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NATIONAL DEFENSE RESEARCH COMMITTEE

REPORT NO. A-91 : PROGRESS REPORT

THE EROSION OF GUNS

Part Two: The Characteristics of Gun Erosion

DEFENSE RESEARCH CENTER
ABERDEEN PROVING GROUND
MARYLAND

by

John S. Burlew

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THE EROSION OF GUNS

Part Two: The Characteristics of Gun Erosion

by

John S. Burlew

Approved on October 31, 1942
for submission to the Section Chairman

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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, to the project designated by the Navy Department Liaison Officer as NO-23 and to Division A projects PA-230 and PA-240. Part of the work of preparation of this report was performed under Contract OEMsr-51 with the Carnegie Institution of Washington.

This report has been issued in two volumes. The present volume comprises Part Two, on the characteristics of gun erosion. The preceding volume was issued as NDRC Report A-20, (OSRD No. 882) and comprised Part One, on the fundamentals of ordnance relating to gun erosion. The "Bibliography and Author Index" on page 243 of the present volume pertains only to Part Two, but the "Subject Index" on page 259 pertains to both parts of the report.

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THE EROSION OF GUNS

Part Two: The Characteristics of Gun Erosion

CHAPTER VIII. MAGNITUDE OF EROSION

59. The two chief characteristics of erosion are its extent and the nature of the eroded surface. The exact dimensions of the bore of a particular gun at any given time depend on so many factors, some of them uncontrollable, that each gun is a separate problem. On the whole, however, the erosion of all guns -- except those fired extremely rapidly -- follows the same pattern, so that it is possible to describe these two characteristics in general terms.

60. Variation along the bore

The increase in diameter of the bore of an eroded gun is not uniform along its length, but is highly localized at the two ends. In the middle of the bore, between the two eroded regions, the diameter frequently is less than it had been originally, because of fouling or coppering, which is the formation of a metallic deposit on the surface of the bore (Sec. 67).

The greatest amount of erosion occurs at the breech end, where a region of considerable enlargement of the bore extends forward from the origin of rifling (Sec. 11) for a distance of several calibers, the maximum enlargement being at a small fraction of a caliber in front of the origin, namely, at the point where the lands had first attained their full height when the gun was new. The erosion of the lands is usually two or three times as great as that of the

grooves,^{48/} as is illustrated for a 3-in. M3 gun liner No. 881 in Figs. 2 and 3. The former is a combination of five star-gage records made at different periods in the life of the gun. The latter is a cross-sectional diagram with an exaggerated scale. Only erosion at the breech end is apparent because that at the muzzle was so slight in comparison.

In a case gun (Sec. 21) erosion of the centering cylinder extends toward the chamber from the origin of rifling only as far as the mouth of the cartridge case. The increase in diameter in the middle of this region is usually a little greater than that of the grooves at the origin. In a bag gun (Sec. 21), on the other hand, the increase in diameter of the centering cylinder becomes progressively less to the rear of the forcing cone, and is negligible after a distance of one to two calibers. The chamber does not erode.

Muzzle erosion is always much less than breech erosion, and in some small-caliber guns it is scarcely noticeable until the end of life. The maximum increase of diameter in this region occurs at the muzzle itself. Here the lands usually wear more rapidly than the grooves.

Erosion usually is not circularly symmetrical. However, the dissymmetry is frequently not reported, for one of the two common types of star gage (Sec. 14) gives only an average diameter, based

^{48/} Dr. P. R. Kisting (personal communication, Aug. 22, 1942) points out, however, that in a recent endurance test of the 37-mm gun M1A2 (see Sec. 107), it had been observed that when double-base powder was used as the propellant the increase of diameter at the origin of rifling was greater across the grooves (0.035 in.) than across the lands (0.030 in.) after slightly more than 1200 rounds.

on lengths of three radii 120° apart. Some writers have suggested that erosion of the muzzle is regularly greater at certain positions around the circumference of the tube (referred to as different "o'clocks" in analogy to the positions on a clock face), but such a generality does not seem to apply to all guns. In three well-worn 155-mm guns, for instance, in which both vertical and horizontal diameters were measured, the difference between the two diameters across the lands at different positions along the last three caliber lengths of the gun varied from 0 to 0.03 in., the horizontal diameter being the greater in two of the guns and the vertical the greater in the other [Weyher, 1939].

61. Variation with number of rounds

The average extent of erosion is frequently measured by the increase in diameter of the lands at the origin of rifling or just in front of it. When this increase -- denoted usually by E and expressed in inches -- is plotted as a function of the number of rounds, the typical curve which is obtained for cannon fired slowly shows that the rate of increase in diameter of the lands at the origin becomes less during the later stages of erosion. This relation is illustrated by Curves A and B in Fig. 4. Curve A which is the standard curve for an unplated 14-in./50-caliber Navy gun, has been expressed by the exponential function,

$$E = 0.349 (1 - e^{-0.01065N}), \quad (\text{VIII-1})$$

where N is the number of equivalent service rounds. ^{49/} Curve B

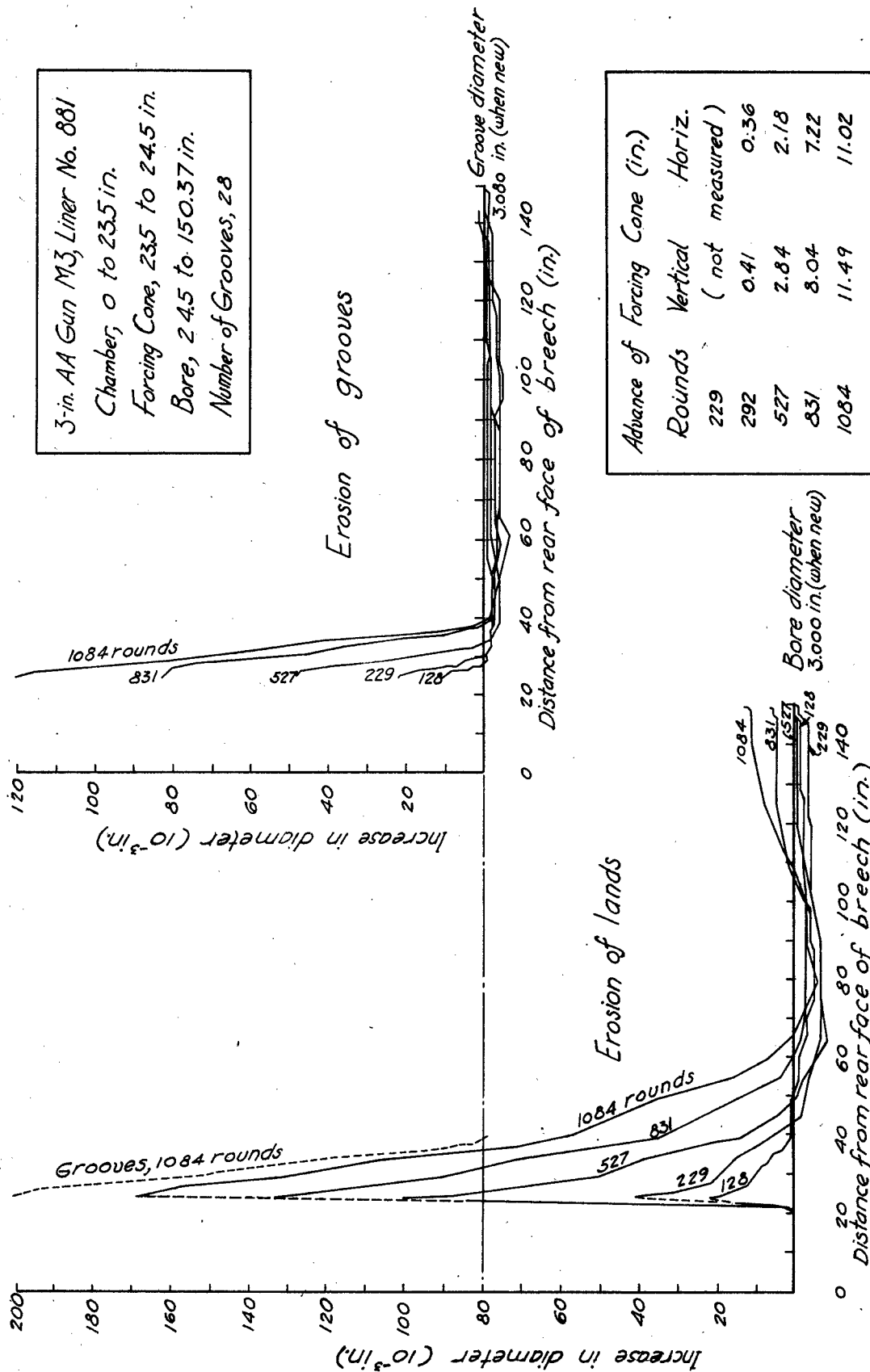


FIG. 2. EROSION OF 3-IN. GUN LINER.

