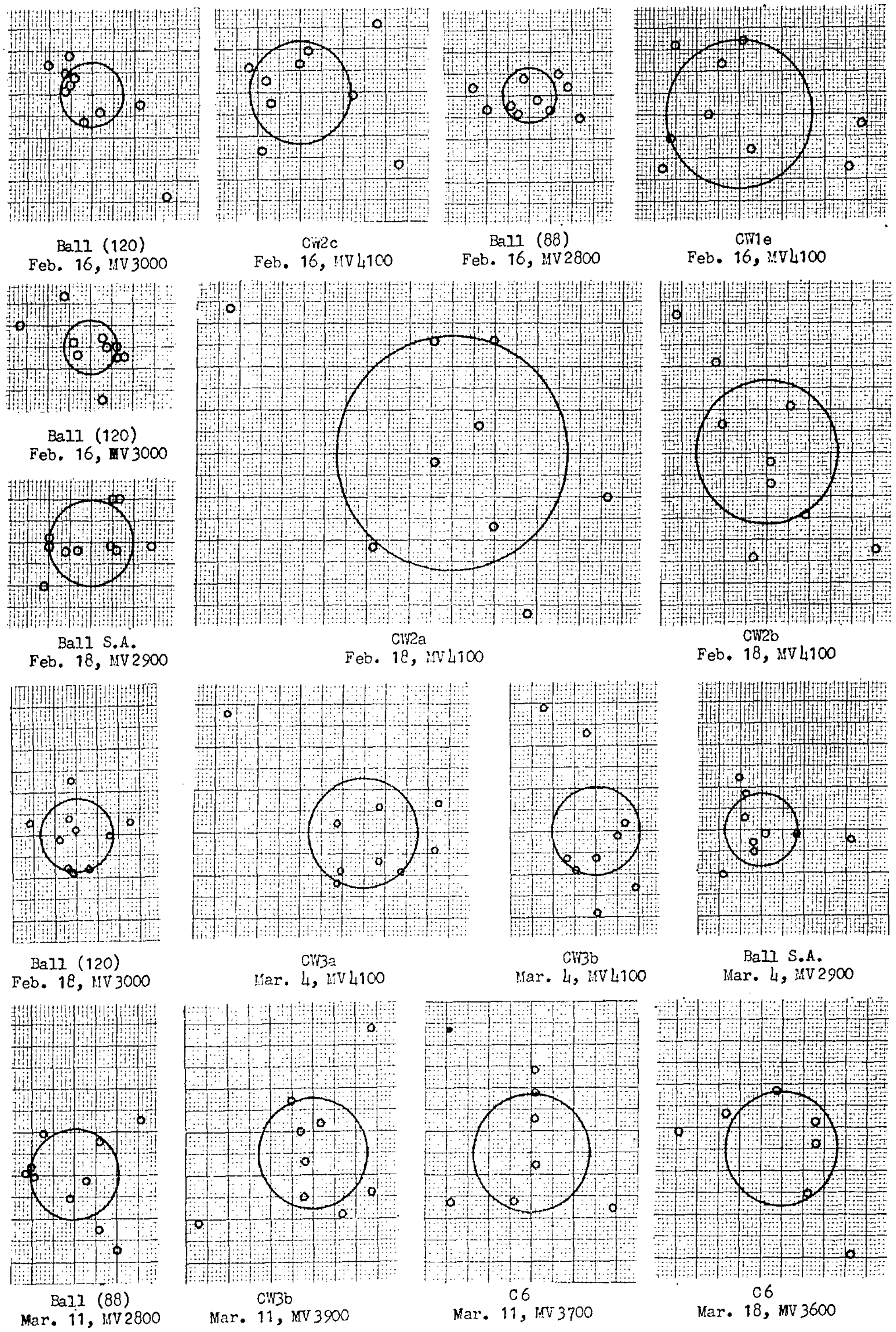

Fig. 10. Dispersion results; 1 div = 1 cm at 200 yd; MV, muzzle velocity (ft/sec).

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difference in diameter of the gun tubes used. The tube used through February 4 (Tube No. 2) is the smallest of our four tubes and has 0.002 in. less diameter across the lands than the succeeding tube, No. 3. Tubes were changed because of a damaged land in No. 2. Results using the same tube are more consistent.

It is satisfactory that the more workable designs -- CW2c, 3a, 3b, and 6 -- average about 0.5 mil in probable error even though the larger tube was used, since this probable error is the boundary of acceptability for ammunition. The only direct comparison between sliding and solid bourrelet was made on February 16 between CW1e and CW2c (see Table IV and Fig. 10).

In an effort to obtain a comparison between rounds fired for dispersion on different days and in different tubes, the following procedure was used. Four measures of the dispersion -- average distance from center of pattern, distance of the median shot, height plus width of total pattern, and the longest distance between two shots out of nine or ten in each determination -- were divided by nominal values characteristic of standard ammunition and averaged to give the ammunition an "accuracy rating." The rating for sabot ammunition is then compared with the rating of the same kind for standard ammunition obtained on the day of the test. The quotients of the ratings obtained in this way are shown in Table V. A graph of the dispersion factors thus obtained versus the product of angle of cone and length of slide is given in Fig. 11. This shows a monotonic decrease in dispersion as the amount of take-up by the collar increases. The best performance is 40 percent larger in dispersion than standard. This is to be compared with 100 percent increase in dispersion when no sliding bourrelet was used. It thus appears that windage plus compressibility of the plastic is a serious item in the construction of accurate sabot ammunition. This conclusion is substantiated by the greatly improved accuracy of CW2a in the small tubes (compare results of February 4 and 18). The amount of expansion of the bourrelet is limited by the elastic properties of the reinforced plastic. With stronger material, the accuracy may be further improved by the sliding device.

[redacted]

Table V. Ratio of accuracy ratings for sabot and standard ammunition.