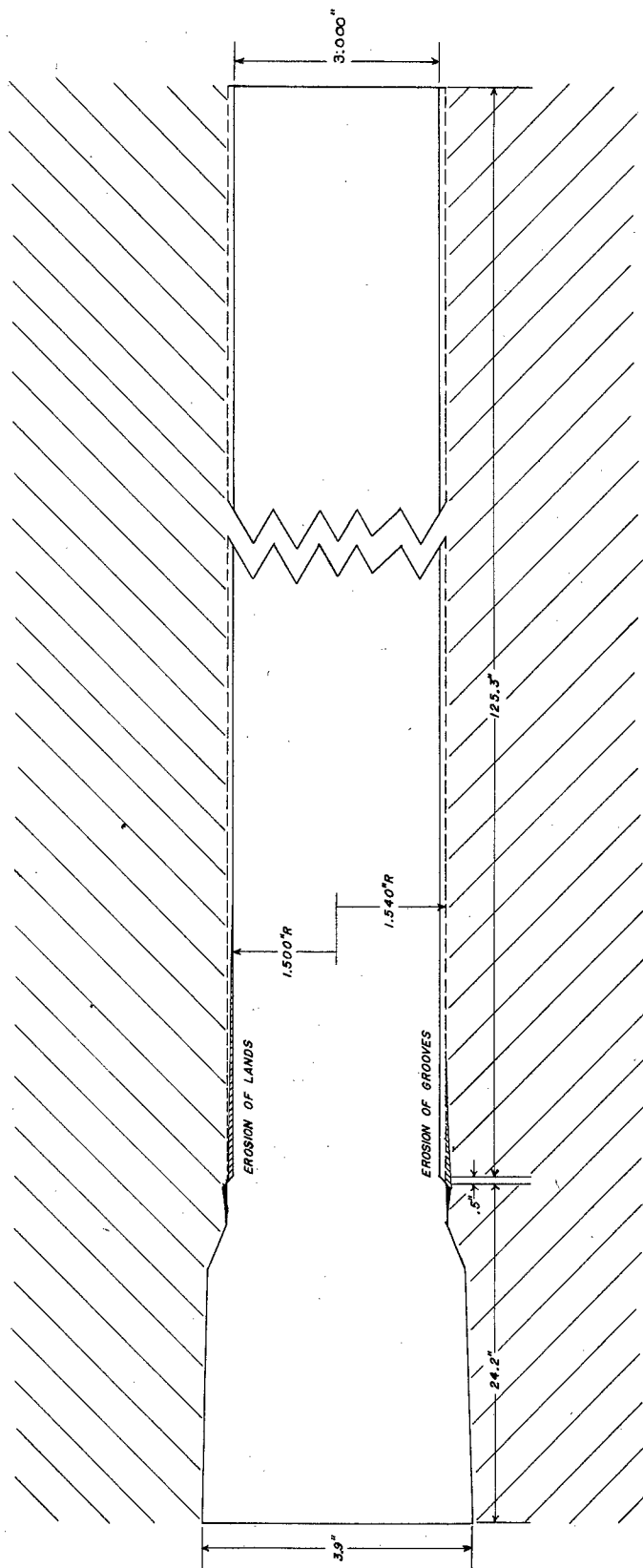


Fig. 3. Erosion of 3-in. gun after 1084 rounds. The vertical scale is five times the horizontal scale.

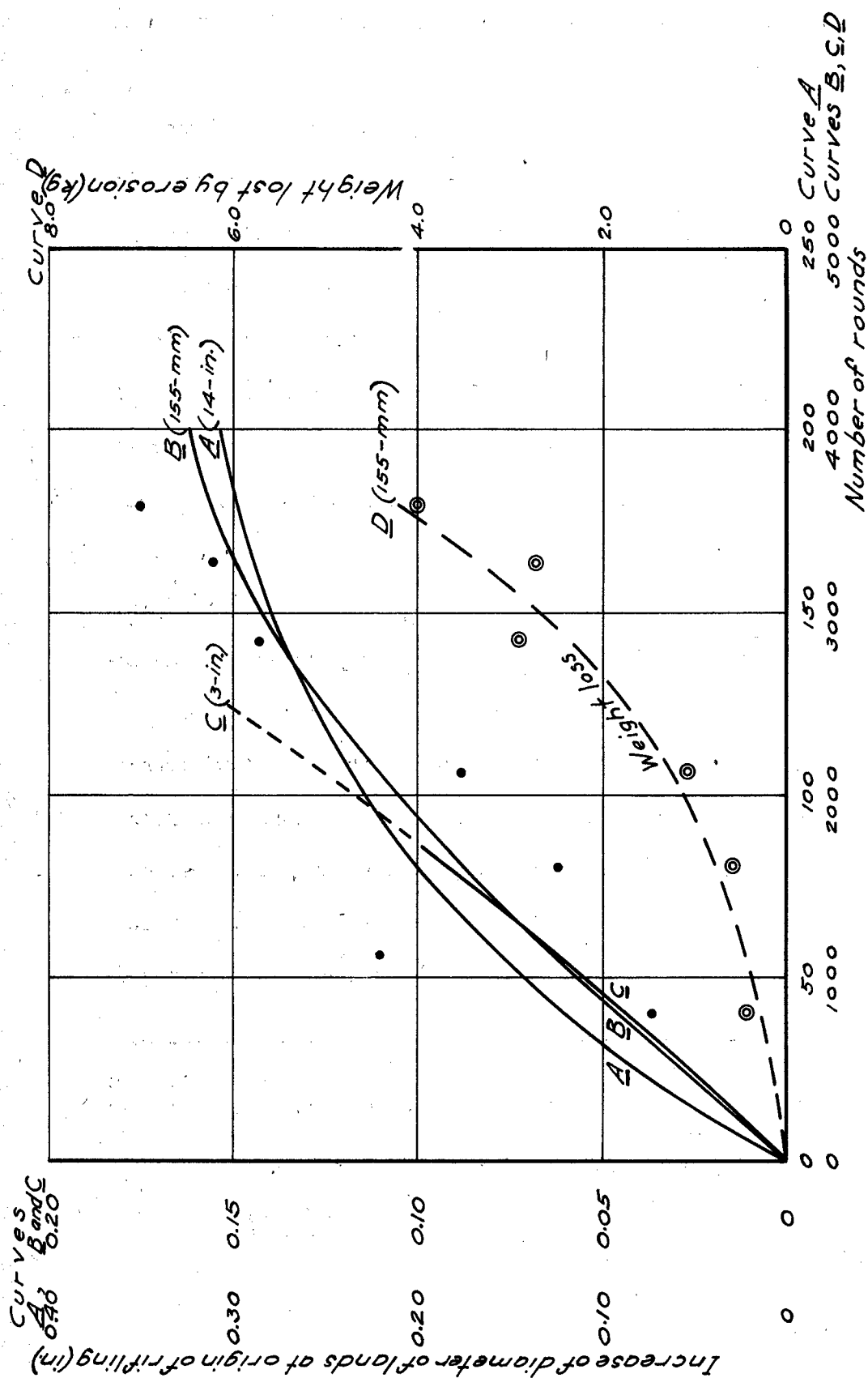


Fig. 4. Erosion as a function of the number of rounds. Curve A, 14-in./50-caliber unplated Navy gun; Curve B, 155-mm guns, G. P.F.; Curve C, 3-in. antiaircraft guns; Curve D, loss of weight of 155-mm guns; the dots (•) and corresponding circles (⊙) refer to seven particular 155-mm guns.

represents data for sixty-two 155-mm guns, G.P.F., in different stages of wear [Weyher, 1939].