Date (1943)	Type	Bourrelet Design*	Ratio of Accuracy Ratings for Sabot and Standard Ammunition**
2-4	CW2a	3° × 0.10 in.	1.45***
2-16	CW2e	3° × 0.16 in.	1.62
2-16	CW1e	none	1.95
2-18	CW2a	3° × 0.10 in.	3.19
2-18	CW2b	3° × 0.13 in.	2.31
3-4	CW3a	3° × 0.15 in.	1.70
3-4	CW3b	4° × 0.15 in.	1.39
3-11	CW3b	4° × 0.15 in.	1.45
3-11	C6a	3° × 0.13 in.	1.22
3-18	C7	4° × 0.15 in.	3.52
3-18	C6a	3° × 0.13 in.	1.37
6-1	CW6	4° × 0.15 in.	1.56

*The first figure indicates the semivertical angle of the cone and the second the distance that the bourrelet moves.

**Accuracy ratings were based on four measures of dispersion that are described in Sec. 12(c).

***Small tube.

Table VI. Data on firing of steel AP projectiles.

Number of Rounds	Date (1943)	Type	Mass (gm) Proj	Sabot	Powder	Est. Muz. Velocity (ft/sec)	Max. Yaw (deg)	Dispersion (mils at 200 yd) Horz.	Vert.	To Test
			Caliber 20-15 mm projectiles							
1	1-7	C5c	61	19	29.4*	3500	11			Performance
1	2-4	C5c	61	18	21.6	3420	3			Yaw
1	2-12	C6a	61	18	25.0*	3170**				Velocity
8	3-11	C6a	61	18	29.8*	3700		0.40	0.48	Dispersion
1	3-17	C6a	61	18	29.8*	Sabot failed in gun				
7	3-18	C6a	61	18	29.0*	3600		0.50	0.46	Dispersion
13	5-20	C6a	61	18	28.0					Rapid fire
			Caliber 20-11 mm projectiles							
1	3-17	C7	19	16	27.8	5300***	0			
9	3-18	C7	19	16	27.8	5300		1.35	1.05	Dispersion

*Powder FNH M2, 0.023-in. web, lot HES 3614. **Measured.
***Average instrument velocity 5000 ft/sec at 75 ft.

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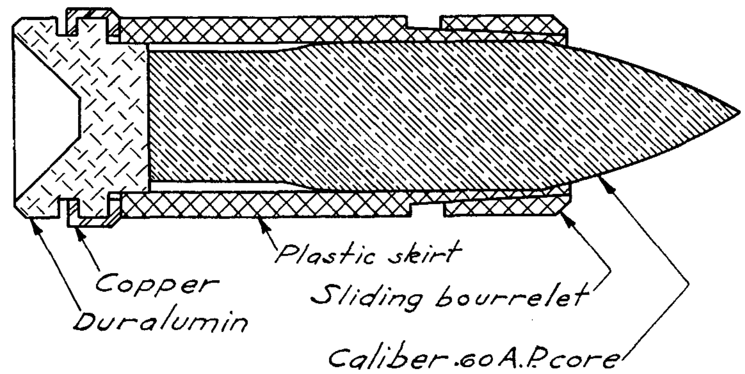

Fig. 12. 20-15 mm sabot assembly made by mounting experimental caliber .60 A P core in a sabot similar to CW2b.

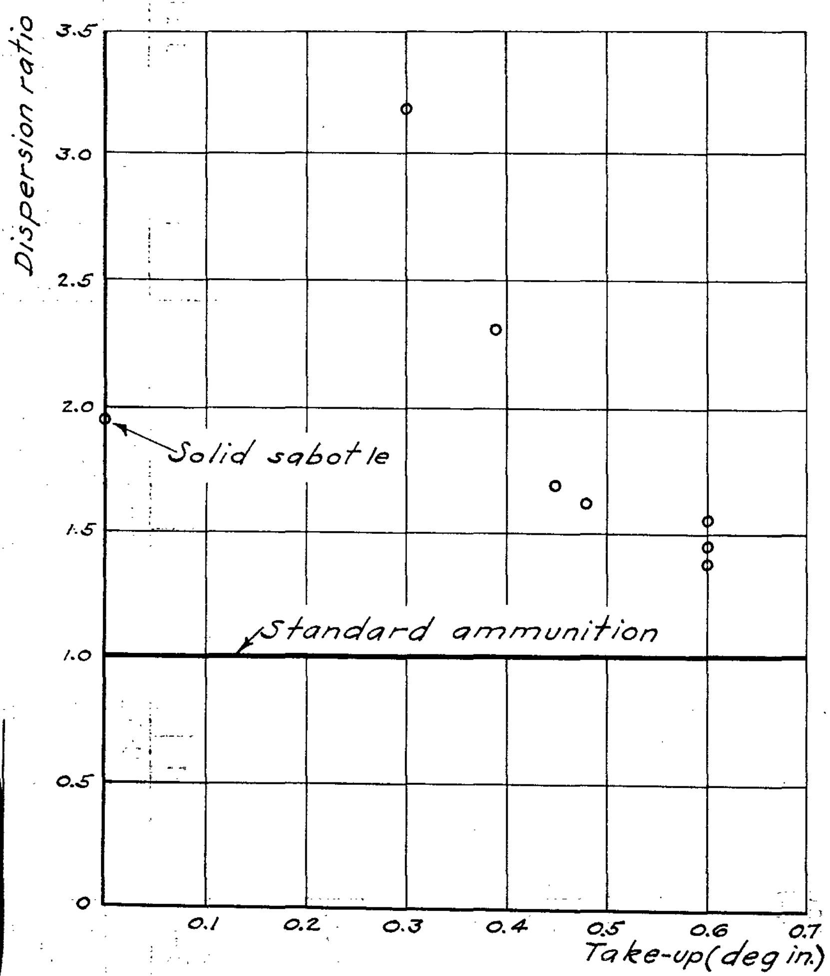

Fig. 11. Dispersion relative to standard ammunition of Elkonite projectiles as function of take-up — that is, axial motion times half angle of cone — afforded by sliding bourrelet.

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[redacted]

(d) AP steel projectiles. -- Thus far 28 rounds of steel AP cores loaded with 29.0 gm of HES 3614 (FNH M2; 0.023-in. web) have been fired for yaw and dispersion. Of these rounds, 18 were made by mounting the experimental caliber .60 AP core in a sabot similar to CW2b (see Fig. 12). The cores were used without base cup or windshield. Two dispersion tests were made, and the ratios to standard ammunition are included in Table V under C6. The absolute values of dispersion in Tube No. 3 are within 0.5 mil in both cases. Details of the firing are given in Table VI under caliber 20-15 mm projectiles.

Also included in Table VI are the data on 20-11 mm steel projectiles C7 fired for yaw and dispersion. These cores were made from caliber .50 AP cores by grinding off the rear portion until the core weighed 19 gm. This amounted to about 7/16 in. and included all of the boattail. The ogive on the resulting projectile is thus disproportionately long, especially since the AP sabot was very short. This probably accounts for the wide dispersion obtained with this model. The muzzle velocity was between 5300 and 5400 ft/sec. The measured maximum yaw of 0^{o} is evidently accidental in view of the large dispersion. Thirty of these projectiles were transmitted to Princeton University, Division 2, National Defense Research Committee, for tests against plate.

Work on the 20-15 mm type C6 is being continued to determine (i) the advantage in accuracy and yaw gained by the sliding bourrelet [for this a number of rounds without collar (C5) and a number with collar (C6) are being made from phenolite tubing] (ii) adaptability to automatic fire; and (iii) adaptability to molding of straight sabot (C5) and comparison with the same design as machine made.

On May 20 some rounds of C6 were taken to Deephole to test for automatic action using the drum feed. With the muzzle brake removed the rounds operated satisfactorily without any other alteration of adjustment. One 7-round and one 6-round burst were fired. The sabots were not held together tightly enough for the feeding action and only about half of the rounds behaved well outside the gun, presumably

[redacted]

because of separation before firing. The rounds for further test will be more securely integrated.

13. Series A: axial-type sabots

Figure 13 shows the various designs of the axial-type sabot and Table VII gives firing data. The first design of the gas-operated, axial-type sabot was completed in August 1942. This design (A1) was found faulty in that the rotating band, which was pushed on from the front, blew off. Also the hole into the gas chamber showed considerable erosion.

Design A2 remedied the faults of A1 since in this model the rotating band was screwed on and a small steel plug was placed in the rear to prevent erosion. Two sabots of design A2 having a 1/32-in. hole in the erosion plug showed no sign of having separated at 100 ft while a third having a 1/16-in. hole in the plug failed by having the gas chamber blow apart.

In design A3 the duralumin was all in one piece. Three of these were fired at the Michaelsville Range, Aberdeen Proving Ground where attempts were made by H. G. Edgerton to photograph the bullet at the muzzle and by J. L. England down the range at 50 yd. No pictures were obtained at the muzzle, while at 50 yd, pictures of two of the shots were obtained -- one of the projectile without sabot and the other in which the projectile and sabot were together. In the latter no separation was apparent at the end of the range (100 yd) while in the former separation had occurred prior to 50 ft, as indicated by the yaw card. The third sabot of this model fired showed no sign of separation either at 50 ft or 100 yd.

Design A4a had a copperplated bourrelet and a crimped-on rotating band as developed by J. Jost and was otherwise similar to A3. The sidewalls supporting the bourrelet proved to be too weak with the result that the sabot failed in the gun. Design A4b was an attempt to remedy this in that the rotating band screwed on from the rear and none of the side walls were cut away. This model failed to separate at all.

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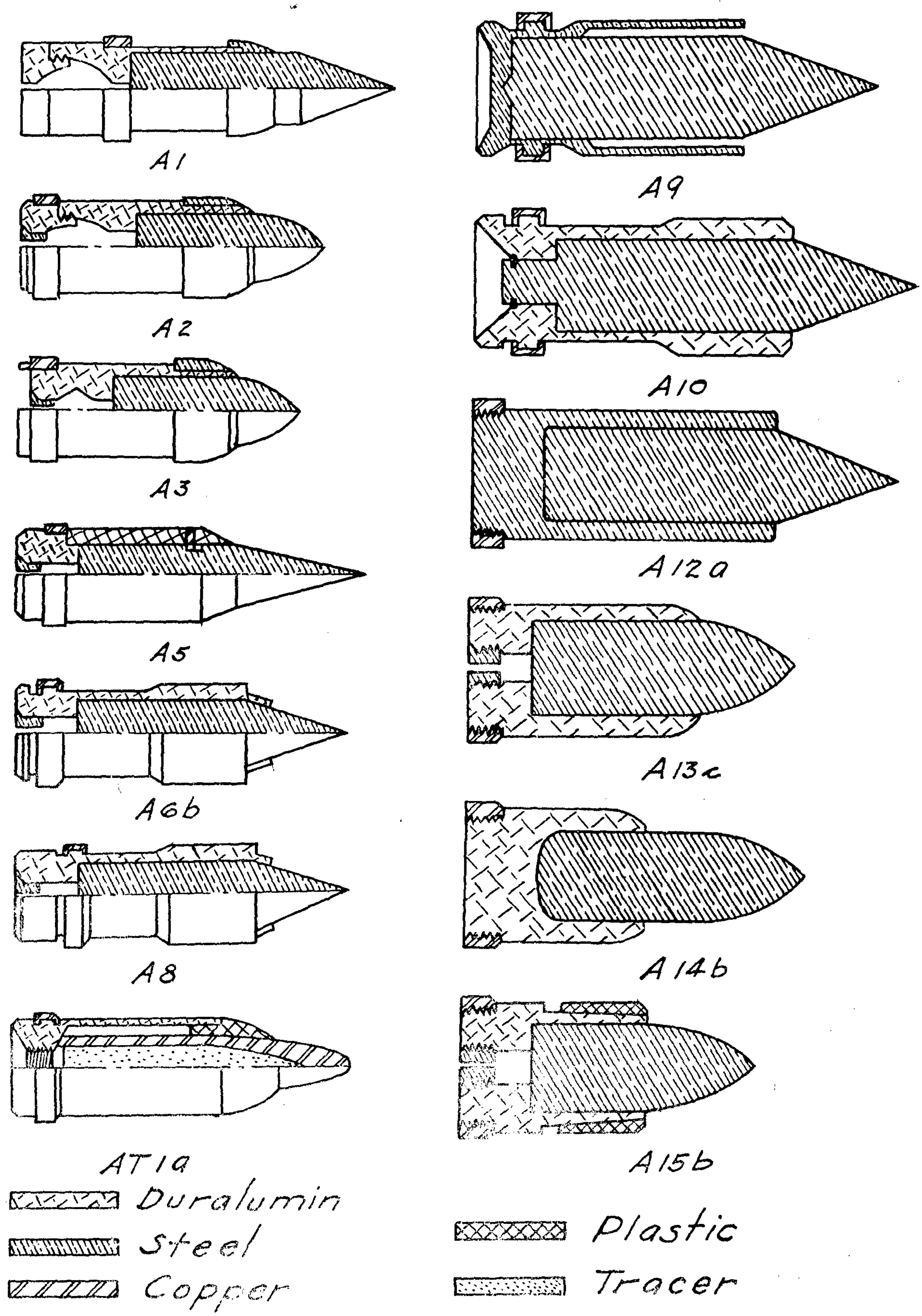