For a number of 3-in. antiaircraft guns, M3, which had been fired more rapidly, however, the rate of erosion did not decrease with time. Curve C^{50/} in Fig. 4, which shows the increase in diameter of these guns at the origin of rifling, is slightly concave upward.

Curves A, B and C in Fig. 4 extend to the estimated accuracy life of the guns considered (see Chap. XIV). Some European guns that have been fired far beyond this point have shown a subsequent increase in the rate of erosion, the complete curve in such cases being S-shaped.^{51/} A similar condition has recently been observed^{52/} in the case of a 37-mm AA gun M1A2, which was fired mostly rapid fire (5 or 6 rnd/min). From round 5000 to round 6800 there was scarcely any change in the previous increase (0.022 in.) in the diameter of the lands; and then suddenly the diameter increased 0.048 in. during the next 1000 rounds.

These data on the variation of erosion with the number of rounds of the 155-mm guns depend on measurements on different guns, instead of on a series of measurements at different stages in the life of the same gun. Hence they may reflect individual peculiarities of the guns.

^{50/} This curve has been drawn on the basis of star-gage records in the files of the Ballistics Section, Ordnance Department, U.S. Army.

^{51/} P. R. Kosting, personal communication, Aug. 13, 1941

^{52/} Watertown Arsenal photograph No. W. A. 639-4076, based on Firing Record No. 8097; P. R. Kosting, personal communication, Aug. 22, 1942.

The three guns that had been fired the largest number of rounds were of French manufacture and of unknown characteristics; the other five had been made in the United States at the close of World War I. One of the latter group showed an excessively high rate of erosion, but it was suggested that this might have been an erroneous indication caused by an error in the number (1125) of rounds recorded.

It has been noticed by the present writer that the points (solid dots) in Fig. 4 representing the increase in diameter of the bore of these guns (see fourth column of Table XVI) do not fit at all on Curve B. Instead, it has been found that they fit reasonably well on a parabolic curve with a slight upward curvature. There remains the more likely possibility that the data for the two different makes of gun should be considered to lie on two separate

Table XVI. Erosion of 155-mm guns.

Gun No. ^a	Number of Rounds	Velocity (ft/sec)	E ^b (in.)	F ^c (in.)	Loss of Weight (gm)	
					Total	Per Round
842	812	2398	0.037	0.33	452	0.56
567	1609	2383	.062	.70	590	.44
853	2127	2379	.088	1.06	1023	.49
434	1125 ^d	2365	.110	2.62	1761	1.57
49*	2853	2283	.143	5.47	2889	1.01
44*	3289	2247	.156	7.33	2725	0.83
32*	3597	2215	.175	8.04	4006	1.11

^aThe gun numbers marked with an asterisk indicate those of French manufacture (Puteaux). The others were American made.

^bE, increase in diameter at origin of rifling.

^cF, advance of forcing cone (see Sec. 125d).

^dIn the original report [Weyher, 1939] it is suggested that the number of rounds reported for this gun may be too small. On the other hand, the steel in this gun may have been of poor quality; for, on the graph showing the erosion of 62 155-mm guns as a function of the number of rounds, several other guns showed an equally high rate of erosion.

curves, each of the general shape of Curve B. This possibility does not seem to have been considered in the original investigation, for the report [Weyher, 1939] correlates the various measurements as if the guns were all the same except for the number of rounds fired.

62. Variation with caliber

The depth of erosion per round and also the maximum depth of erosion at the end of life increase very greatly with increase of caliber. Representative values of the former quantity for several guns of about the same muzzle velocity but different calibers are given in Table XVII. It should be remembered that the variation in the rate

Table XVII. Comparison of average erosion per round for guns of different caliber; velocity, 2500 to 2750 ft/sec.

Gun	Rounds	Erosion at Origin of Rifling	
		Lands (10^{-3} in.)	Grooves (10^{-3} in.)
37-mm M3 Tube No. 22708	902 to 1472	0.047	0.026
3-in. AA Gun M3 No. 640	326 to 528	.17	.12
8-in. M1888 MII No. 56	62 to 127	.35	.27
14-in. M1920 MII No. 11	123 to 154	1.1	.96
16-in. M1919 MII No. 2	123 to 152	2.8	1.4

of erosion of guns of the same caliber and muzzle velocity is quite large, and that therefore the values given in Table XVII should not be considered as establishing a functional relation between erosion and caliber. They are merely illustrative of possible values.

63. Advance of the forcing cone^{53/}

The forcing cone (Sec. 10) does not retain its original position, but gradually moves forward as erosion proceeds. At the same time the angle of the cone becomes less steep, because of rounding off of the front of the conical surface. The advance of the forcing cone, which is one way of expressing the extent of erosion, is measured with a special tapered plug gage^{54/} that is inserted through the breech until it is stopped by contact with the forcing cone. The fifth column of Table XVI lists the advance F of the forcing cone for some 155-mm guns.

64. Weight of metal lost

The weight of metal lost during the erosion of a gun is not readily determined. It is not directly proportional to the increase in diameter at the origin of rifling, because the length of the eroded region increases toward the muzzle at the same time that the diameter at the origin is increasing. On the other hand, this forward extension is slower than the increase of diameter, so that the loss of weight is proportional, not to the square of the increase of diameter, but presumably to some power less than two.

^{53/} The use of the advance of the forcing cone as a criterion of the end of life is discussed in Sec. 125(d).

^{54/} A plug gage that made contact at only two diametrically opposite points in the bore was recommended by Weyher [1939]; but subsequent experience at Aberdeen Proving Ground showed that if this gage were inserted in the bore at a slight angle, it could be pushed beyond the forcing cone. Hence its use for routine measurements has been discontinued. (Arthur E. Jewell, Instruments Section, Aberdeen Proving Ground, personal communication, Sept. 2, 1942.)

An estimate of the weight of metal lost from the breech end of a 155-mm gun tube -- that at the muzzle is insignificant -- has been made by the present writer on the basis of the star-gage records of the guns listed in Table XVI. The area^{55/} under the erosion curve of the star-gage measurement of the diameter plotted as a function of distance along the bore was computed separately for the lands and for the grooves. The space formerly occupied by the material eroded away from the lands was considered as being represented by half the volume of the solid of revolution obtained by rotation of the area under the erosion curve about the axis of the bore; and similarly for the grooves. Hence the total volume V_T of material lost is, according to the theorem of Pappus,

$$V_T = V_L + V_G = \frac{1}{2} \pi (DA)_L + \frac{1}{2} \pi (DA)_G, \quad (\text{VIII-2})$$

where \underline{D} is the mean diameter of the section resolved, \underline{A} is its area,^{56/} and the subscripts \underline{L} and \underline{G} refer to lands and grooves,

^{55/} De Sveshnikoff [1933, p. 659] had measured the area under the erosion curve of caliber .30 machine-gun barrels with a planimeter. He remarked that "aside from giving a general idea of the dimensional change of the bore at the breech and the muzzle end, the measurements do not appear to yield information of any value."

^{56/} The grooves are regularly wider than the lands, sometimes as much as 25 percent (cf. Table I). Hence the following equation is more formally correct than Eq. (VIII-2):

$$V_T = \left(\frac{L}{L+G} \right) \pi (DA)_L + \left(\frac{G}{L+G} \right) \pi (DA)_G, \quad (\text{VIII-3})$$

where \underline{L} and \underline{G} represent the width of the lands and of the grooves, respectively. For $L/(L+G) = 0.4$, Eq. (VIII-2) gives a result 10 percent greater than that obtained from Eq. (VIII-3), but this difference is scarcely as great as the uncertainties inherent in the calculation, since no provision can be made for local irregularities of the bore surface between the points touched by the star gage.

respectively. The corresponding weight of material lost was computed by the use of a nominal factor of 7.8 gm/cm^3 for the density of steel.

The total weight of metal lost and also the average loss per round are recorded in Table XVI. It will be seen that the guns (neglecting No. 434) may be separated into two groups on the basis of the rate of the loss of weight. Interpretation of this result is complicated by the fact that the two groups differed in two respects, namely, in the number of rounds fired and in manufacture. It might be concluded that the rate of erosion, as measured by the loss of weight, suddenly increased above about 2000 rounds; on the other hand, it seems somewhat more likely that the two kinds of gun differed in erosibility (Sec. 61). A definite choice between these two possibilities cannot be made on the basis of the data available. What is needed are measurements of the same gun at different stages of its life.

It was stated by Siwy [1908, p. 67] that a 28-cm gun lost about $1/3 \text{ kg}$ of steel at each round, but he made no mention of the basis of this estimate. It seems to be fairly reliable, as indicated by a calculation made by the writer of the loss of weight of a 12-in. (30.5-cm)/45-caliber Mk. V gun.^{57/} On the assumption that the lands occupied 50 percent of the circumference of the bore, the weight lost from the lands alone was 410 gm/round . The fact that

^{57/} The calculation was based on the erosion curve of the lands of this gun, published as Sketch No. 14 in Naval Ord. [1912].

this gun was somewhat larger than that referred to by Siwy gives ample allowance for the weight lost by erosion of the grooves, which would have been less than that from the lands. It is important to notice that the rate of removal of metal is several hundred times as great for this size of gun as for the 155-mm gun already referred to, the diameter of which is half that of the 12-in. gun.

65. Scoring

When the surface of the bore of a gun tube has been eroded into relatively deep troughs, it is said to have been scored. This condition may result from local imperfections in the steel or, more usually, it is simply the final stage in erosion that at first was fairly uniform. The latest report by Kosting and Peterson [1942] concerning eroded guns points out that the scoring in the 37-mm gun M1A2 which they had examined occurred in a region where hot gases could begin to expand freely after escaping past the projectile before it started to move forward. This observation seems to confirm the opinion held in different quarters, which was summarized by Greaves, Abram and Rees [1929, p. 118] in these words: "It seems probable, therefore, that scoring begins (if it occurs at all) after some general enlargement of the bore has already taken place, and is due, at least in part, to gas-washing produced by the escape of propellant gases past the driving band during the initial stages of motion of the projectile."

66. Pastilles

Pastilles are small shallow depressions in the bore of a gun, ranging in depth from 0.02 to 0.05 in., and having varying diameters. They are of two types -- bulbous and granular. They were found only in 75-mm guns and in a few 155-mm howitzers, used by both the French and the A.E.F. in World War I. Scarcely any were reported by the British or Germans. None were found in antiaircraft guns [Miller, 1920, pp. 61-64].

A graph [Miller, 1920, Fig. 20] of the location of 526 pastilles found in 223 75-mm guns along the bore of the gun showed that the maximum frequency of occurrence was at a distance of 67.5 in. from the muzzle,^{58/} which was near the point of maximum pressure in the gun. Nearly all the pastilles occurred in the bottom quadrant of the bore.

Two possible causes of pastilles have been proposed. Some French ordnance inspectors in World War I suggested that unburned fragments of US No. 3 powder (multiperforated grain), left in the bore of the gun, detonated by impact of the next shell. Soldiers operating 75-mm guns in the field, however, suggested that the tin-lead anticoppering compound formed a globule of bronze by fusion with copper and then was pressed into the bore by the next projectile [Miller, 1920, pp. 67, 68, 71]. Neither opinion has been verified.

^{58/} The length of rifling was 87.8 in.

Pastilles have been alleged as a cause of prematures. Hence they have a great effect on the morale of a gun crew, in some instances causing the crew to destroy a gun which had them. They are also supposed to reduce muzzle velocity by allowing escape of gas, and to serve as a starting point for further erosion [Miller, 1920, pp. 72-74]. However, this latter effect seems very doubtful in view of the findings of Kosting [1936]. As a result of a compilation of all essential data on pastilles preparatory to initiating a metallurgical investigation of them, Kosting found that "the dimensions of the pastilles do not change within the accuracy of measurements ($1/64$ in. approximately) during subsequent firing." For example, the pastilles in four 155-mm howitzers examined after 23, 177, 307 and 411 rounds subsequent to the original measurement of the pastille, showed no enlargement. Hence, pastilles probably can be safely neglected as far as erosion is concerned.

67. Coppering, or metal fouling

The metallic deposit that forms on the surface of the bore of a gun, usually referred to as copper, is generally considered to consist principally of metal rubbed off the rotating band. Thus Tolch [1936a] reported that the copper in a 105-mm gun consisted of a mixture of copper and iron oxides in a matrix of free copper. The analysis showed: total copper, 71.42 percent; total iron, 9.65 percent; lead, 0.33 percent; and oxygen combined as CuO and FeO , 18.61 percent. The presence of copper is more extensive than a superficial examination might indicate, for its surface is frequently blackened

by copper oxide. Heating a section of the bore in a current of hydrogen reduces the oxide, and then the true extent of the coppering is apparent.

Coppering is greatest in the central section of the bore, where it may decrease the diameter as much as 0.01 in. In a given gun it is usually thicker in the grooves than on the lands. It sometimes occurs on the surface of the eroded section near the breech. Inasmuch as a deposit in this region is likely to be removed by later firing, it may be the cause of irregularities in the apparent erosion at that point.

The principal ill effect of coppering is that the movement of the projectile is slightly less regular. The corresponding irregularity in the rate of burning affects the muzzle velocity of the projectile and hence its range.

68. Effect of fouling on erosion

The possible influence of fouling of the bore on erosion was suggested by Hardcastle [1904], who had observed that cupronickel from the jacket of the bullet worked into cracks in a caliber .303 rifle barrel. Its presence was shown by immersing a polished section of a barrel in ammonia for a week. Hardcastle claimed that erosion was partially caused by alloying of the steel with the cupronickel. The mechanical enlargement of cracks by copper from the rotating band was considered by Howe [1918] to be an important cause of erosion (see Sec. 70).

It has also been suggested^{59/} that the zinc in gilding-metal bands might have a deleterious effect on the steel of the bore surface, which might explain the observation [Ord. Dept., 1926] that in the first trials of such bands a slight increase occurred in the erosion of a 3-in. liner, No. 35. The original report on the firing had suggested that the greater erosion might have been caused by the increased width of the band. None of these suggestions has been investigated.

69. Removal of copper

Copper may be removed from a gun by several methods. Tin, lead-tin alloy or lead may be mixed with the powder, either in every round or in special decoppering rounds. Projectiles may be fitted with rings or disks made of lead-tin alloy. Copper may also be removed by swabbing the bore with an alkaline solution, or by scraping. The British have used tinfoil regularly in ammunition, but the American services have not, except for small arms. Within the past year, however, the U.S. Navy, having found that its guns were coppering badly during sustained rapid fire, has begun the practice of adding about 0.2 percent of pulverized lead to the powder every round.^{60/} Coppering of U.S. 37-mm guns in service in the Middle East has been reported by the British to be very serious, and they have requested that the American-made ammunition for these guns be supplied with tinfoil [O.B.P., 1942b].

^{59/} By Col. G. F. Jenks; personal communication, Aug. 20, 1941.

^{60/} Lt. B. D. Mills, personal communication, August 1942.

According to Paquelier [1929], decoppering by the use of solder is harmful, as shown by some firings of two new 47-mm guns at Gâvre in 1925. The gun that had been fired with projectiles having bands of solder had eroded more after 650 rounds than the other, which had been fired under exactly the same conditions except that no solder bands were used. In the one case the muzzle velocity decreased 136 ft/sec, whereas in the other it decreased only 79 ft/sec. No other reference to this effect has been found.