Fig. 13. 20mm sabot-projectiles of Series A.

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Design A5 was made with an unsplit skirt of phenolite, which broke up under centrifugal force. Nothing further has been done with plastics in axial-type sabots.

A smaller gas cavity was used in A6a, and it also had a hardened drill-rod projectile. Two of this type were fired with 0.035 gm of black powder in the gas chamber and the third with none. All three separated and hit the target at about 200 yd within a circle of radius 9 in.[15/] The sabot of one of the two with the black powder apparently failed in the gun, but this did not seem to affect the aim too badly. The yaws were considerable -- between 8° and 42°, the smaller value being for the one shot without the black powder. Design A6b was similar to A6a except for minor details. The dispersions of these were considerable; only half of them hit the 3×5-ft target at 210 yd. In order to insure rotation, four of these projectiles had a slightly concave base. The dispersion of this group was about as bad as for the six with plane bases. In both cases the base of the sabot received a permanent set of about 1 mm. Also, an examination of one of the sabots fired with the plane base indicated that the projectile did not receive all of the rotation. In addition, there was a considerable deposit of aluminum and aluminum oxide on the inside walls of the sabot. Any of these factors might have been the cause of the wide dispersion.

Design A7 was similar to A6b except that it had an adjustable cavity. The sabot broke apart in the gun and while the projectile separated with a considerably smaller amount of gas, the results were not conclusive as to the amount of cavity necessary.

Design A8 had a rotating band over the base of the projectile but in other details was similar to A6b. Both of the sabots that were fired broke up in the gun.

Models AT1a and AT1b were designed to separate by force of the gases emitted by the tracer. Variant a had a molded plastic "nose"

15/ In all subsequent designs of axial sabots except where noted, a hardened steel projectile was used. All previous models had soft steel projectiles.

that failed. The nose of variant b was duralumin, and this model showed little yaw. There is some doubt, however, that the tracer bullets stood up under acceleration. The tracer did not ignite in either round. This design is not successful.

In A9 and A10 there was considerable clearance between the core and the sabot, except near the base of the core (where the closer fit permitted centering of the core). In the case of A9, which was made of steel, the sabot broke up when a soft projectile was used. With a hardened projectile it apparently remained whole, but the projectile had a large yaw. The duralumin model, A10, failed in the gun.

Design A6c had different sized holes drilled in the steel plug to admit the gas to the gas chamber. This did not improve the bad yaw.

Design A11 was similar to A6 with two exceptions; it had a plastic collar instead of the copperplated bourellet and there was no gas hole -- in other words, the sabot was to be pulled off by the drag of the air. Two of these were fired, both exhibiting the same characteristics. Up to about 70 ft from the muzzle of the gun, the projectile and sabot traveled apparently in one piece with very slight yaw. The projectile and sabot then separated and both pieces had a large yaw. One of the sabots was later recovered and found to be whole. From this behavior it was concluded that the sabot-projectile combination was so long just before separation that it had an insufficient stability factor and therefore developed a large yaw. On the basis of this conclusion, it was decided to use a considerably shorter projectile -- a 14-mm projectile with the shape of the 37-mm, M74. This would permit the shortening of the sabot as well.

The variants of A12 used the long 14-mm projectile and a solid steel sabot of various lengths. Variant a (total length 1.8 in.) and variant g (total length 0.9 in.) had no gas chamber. The weight of the sabot was comparable to the weight of the projectile and tests showed that the sabot was not taken off by drag alone. Therefore, a small chamber was put in variants b, c, d, e and f. Variant b

 [redacted]

(1.65 in. long) was filled with black powder and separated with a yaw of about 40° Variant c (1.50 in. long) with no black powder, did not separate. Variant d (1.35 in. long) separated with about 10° yaw. Variants e and f (1.20 and 1.05 in. long), both with black powder, failed to separate, apparently because of the failure of the black powder to ignite. The conclusions from these tests were the same as for design A11; that is, just before separation the sabot-projectile combination was insufficiently stable, and hence, a large yaw resulted. When the combinations were shorter just before separation, the yaw was correspondingly less.

The class A13 was a duralumin sabot similar to A12, but with the short 14-mm projectile. Models a, b and c were gas operated; d, e and f were drag operated. The gas-operated models exhibited the least yaw as a group; and the shortest one of these the least yaw in the preliminary firings of one shot of each length. On the basis of these results, ten of variant a were made up for a dispersion test. After six shots, so few hit the target that the remaining four were shot for yaw. The results were 10°, 13°, 26°, 36° A13h was made longer than any of the previous A13 models. Four of five separated with the following yaws: 3°, 11°, 23°, 33°

Design A14 was similar to A13 but used a rounded projectile. Of the first two constructed, A14a (the longer sabot) had a yaw of 13°, while A14b (the shorter one) had a large yaw. Design A14c was similar to A14b, but had a gas chamber. The maximum yaw of this design was about 10° When these results were compared with the results of A13c and A13h, we concluded that the amount of yaw was not affected by any of these design modifications.