CHAPTER IX. THE ERODED SURFACE

70. The system of cracks

During the firing of a gun the surface of the bore gradually becomes covered with fine cracks which are frequently referred to as "heat checks." A typical example of them is shown in Fig. 5,^{61/} which is a photograph of a section of the bore surface at the origin of rifling of a 37-mm Browning automatic gun M1 after 8032 rounds, which was about the end of its life [Kosting, 1940]. Just how early in the life of a gun such cracks begin to develop does not seem to have been determined.

The pattern of the cracks consists of small areas, nearly rectangular in outline, that are bounded by two principal series of discontinuous cracks at right angles to each other. Within each such rectangle a series of finer cracks forms a separate network. Another characteristic of the cracks is that they are puckered, so that they resemble the cracks formed in river-bottom mud when it dries out in the sun.

Some of the cracks are wider and deeper than others. On the lands -- shown by the darker parts of Fig. 5 -- these prominent cracks are transverse, whereas on the grooves they are longitudinal. De Sveshnikoff [1921a, p. 20; 1922, p. 306], when he noticed this condition in eroded machine-gun barrels, remarked that these

^{61/} This photograph and also Figs. 6 and 7 were obtained for this report through the courtesy of Lt. Col. S. B. Ritchie and Dr. P. R. Kosting, of Watertown Arsenal.

directions were the same as those of the tool marks left on the lands and on the grooves, respectively. Carter [Guion, Carter and Reed, 1937] also observed that many cracks in a 1.1-in. Navy gun started at tool marks. Kosting,^{62/} however, although he does not deny that many cracks start from tool marks, emphasizes that many more cracks occur than there are tool marks to start them.

The radial depth of the cracks varies along the length of the bore, being in general greater toward the breech end. The deepest cracks of all usually occur where the driving edge of a land meets a groove. (This side of the lands is toward the top of Fig. 5.) The depth of the cracks varies considerably in different guns, but without any apparent regularity. Thus de Sveshnikoff [1933, Table II] reported that the maximum depth of cracks in 26 machine guns varied from 0.6 to 3.2 mm, whereas Fay [1916] reported that the maximum depth of cracks in a 12-in. gun he examined was 1 mm. Fay also observed that in the region of greatest erosion in this gun -- near the origin of rifling -- the cracks were the deepest and also the fewest. The number of cracks per inch at the bore edge of a section of an eroded gun near the origin of rifling was reported by Kosting [1940, Table 7] as 325 for a worn-out 37-mm Browning automatic gun M1 and by Kosting and Peterson [1942] as 401 for a worn-out 37-mm gun M1A2. Some of these cracks, which varied in depth from a few microns to 0.6 mm, are shown in Fig. 6.^{63/}

^{62/} P. R. Kosting, personal communication, Aug. 22, 1942.

^{63/} The present Fig. 6 was Fig. 8 in Kosting [1940].

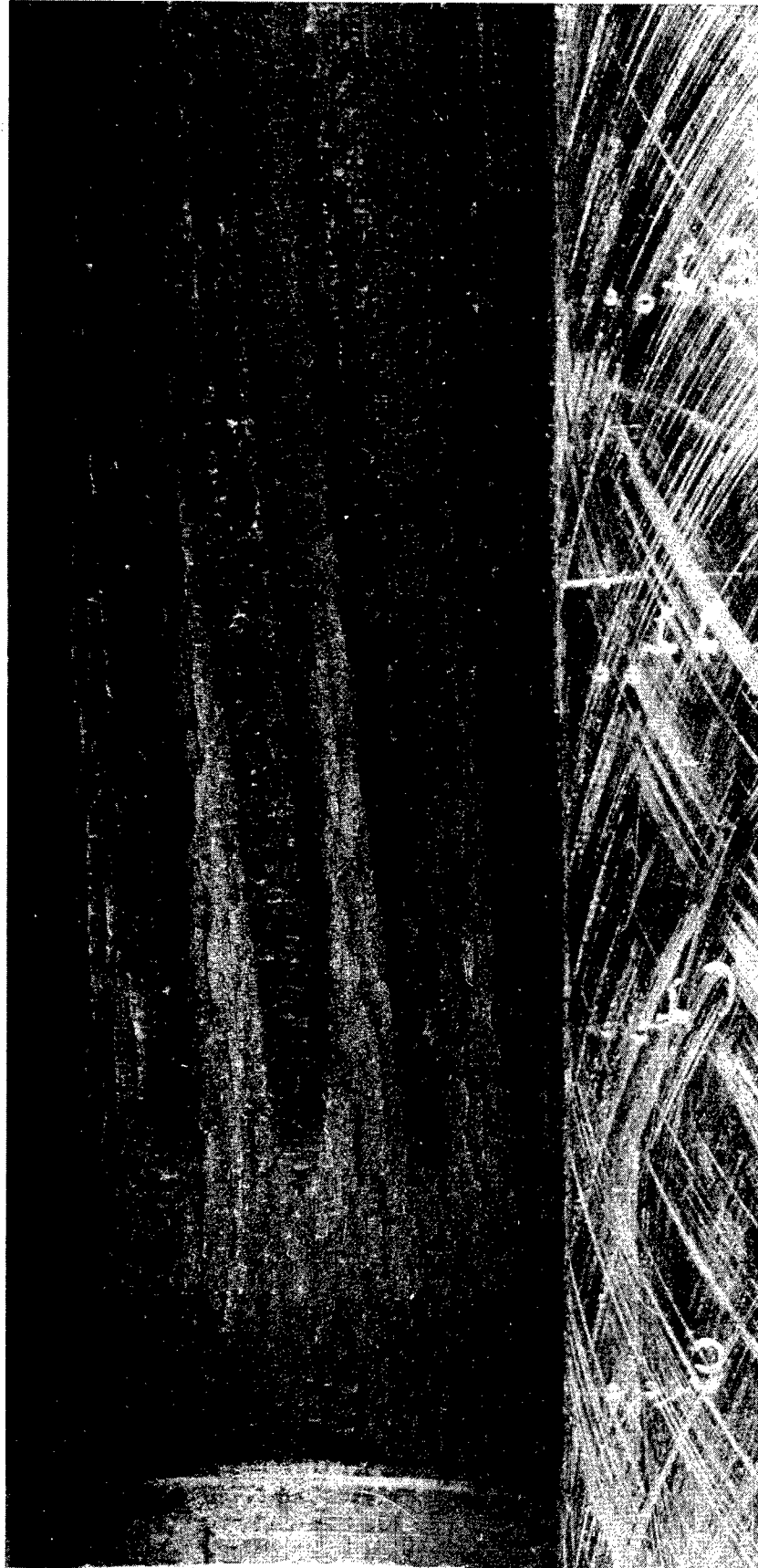


Fig. 5. Section of the bore surface at the origin of rifling of a 37-mm Browning automatic gun M1 after 8032 rounds.

The radial cracks ordinarily are not deep enough to affect the strength of the tube. Howorth [1910] expressed the opinion that a split, when it does occur, is an extension of such a crack; this suggestion was confirmed by later experience at Woolwich Arsenal [Greaves, Abram and Rees, 1929] with respect to cracked carbon-steel liners.

The cracks in a 14-in. gun were found by Howe [1918, Sec. 29] to be filled with copper, which was covered with a layer of black copper oxide and dirt. This he removed by heating a section of the tube in hydrogen. He reported that a "careful examination of the longitudinal and transverse sections indicates that this copper reaches nearly, if not quite, to the roots of the cracks, but in many cases it does not reach to their tops, that is, it does not fill them flush, though from many cracks of the main network, it projects in the form of a thin network of dikes." He also found that the copper color of these dikes could be revealed by rubbing them lightly with fine emery paper.

The cracks are generally considered to be caused by expansion and contraction of the surface of the bore, as described, for example, by Tschernoff [1913] and by Howe [1918]. The heating of the surface of the bore by the powder gases is so rapid that only a very thin layer of metal becomes hot enough to be in the plastic state. The expansion of this layer is restrained to two dimensions by the rigid colder layers beneath, and hence it tends to buckle; then, after the hot gases have passed, it is quenched so rapidly by the cold metal beneath that it becomes rigid before it has time to

contract to its original state. The volume changes involved in the thermal transformation of the steel exaggerate the results of normal thermal expansion.

Lack of ductility imparted by the alteration of structure that takes place in the surface layers (Sec. 71) is usually assumed to be a strong contributing factor; but Greaves, Abram and Rees [1929, p. 117] pointed out that "experiments show that surface cracking of an intercrystalline character may occur under the action of hot gases in metals which will not harden on quenching." At any rate the cracks are not limited to the altered layer. Their continuation to several times the depth of this layer was considered by Howe [1918, Sec. 31] as evidence that they had been deepened by the "wedging action" of the copper that filled them. Greaves, Abram and Rees [1929, Fig. 28] also published a photograph showing this action.

71. The altered layer

Microscopic examination of the polished cross-sectional surface of a segment of an eroded gun tube shows that the structure of the metal has been altered for a short distance beneath the surface of the bore. Although the alteration can be seen in an unetched specimen, it is made more apparent by etching the surface, for instance with 2-percent nital, which is a 2-percent solution of nitric acid in ethyl alcohol. Then the altered layer, which does not etch readily, appears white in contrast to the rest of the steel, as shown in Figs. 6(b), 7(a) and 7(b),^{64/} and hence has frequently

^{64/} The present Fig. 7 shows photomicrographs obtained by Kisting for a 3-in. antiaircraft gun similar to those that he published for a 75-mm gun [1939b] and a 37-mm gun [1940].

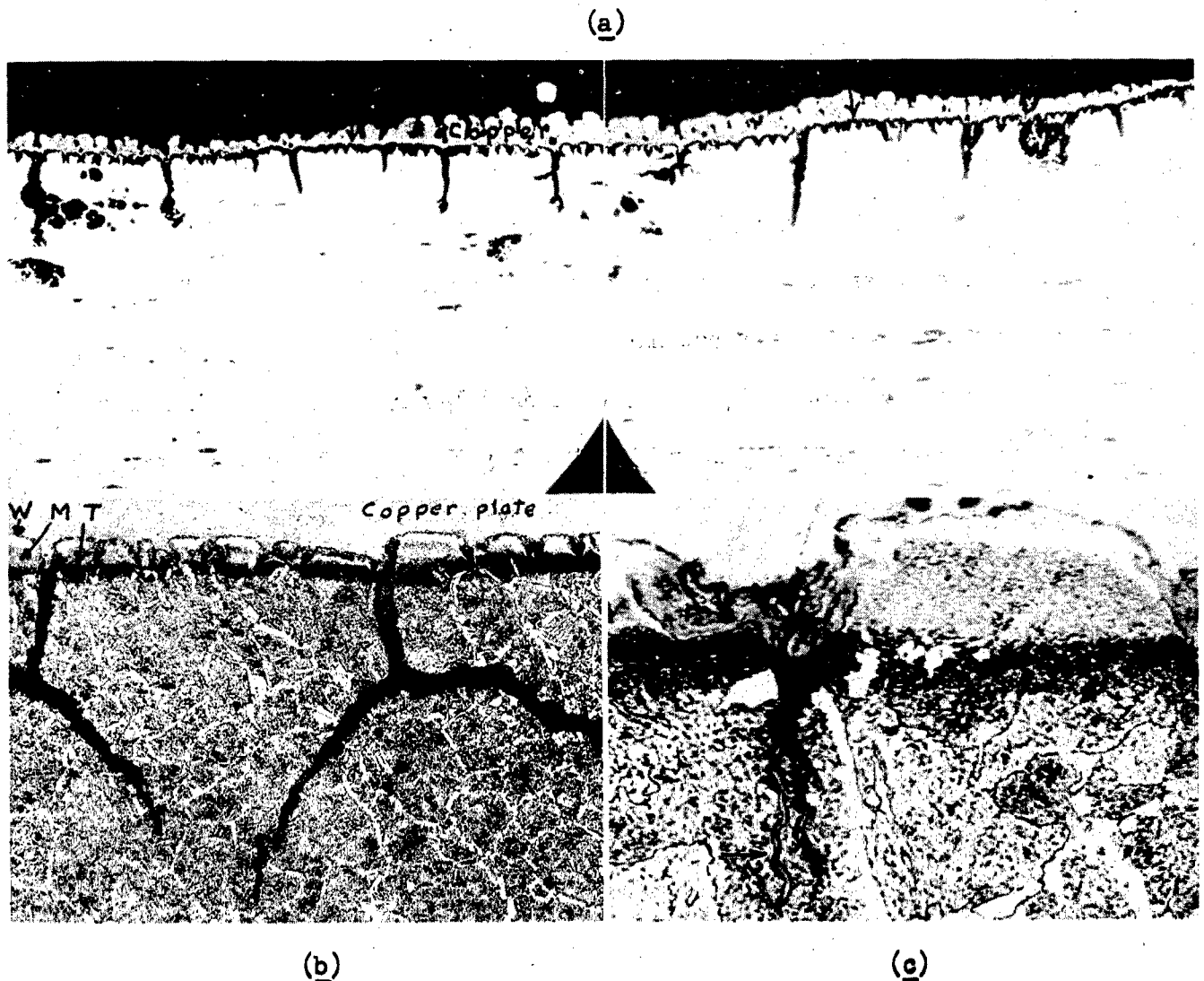


Fig. 6. Interior voids, uneven bore edge and cracks in 37-mm gun Ch46C. The specimens were copperplated prior to polishing. The bore edge is on top. (a) Unetched, showing interior voids in the region of maximum erosion, $\times 25$. (b) Etched with nital, showing cracks and uneven bore edge, $\times 100$; T, troostite band; W, white layer; M, martensitic layer. (c) Etched with nital, $\times 500$; the horizontal arrow at the bottom indicates an incipient crack with grey outline. [Watertown Arsenal 639-2578.]