Design A15 is quite similar to A-13, with a collar added. The yaw of A13 was 14° with black powder and 35° without (one shot each). It was decided that the sabot was a little short for the projectile. The projectile was accordingly shortened so that its total length was 1.35 in. instead of 1.6 in. The maximum yaw was 9° Three of these were shot at the target at 200 yd with no success at hitting it.

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Table VII. Data on rounds fired in Series A and B; caliber, 20-40 mm.

Number of Rounds	Date	Type	Mass (gm)			Est.Muz. Velocity (ft/sec)	To Test
			Proj.	Sabot	Powder		
Series A (1942)							
2	9-8	A1	51	37	20.7	3200	Performance
3	9-18	A2	41	37	20.7	3300	Performance and photographs
3	11-21	A3	41	32	22.2	3580	Performance
2	12-10	A4a	50	26	21.9	2490	Performance
3	12-10	A5	48	22	22.5	3670	Phenolite sabot
3	12-15	A4b	50	34	21.2	3300	
1	12-18	A4a	50	26	22.0	3500	
3	12-18	A6a	52	27	21.6	3420	Black powder ejection and hard projectile
1	12-22	AT1a	44	18	30.0*	3980	Tracer ejection
1	12-22	AT1b	44	20	23.2	3850	Tracer ejection
7	12-31	A7	53	30	21.3	3330	For minimum cavity in base
Series A (1943)							
2	1-6	A6b	53	25	21.8	3460	Picture, hard projectile
1	1-6	A8	53	26	21.7	3430	Picture, soft proj.
4	1-7	A6b	53	25	21.8	3460	Dispersion, concave base projectile
6	1-14	A6b	53	25	21.8	3460	Dispersion, plane base projectile
1	1-14	A8	53	26	21.7	3430	Performance
1	2-12	A9	53	28	21.5	3400	Performance (soft steel projectile)
1	2-15	A9	53	28	21.5	3400	Recovering (soft steel projectile)
1	2-24	A9	53	28	21.5	3400	Performance (hard steel projectile)
1	2-24	A10	50	21	22.5	3680	Performance
3	2-23	A6c	47	25	22.1	3570	Various size of holes in rear of sabot
2	3-9	A11	47	24	22.2	3620	No gas chamber

[redacted]

Table VII. [Continued.]

Number of Rounds	Date	Type	Mass (gm) Proj.	Mass (gm) Sabot	Mass (gm) Powder	Est.Muz. Velocity (ft/sec)	To Test
				Series A (1943), continued			
1	3-9	A12a	47	70	31**		All steel sabots of various lengths; fired for performance
1	3-9	A12g	47	42	31**		
1	3-11	A12b	47	65	31**		
1	3-11	A12c	47	60	31**		
1	3-11	A12d	47	56	31**		
1	3-11	A12e	47	52	31**		
1	3-11	A12f	47	47	31**		
1	3-17	A13a	41	24	23.1	3830	Duralumin sabot with gas chamber; fired for performance
1	3-17	A13b	41	26	22.9	3780	
1	3-17	A13c	41	28	22.7	3720	
1	3-17	A13d	41	24	23.1	3860	Duralumin sabot, no gas chamber; fired for performance
1	3-17	A13e	41	25	22.9	3790	
1	3-17	A13f	41	27	22.7	3720	
10	3-25	A13a	37	20	24.0	4100	Dispersion and yaw
1	3-25	A13g	37	20	24.1	4140	Performance
1	3-30	A14a	37	21	23.9	4050	Performance
1	3-30	A14b	37	20	24.0	4100	Performance
1	3-30	A14c	37	20	24.0	4100	Performance
5	4-13	A13h	37	22	23.7	4050	Performance
2	4-13	A15a	38	18	24.0	4100	Performance
8	5-18	A15b	31	18	25.4	4440	Dispersion and yaw
1	5-18	A16	38	18	24.0	4100	Performance
				Series B (1942)			
2	12-18	B1	47	15	24.2	4200	Operation
2	12-22	B1	47	15	30.0*	3980	Operation
3	12-31	B2	36	23	23.8	4040	Operation (iron rotating bands)
				Series B (1943)			
4	1-5	B3	45	16	23.6	4000	Photograph and dispersion

*Powder FNH M2, 0.023-in. web, lot HES 3614.

**Standard 20-mm powder used because of heavy weight. Velocity estimated as being above 3000 ft/sec.

[redacted]

The target was then moved to 100 yd where the dispersion of the five remaining shots was very large.

Design A16 was quite similar to Critchfield's CW3b except that the sleeve was made of duralumin instead of plastic and was not split. It was thought that the base would separate from the duralumin, and thus result in the parts that separate axially being that much shorter. The duralumin sleeve broke up under centrifugal force.

Of all the designs of axial sabots, there were none that were successful. It was found that it is possible to have the sabots separated either by drag alone, by gas pressure or by a small charge of black powder, but in each case the sabots usually separated with a large yaw. In addition, it was found that there was a large dispersion in yaw in the two models of which more than one or two were fired.

14. Series B: boattail sabots

The purpose of Series B was to investigate the feasibility of using the boattail on subcaliber projectiles with the base exposed to the propellent gases so as to facilitate tracer ignition. The operation of this type of sabot was satisfactory in most cases, but the accuracy leaves much to be desired. The dispersion of this type seems to be 20 or 30 minutes of arc on the average, but no cause has been established for it. Four rounds of type B1 (Fig. 2) have been tried (see Table VII). Type B2 differs in having a mild steel base and rotating band and a 2^{o} cone taper in the skirt and on the projectile so that no threads were necessary in the construction. The three rounds tried seem wilder than type B1.

Four rounds of B3 have been made and tried. These are like B1 except that the rear locking wire is eliminated and the sabot extends over the ogive shoulder. It was hoped that the longer sabot would improve the accuracy. This type apparently did not separate, and a recovered base indicates that the base seized the rear shoulder of the projectile. Special attention was paid to the rounding of this shoulder, but evidently it was insufficient in this model. The shots with bases attached hit an 8-in. circle at 210 yd and thus provided no encouragement for further development. This series has been abandoned.