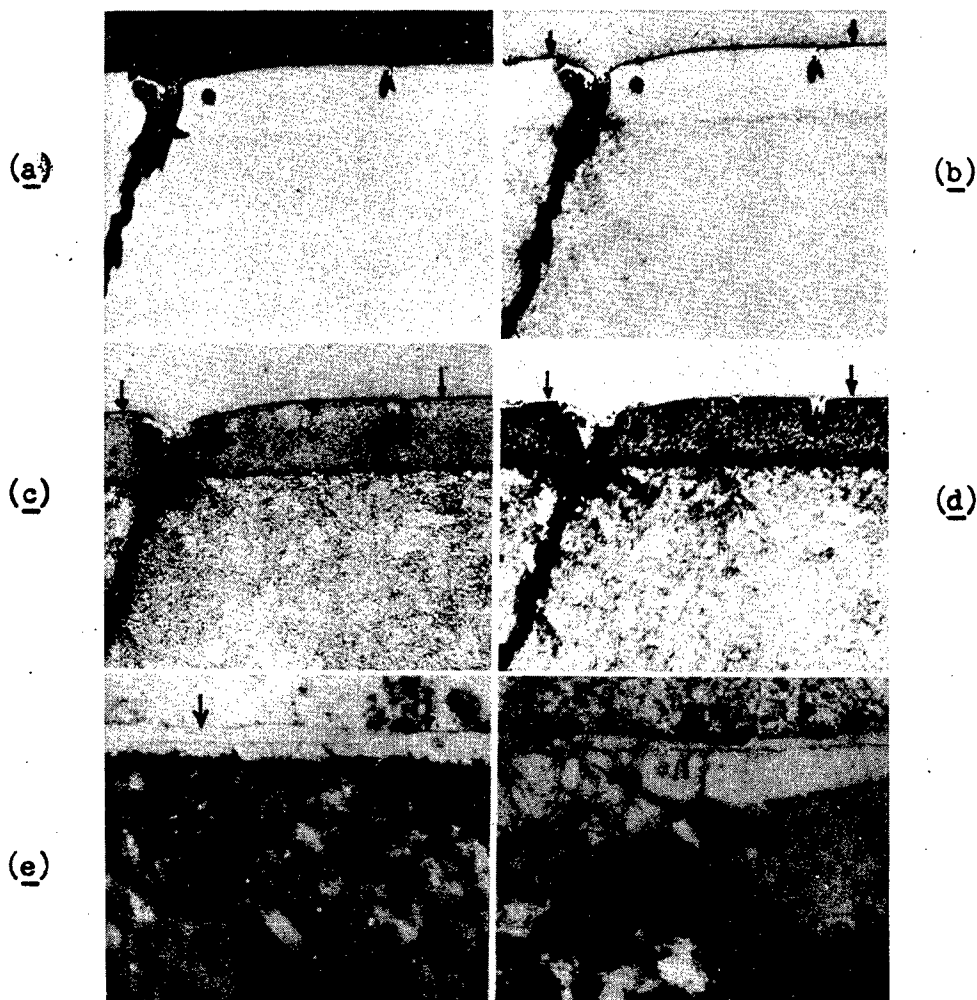


Fig. 7. Hard layer in 3-in. AA gun No. 138. The specimen was copperplated prior to polishing. The bore edge is at the top, as indicated by the arrows. (a) Unetched, hard layer revealed by polishing, $\times 100$. (b) Etched with nital for 8 sec, $\times 100$. (c) Etched with nital for 18 sec, $\times 100$. (d) Etched with nital for 60 sec, showing the white band, dark-etching layer and dark-etching band, $\times 100$. (e) Same as (d), showing two white layers, $\times 1500$. (f) Etched with nital for 30 min; the white band is very complex in places — $\times 1500$. [Watertown Arsenal, 639-2039.]

been called "the white layer." This term seems to have been used first in a report, Tests of metals for 1916, probably by F. O. Langenberg of Watertown Arsenal, to designate what had been referred to earlier by Fay [1916] as the "hard layer" and by Howe [1918] as the "hardened layer." The British writers Greaves, Abram and Rees [1929] called it the "hardened skin." The illustrations of the white layer published by de Sveshnikoff [1925, Fig. 1], by Lester [1929a, Fig. 4], by Greaves, Abram and Rees [1929, Fig. 1] and by Shumate [1938, Fig. 18], closely resemble Fig. 7(b).

Prolonged etching of the altered layer has been shown by Kosting [1939b, 1940] to darken most of it and reveal its composite nature. The altered layer at a magnification of 100 diameters, as shown in Fig. 7(d), consists of a narrow dark-etching layer and an outer white band, which under higher magnification ($\times 1500$) is seen in Fig. 7(e) to be made up of two white layers. The narrow dark-etching transition band had been observed earlier, for example by Bihlman [1921], by de Sveshnikoff [1925, Fig. 1] and by Lester [1929a, Fig. 6] and had been identified by them as troostite.^{65/} The resolution of the main part of the altered layer, however, had not been made before. Hence in reading and talking about "the white layer" in a gun tube, it is important to remember that most writers before 1939 were using this term to refer to the relatively thick white layer shown in Fig. 7(b)

^{65/} The term troostite in the past has not had an exact definition, but has been used to refer to several different types of microconstituent of steel. The authors cited seem to have intended it in the sense of "secondary troostite" as defined by Epstein [1936, p. 266]. See Table XX for a comparison of this structure with related ones.

and that Kosting since that date has been using it to refer to the much thinner layers shown in Fig. 7 (e).

The outer white layer is easily removed by metallographic polishing, if the surface of the bore is not first protected by plating it with copper, nickel or chromium. Kosting [1939b, p. 12] remarked that therefore it may have been absent from some of the specimens examined by other investigators, because not all of them adequately protected the surface. The method of obtaining a high degree of polish of the specimen for examination at very high magnifications has been improved by Miss Mary R. Norton [1935, 1937] at Watertown Arsenal.

72. Thickness of the altered layer

The altered layer regularly increases in thickness toward the breech end of a gun; but, except that it frequently has been reported as being thicker on the driving edge of the lands, it does not vary much in thickness around a circumference at a given distance down the tube. The thickness of the altered layer in a worn-out gun increases with the caliber of the gun. Greaves, Abram and Rees [1929, Table 3] compiled a table of the approximate average thickness of the "hardened skin" for guns of different calibers studied at Woolwich Arsenal, England, that had fired cordite M.D. This table shows that the average depth at the origin of rifling in thousandths of an inch is almost equal numerically to the caliber in inches. A recent measurement by Jones [1942] of the thickness of the altered layer of the inner "A" tube of a

16-in. gun^{66/} showed that it varied from 0.0088 to 0.0113 in. (0.22 to 0.29 mm) in different sections of the bore, but in the report the variation in depth was not correlated with the location of the different sections. This altered layer was made up of a hard layer 0.19 to 0.24 mm thick plus a narrow dark-etching band 0.034 to 0.047 mm thick.

The thickness of the four parts of the altered layer -- "hard layer" -- were measured separately by Kosting [1940] at 21 places along the bore edge of a 1-in. section cut from the origin of rifling of the eroded 37-mm gun shown in Fig. 5. The results are summarized in Table XVIII. Another section of the bore located

Table XVIII. Average thickness of the four parts of the altered layer at the origin of rifling in 37-mm gun No. Ch46C.*

Layer	Average Thickness	
	(in.)	(mm)
First (outer) white layer	0.0003	0.008
Second white layer	.0002	.005
Martensite layer	.0012	.030
Troostite band	.0004	.010

* After Kosting [1940, p. 10].

5 in. from the muzzle of the same gun showed no altered layer. This result, which has been observed also in other guns, is interpreted

^{66/} No. S. 15 (Vickers), fired 225 E.F.C. (see footnote 94), with erosion of 0.633 in. at 1 in. from origin of rifling. The percentage composition of the steel was: C, 0.26; Si, 0.15; Mn, 0.36; S, 0.023; P, 0.034; Ni, 3.60; Cr, 0.65.

by Kosting^{67/} to indicate "that wear at the muzzle should be differentiated from erosion at the breech end."

In a subsequent examination of an eroded 37-mm gun M1A2, No. 109, Kosting and Peterson [1942] found that whereas the entire altered layer was about 60 percent thicker than it had been in 37-mm gun No. C446C (Table XVIII), the white layer on the average was only about 40 percent as thick as that in the other gun. Also in gun No. 109 the white layer was seldom complex. These two guns differed both in composition -- No. C446C contained only Ni as an alloying element; No. 109 contained 2.30 percent Ni, 1.07 percent Cr and 0.31 percent Mo -- and in conditions of firing.^{68/}

For a number of machine-gun barrels -- the number was not stated -- Snair and Wood [1939, p. 609] reported that

This layer extends for a distance of approximately two and one-half inches along the bore from the origin of rifling. It varies in depth along this distance, and if the depth were plotted versus the distance along the bore, the resulting curve would closely resemble a powder pressure-distance curve. This fact establishes a definite relationship between powder pressure developed and layer formation.

This conclusion is open to question, inasmuch as the occurrence of the maximum depth of the altered layer a short distance in front of the origin of rifling might more logically be ascribed to a maximum heating effect there, just as de Sveshnikoff [1921a, p. 18] considered this to be the cause of a maximum number of cracks at that point in the machine-gun barrels which he examined. Snair and

^{67/} Personal communication, Aug. 22, 1942. See also footnote 1.

^{68/} A detailed history of the firing is not available for either gun.

Wood seem to have disregarded the fact that the maximum on the pressure-distance curve means that -- neglecting localized variations of pressure within the gas space -- the maximum pressure is applied all along the barrel from the breech up to the base of the projectile at the point indicated and not just at that point alone. Hence "a definite relationship between the powder pressure developed and the layer formation" would be expected to be accompanied by a depth-distance curve which was parallel to the distance axis from the breech up to the point of maximum pressure and which then decreased toward the muzzle in conformity with the pressure-distance curve.

One eroded gun in which no "nonetching layer" -- that is, no white layer -- was found was a Browning machine-gun barrel that had been fired a total of 5000 rounds in 15 bursts of 100 to 400 rounds each at the rate of 1000 rnd/min. The interpretation of this result was complicated by the fact that it was found that the steel in the gun was WD 1060 -- a carbon steel practically the same as SAE 1060 -- which is seldom used for machine-gun barrels, and that the steel was very dirty, with coarse dendrites present [Kosting, Carter and Reed, 1937].