15. Tests against armor plate

The following sabot projectiles were taken to Princeton University on April 5, 1943 for tests against armor plate:

10 C7, caliber .50 AP cores cut off to 19 gm,
8 CW2c with Mallory 1000 Elkonite cores,
9 full length (3.7 calibers) carbide cores,
9 sawed off (3 calibers) carbide cores.

All cores were essentially 11 mm in diameter and the sabots were patterned after CW3b, being longer than usual for the full-length carbide cores[16/] and shorter for the caliber .50 cores.

On April 5, Cassius Curtis had the following rounds fired at 2-in. homogeneous plate: 2 rounds of C7 (caliber .50 AP cores), 1 full length carbide, 1 regular 20-mm AP, all of which shattered; 3 rounds of short carbide at a muzzle velocity between 3600 and 3800 ft/sec, all of which penetrated while one was recovered whole; 2 rounds short carbide at 30° to normal incidence at a muzzle velocity of 4000 to 4100 ft/sec, both of which shattered.

On April 6, 5 rounds of C7 and 1 round of CW2c Mallory 1000 were fired at $1\frac{1}{2}$-in. plate. Particular results on these and succeeding tests of sabot-ammunition will be reported by Division 2. There are several developments of general interest, however, to be noted here.

The stability of the long carbide cores and of the caliber .50 cores was so low that an appreciable yaw developed -- obviously an undesirable occurrence in trials against armor plate. This difficulty was overcome, however, by finding the position of minimum yaw suitable

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16/ The carbide cores, obtained for us by the Army Ordnance Department, were made by Carboloy Co. and have the same dimensions as the core of the Gerlich 28/20-mm.

for the location of the plate. The short carbide cores showed no appreciable yaw and could be used without finding the position of minimum yaw.

The tests demonstrated beyond doubt the usefulness of the sabot construction for testing purposes at high velocity. No direct comparison between sabot and regular AP ammunition was obtained because of shatter of the regular AP. We have made and sent to Division 2 twenty more of the shortened caliber .50 cores in sabots (C7).

16. Conclusion

The tests so far conducted have provided data on numerous details of construction, and the developmental stage of sabot ammunition for the 20-mm Hispano-Suiza has been brought to a satisfactory conclusion as far as one type of construction is concerned. The sum of these experiences lead to the following conclusions and plans for the future.

(i) The separation of sabot and projectile by trapped propellent gases presents many difficulties, none of which become simplified when heavy cores are used. Work on this type of sabot (Series A) as well as on the boattail type (Series B) will thus be discontinued.

(ii) Almost any design built to separate by centrifugal force and constructed to reasonable tolerances can be fired in the 20-mm cannon and made to hit at 200 yd within 10 minutes of arc of the center of the pattern. Average accuracy for standard ammunition at that range is more like 2 minutes of arc radius for the beaten zone. The sabot problem was thus primarily to attain something like standard accuracy.

(iii) The second main problem of sabot construction is lightness. Our best efforts to date have reduced the weight of the sabot to less than 20 gm. The attendant maximum yaw is roughly 10°, and the best performance is 40 percent larger in dispersion than standard ammunition.

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(iv) The most satisfactory construction is fundamentally a standard subcaliber solid projectile propelled by a duralumin plug and supported by a reinforced plastic skirt. It has been shown that making provision for decreasing the windage between barrel and projectile improves the accuracy of the ammunition. Duralumin is used for the base plug because a considerable volume of metal is necessary to mount the round in the cartridge case and much can be gained in lightness by using duralumin instead of steel.

(v) Development will be continued for the 20-15 mm sabot-projectile adapting it to automatic feed.

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APPENDIX

Reduction in Time of Flight

17. Reduction in time of flight at short range

With standard guns and standard density of loading, the only way to decrease the time of flight of a projectile is to decrease its mass. In general, this has the disadvantage of decreasing the effectiveness of the projectile. There are two notable exceptions to the general rule: one arises in the case where armor must be penetrated, and the other in the case where the standard projectile is larger than necessary for the job intended. The possible role of sabot-projectiles in the exceptional cases has been considered in other reports.

We shall consider the reduction in time of flight at short range, that is, for the small cannon such as used in aircraft and on the ground or deck against aircraft. If an airplane is dodging shell that explode on contact, the probability of being hit varies with the inverse fourth power of the time of flight of the projectile.17/ At very short range the probability then increases as v^4, where v is the muzzle velocity. On the other hand, the effectiveness of the shell (that is, high explosive or shrapnel) decreases as the mass decreases. We shall assume that the damaging effect of a projectile is simply proportional to its mass m. The efficiency of a projectile is then roughly proportional to mv^4 or to E^2/m, where E is the kinetic energy of the projectile at the muzzle. This indicates that the lighter the projectile for a given powder charge, the more effective it will be.

There are two laws of ballistics that militate against use of extremely light projectiles. The first is that in firing very light projectiles a large fraction of the powder energy goes into kinetic energy of the gases. Thus E decreases as m decreases. The second is that light projectiles are slowed down more rapidly by the air so that even at short range the time of flight does not decrease with mass as rapidly as we have assumed.

The effect of the powder gases can be calculated on the basis of Kent's work on that subject.18/ Karush has integrated Kent's equations for the ratio of specific heats $\gamma = 1.22$, so that they may be used for all ratios of powder mass to projectile mass. A very convenient and at the same time very accurate empirical representation of this integration may be expressed as follows. Let v and v_o be the velocities

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

18/ R. H. Kent, Physics 7, 319 (1936).

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of shells having masses m and m_o, respectively, and let q be the mass of powder, Then

$$\frac{v}{v_o} = \sqrt{\frac{m_o + 0.213q}{m + 0.213q}}. \tag{1}$$

As would be expected, v increases less rapidly than $m^{-\frac{1}{2}}$.

For an approximate expression that gives the dependence of time of flight on the mass of the projectile, we assume

$$\frac{dv}{dt} = -\frac{K_D \rho d^2}{m} v^2, \tag{2}$$

$$R = \int_0^T v\, dt, \tag{3}$$

whence

$$T = \frac{m}{K_D \rho d^2 v} \left(e^{(K_D \rho d^2/m)R} - 1\right). \tag{4}$$

In these equations K_D is the drag coefficient, ρ is the density of air, d is the diameter of the shell, R is the range and T is the time of flight. If we take $K_D = 0.10$ and $\rho = 3.33 \times 10^{-5}$ lb/in.^{3} (the density of air at about 9000 ft) as representative values, and if we measure m in pounds, d in inches and the range R in feet, we get

$$T = \frac{10^5 m}{4 d^2 v} \left(e^{4 d^2 R/10^5 m} - 1\right). \tag{5}$$

In the calculations that follow, we shall make use of Eqs. (1) and (5) to get a comparison of the efficiencies of shell of various weights. According to the argument advanced at the beginning of this section, the quantity mT^{-4} should be a fair measure of the effectiveness of a projectile. Therefore, we shall calculate the ratio $mT^{-4}/m_o T_o^{-4}$ (where the subscript o indicates the corresponding quantity for standard projectiles) for several short ranges and for existing guns. For this purpose we define a quantity y, where

$$y \equiv \frac{m T_o^4}{m_o T^4} = \frac{m_o^3 d^8}{m^3 d_o^8} \left[\frac{e^{4 d_o^2 R/10^5 m_o} - 1}{e^{4 d^2 R/10^5 m} - 1}\right]^4 \left[\frac{m_o + 0.213q}{m + s + 0.213q}\right]^2. \tag{6}$$

In Eq. (6), the possibility of having different diameters for the projectile has been admitted and a term s, the mass of the sabot, has been added to m so that the formula may be applied to subcaliber projectiles.

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At first, however, consider the full-caliber projectile of light weight as a possible solution to the problem of increasing $\underline{y}$. Then $d = d_o$ and $s = 0$. The optimum values of $\underline{m}$ (lb) and of y_{max} are given in Table VIII for existing 20-mm, 37-mm and 57-mm guns.

Table VIII. Calculated optimum values of $\underline{m}$ and y_{max} for several existing guns for light projectiles and for subcaliber projectiles with sabot.

Gun / $\underline{R}$ (yd)	20-mm	37-mm	57-mm	20-mm	37-mm	57-mm
	Without sabot $\underline{m}$ (lb)			y_{max}		
100	0.038	0.192	0.634	3.47	3.55	3.31
200	.055	.259	.846	2.65	2.85	2.73
500	.106	.444	1.322	1.68	1.93	2.06
1000	.185	.736	2.067	1.20	1.42	1.55
	With sabot $\underline{m}$ (lb)			y_{max}		
All	0.051	0.30	1.02	1.88	1.79	1.68

The optimum value of $\underline{y}$ if a sabot is used is also given in Table VIII. In this calculation the mass of the sabot is assumed to be $0.1 m_o$ and $\underline{y}$ is considered as a function of $\underline{m}$ and m/d^2 and minimized with respect to $\underline{m}$. We then find a definite value of $\underline{m}$ as shown in Table VIII, but the maximum $\underline{y}$ occurs at $m/d^2 = \infty$. The largest practical value of m/d^2 is really m_o/d_o^2, especially in automatic guns, so the latter value was chosen. The final result is simply

$$y_{max} = \frac{(m_o + 0.213q)^2}{4(s + 0.213q)\, m_o} . \qquad (7)$$

From Table VIII we may conclude that at close range -- 200 to 500 yd -- the effectiveness of small cannon shell may be improved by a factor of two or so. This is based upon the assumption that effectiveness is proportional to the mass of the shell and inversely proportional to the fourth power of time of flight. It is particularly interesting that only at rather long range does the subcaliber projectile compete with the full-caliber projectile of light weight. This merely means that the improvement in ballistic coefficient which a sabot makes possible does not have sufficient effect at short range to offset the loss of mass in the sabot.

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A further practical difficulty with the proposed sabot projectiles is that they must be as long as the standard projectile but of only about 40 percent standard diameter. This makes them difficult to stabilize and probably also impairs their explosive effect. Altogether, it appears that for close-range firing the development of light-weight, full-caliber projectiles is a more promising course than the use of sabots.

While the results of Table VIII are calculated for air density at about 9000 ft, they are readily applicable to other densities. For example, suppose the firing to take place at an altitude at which the air pressure is one half as great. We need only to multiply the ranges given under R by 2 to find the proper range at that altitude. In general, divide R by the ratio of densities. Range does not enter into the comparison with subcaliber projectiles because the ballistic coefficient is assumed to be unchanged in that comparison.

18. Reduction in time of flight at long range

Firing a lighter-than-standard projectile from a gun does not necessarily lead to shorter times of flight. This is especially true at long range. The limitation is on the ballistic coefficient of the projectile. It is advantageous, of course, to make the projectile as long and slender as possible, and thus use a sabot, but the length is limited by the strength of the materials used and the maximum acceleration.

If v is again the muzzle velocity and L is the length of the gun, the average acceleration of the projectile is $v^2/2L$. We shall assume the maximum acceleration a_m to be twice the average, that is,

$$a_m = v^2/L. \tag{8}$$

Let the maximum load that may be put in compression on the material used in constructing shell and sabot be S. The value of S under rates of loading that prevail in a gun is not known, but we shall assume that S is 70000 lb/in², the ultimate compressive strength of strong duralumin. Although S is well above maximum pressures allowed in a gun, the use of a sabot entails the concentration of forces on an area smaller than the bore area and thus places more stringent conditions on design. Let m be the mass of the subcaliber projectile alone -- that is, exclusive of sabot -- and d its diameter. Then,

$$ma_m \leq \tfrac{1}{4}\pi\, Sd^2 \tag{9}$$

must be satisfied. We shall assume the limiting condition of equality and, applying Eq. (8), obtain

$$m/d^2 = \tfrac{1}{4}\pi\, SL/v^2. \tag{10}$$

Equation (10) shows that the maximum ballistic coefficient decreases rapidly with muzzle velocity. At long range, therefore, there must be an optimum muzzle velocity with which a given gun should be fired. This optimum velocity depends only on the length of barrel, strength of materials, range and angle of sight. We shall use an approximate form of the vertical trajectory in order to get a representative value for v. The equation of motion is

$$dv/dt + \lambda v^2 + g = 0, \tag{11}$$

and we assume λ to be constant throughout the range, that is,

$$\lambda \equiv K_D \rho d^2/m, \tag{12}$$

although K_D increases and ρ decreases somewhat with time (height). For the value of S we have assumed, and for $\rho = 3.33 \times 10^{-5}$ lb/in^3 (density at about 9000 ft) and $K_D = 0.10$, we get

$$\lambda = 2.3 \times 10^{-11} v^2/L, \tag{13}$$

where L is measured in feet and v in feet per second.

The range R and the time of flight T are related by

$$R = \int_0^T v\, dt, \tag{3}$$

and the final form of the equation for T is

$$T = (g\lambda)^{-\frac{1}{2}}[\phi_0 - \arccos (e^{\lambda R} \cos \phi_0)], \tag{14}$$

where

$$\tan\phi_0 \equiv v(\lambda/g)^{\frac{1}{2}}.$$

The optimum muzzle velocity with which to fire a given gun at the vertical range R is then obtained by minimizing T with respect to v while holding R and L constant. It happens that the minimum of T is extremely flat so that the greatest practical gain may perhaps be obtained by choosing a muzzle velocity somewhat lower than the optimum. The muzzle velocity required for a time of flight 5 percent longer than the minimum will be called the "ideal" muzzle velocity; it appears under v_i in Table IX for six different guns and for several ranges. The "ideal" time of flight T_i (1.05 times the minimum) and standard time of flight T_s are also given in this table. The numbers are only crude approximations to true times of flight but serve for comparison.

By assuming some particular weight of sabot for each gun and taking into account the motion of the powder gases, we can determine the weight that a subcaliber projectile must have in order to give the required muzzle velocity. This assumes the standard amount of

Table IX. Comparison of "ideal" time of flight with standard time of flight for ideal sabot-projectiles fired from various guns.

Gun	Mass of Sabot (lb)	Range (10^3 ft)	"Ideal" Muzzle Velocity* v_i (ft/sec)	m (lb)	d (in.)	Standard Time of Flight T_s (sec)	"Ideal" Time of Flight** T_i (sec)
3-in.	2.5	20	3750	3.1	1.49	11.2	7.2
		30	3050	6.5	1.76	22.7	13.7
		40	2800	8.4	1.87	--	23.0
90-mm	4.1	20	4300	3.9	1.67	10.0	6.5
		30	3500	9.1	2.07	18.3	12.7
		40	3100	13.3	2.22	35.2	21.7
		50	2900	16.1	2.28	--	33.3
105-mm	6.5	20	5100	1.7	1.10	10.0	5.3
		30	4100	7.7	1.90	18.3	10.5
		40	3600	12.2	2.09	35.2	16.5
		50	3250	17.2	2.28	--	25.0
4.7-in.	9.6	20	5450	3.7	1.62	8.0	5.0
		30	4400	13.5	2.52	13.8	9.8
		40	3800	23.1	2.85	22.0	15.7
		50	3450	31.2	3.03	36.5	23.3
155-mm	20.7	30	4370	15.5	2.70	15.3	9.9
		40	3800	27.9	3.13	24.5	15.6
		50	3400	41.7	3.50	49.0	23.8
8-in.	47.0	30	4950	19.0	3.00	14.1	8.7
		40	4030	63.0	4.75	20.9	13.6
		50	3850	76.0	4.66	30.2	19.6

*The muzzle velocity required for a time of flight 5 percent longer than the minimum.

**The time of flight corresponding to the "ideal" muzzle velocity.

powder with web thickness appropriate to the more rapid expansion of the gases. Knowing m, we may then calculate d. Both m and d appear in Table IX.

Several immediate conclusions may be drawn from the results presented in Table IX. One is that it is impracticable to minimize times of flight at 20000 ft vertical by use of the sabot because the projectile would be too light to damage an airplane even in a direct hit. A second point is that none of the ideal projectiles indicated would be stable under rotation alone. Thus, it would be essential to add fins. A third conclusion might be that it is quite practicable to minimize times of flight at 30000 ft for guns less than 5 in. in bore, since the subcaliber projectiles best suited to these conditions are at least one fourth as heavy as the standard projectile and times of flight are reduced to 60-70 percent of standard. A particularly favorable example is the 3-in. gun for which the subcaliber projectile is about half standard weight and the time of flight is 0.60 of the usual one at 30000 ft.

The usefulness of the sabot in long range work depends upon the relative weights that must be given to mass of projectile and time of flight. Any of the shells proposed as ideal at 30000 ft are probably adequate to bring down an airplane with one direct hit. If direct hits are desired, time of flight alone is essential and the effectiveness of a round would be measurably increased by use of the sabot.

Note added in proof

The kinetic energy of powder gases can be taken into account by adding a fraction of their mass to that of the projectile. The fraction varies from one third to one twelfth as the projectile mass decreases to zero. In the analysis just given, an average fraction -- 0.213 -- covering a wide range of masses was chosen. Actually, the practical range of projectile masses turned out to be somewhat smaller and in this narrower range an average of 0.270 would be more applicable. The influence of this fraction on practical results is so small, however, that a recalculation is not warranted. -- C. L. C.

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TITLE: Development of Subcaliber Projectiles for the Hispano-Suiza Gun

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ABSTRACT: Plain + Sabot Projectiles

Methods are outlined for the construction of subcaliber projectiles for the Hispano-Suiza gun using a sabot. Cores both of tungsten-copper, "Elkonite", with a density of 14.5 gm/cm^3, and of steel were used. Design drawings and a brief description of the sabot materials and methods of assembly are given. A detailed analysis of the performance of these projectiles is given as a result of firings for yaw, dispersion and muzzle velocity. Successful designs that worked on a centrifugal principle were made, but there was no success with those in which the sabot separates axially. Preliminary firings were made with finned projectiles in a sabot.

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