73. Similar altered layer on other steel surfaces

The erosion surface of a gun tube resembles in many respects surfaces that may be produced by treatment of steel in a number of different ways. In the gun itself the surface of the chamber -- if a cartridge case is not used -- is covered with cracks that differ from those in the bore only in that the network is more uniform and

lacks the prominent unidirectional cracks which characterize the surface of the lands and grooves. The structure of the surface is altered in the chamber just as in the bore.

The pressure plugs inserted in a 12-in. gun for measuring the maximum pressure also were found by Fay [1916, p. 2241] to show an altered layer around the edge of the central hole and around the edge of the plug itself. The surface of the plug was covered with cracks. Greaves, Abram and Rees [1929, p. 116] used this phenomenon to study the formation of the altered layer. They placed cylinders of 0.8-percent carbon steel (pearlitic) in the chamber of a 15-in. gun during firing. After one round the altered layer was 0.0037 in. thick, after five rounds, 0.0114 in., and after 10 rounds, 0.0118 in. The last thickness is the same as that which they listed for the bore of a 15-in. gun. A similar altered layer was reported [Greaves, Abram and Rees, 1929, p. 115] as occurring "on the base of proof shot or shell of large caliber, and in fact on any steel surface on which the propellant gas has acted for a sufficient time."

The surface of an erosion vent plug frequently shows an altered layer -- "white layer," in the older sense, -- such as that illustrated by Greaves, Abram and Rees [1929, Figs. 56 to 71]. Among 41 alloy steels tested in erosion-plug experiments and afterwards examined at Watertown Arsenal [see Sec. 94(b)], only a few specimens showed a white layer. These specimens were low in manganese; with 2 percent or more of manganese, no white layer was formed. The three steels that showed the most pronounced white layer contained vanadium [Ritchie, 1928].

A phenomenon that may be related to the erosion of steel by powder gases is the Munroe effect. During his experiments on smokeless powder, Charles E. Munroe discovered that when a disk of gun-cotton is detonated on a horizontal steel plate, any indentations or raised characters originally on the under side of the disk are reproduced in reverse on the upper surface of the plate [Marshall, 1920; Browne, 1939, p. 1306]. No metallographic examination seems to have been made of a steel surface acted upon in this way.

Steel surfaces that have been suddenly heated by friction also show an altered layer. Greaves, Abram and Rees [1929, p. 116] have enumerated the following cases with original references:^{69/} (i) steel rails; (ii) heavily braked railway tires; (iii) wire rope on a pulley; and (iv) a ball bearing run dry. The heat checking of the surface of brake drums, described by Walther [1938], was explained by him in much the same terms as were used in Sec. 70 for the cracks on the bore surface of a gun.

Steel can also be eroded by an electric arc. De Sveshnikoff [1921a, p. 10; 1921b, p. 163] reported that when an electric arc was struck with either a copper or a carbon electrode against a piece of gun steel, the area around the central hole produced by the arc developed a number of cracks and acquired a martensitic structure^{70/}

^{69/} (i) J. E. Stead, Proc. Inst. Mech. Eng. (1899), p. 77; W. H. Merrett, Proc. Inst. Mech. Eng. (1904), p. 140; J. W. Bampfylde, J. Photomicrographic Soc. 14, 23(1927). (ii) H. Brearley, Metallurgist 1, 132(1925). (iii) E. A. Atkins, J. Iron and Steel Inst. (1927), p. 443. A more recent contribution to the third subject is E. M. Trent, "The formation and properties of martensite on the surface of a wire rope," J. Iron and Steel Inst. 143, 401-419(1941).

^{70/} See Table XX for definitions of these structural designations.

that merged rather abruptly into the original ferrite-sorbite structure^{70/} of the specimen. Greaves, Abram and Rees [1929, Fig. 15] have also published an illustration of the structure of the altered layer produced in this way.

Chemical action also can produce an altered structure on the surface of steel. Four steel bottles used by the General Chemical Company to contain nitrogen and hydrogen at a pressure of 1500 lb/in.² and a temperature of 500 to 600°C failed after varying periods of service. Wheeler [1922, p. 257] found that "when these containers were cut open and the cross-section surface polished, they showed an inside zone with a different luster from the rest of the metal. Upon etching, this zone was almost unaffected while the rest of the metal etched normally." A similar alteration of steel was obtained by exposing it to the action of ammonia at a temperature of 600 to 700°F.

This effect has been confirmed by later investigators. Thus microscopic examination of a longitudinal section of a machine-gun barrel made of "nitralloy G" that was nitrided by heating in ammonia after machining showed that a white layer was present both inside and outside the tube [Lester, 1929b]. A white layer was formed on the surface of specimens of a series of steel alloys of about the composition of centrifugally cast steel, when they were casehardened both by nitriding and also by cyaniding [Shumate, 1938]. A white layer similar in appearance to that present in an eroded gun bore, but much thinner, was formed on a piece of steel heated in gaseous ammonia at 900°F for 15 hr. It was suggested

that the layer in the gun tube is thicker than that produced artificially by reason of the high pressure in the gun [Snair and Wood, 1939, p. 619]. The appearance of a fused surface that is often seen in an eroded gun bore was produced artificially by treating a rough groove in a piece of steel with ammonia at 650°C ^{71/} and then rough polishing the piece. A photograph of such a surface at a magnification of 50 diameters was published [Wheeler, 1922, p. 296].

Hydrogen at high temperatures and pressures has a marked action on steel [Inglis and Andrews, 1933; Naumann, 1937]. As pointed out by Kosting,^{72/} various types of layer are formed which may vary in their resistance to attack by common etchants. In some respects some of these layers are not unlike those observed in eroded machine-gun barrels.

V. Stefanides, in a discussion printed with the paper by Snair and Wood [1939] on the white layer, suggested that hydrogen and water vapor "may play a more important role than they are being given credit for. The austenite, when formed in the presence of H_2O , which evidently breaks down, and the oxygen goes into solution with the carbides, forms a more stable austenite which is hard to break down, requiring higher temperatures than austenites without the oxygen in solution."

^{71/} The duration of the treatment was not stated; other experiments lasted 20 hr at this temperature.

^{72/} Personal communication, Aug. 22, 1942.

74. Hardness of the altered layer

Although many writers in describing the bore surface of an eroded gun have referred to the altered layer as a "hardened layer," few measurements exist to show just how hard it is. In fact, some of the early metallurgists seem to have considered it a hardened layer simply by analogy with previously known hardened layers on tempered steel. Thus Osmond [1901] made no mention of having determined the hardness of the layer he described.

Fay [1913, p. 133] did measure the hardness, both with a scleroscope and with a Brinell ball. Although the results by the two methods are decidedly inconsistent, as is shown in Table XIX, they do indicate a greater hardness at the surface of the bore than deeper within the metal of the tube. This conclusion was confirmed by the measurements of Jones [1942] of the bore of an eroded 16-in. gun liner.^{73/} He found that the hardness at the surface

Table XIX. Hardness of altered layer at surface of bore of 12-in. gun specimens.*

Specimen		Hardness Number				
No.	Distance from Muzzle (in.)	Scleroscope			Brinell	
		Land	Groove	Back ^a	Groove	Back ^a
A	0	33	27	31	192	170
B	120	34	28	31	166	156
C	240	38	33	31	187	170
D	325	47	43	32	187	149
E	337	48	48	30	187	149

* After Fay [1913, p. 133].

^a The reverse side of the trepanned specimen, to indicate the hardness of the unaltered steel.

^{73/} See footnote 66.

varied from 630 to 655 D.P.H., whereas at a depth of 0.001 in. below the surface it was a little greater, from 660 to 710 D.P.H. Measurements at successively greater depths showed that the hardness decreased uniformly with depth until below 0.009 in. the hardness was 260 D.P.H., that of the unaltered steel. Shumate [1938, p. 22] reported that he was not able to measure with certainty the hardness of the altered layer on the surface of the bore of an eroded liner for a 105-mm gun, using a Vickers hardness tester.

Greaves, Abram and Rees [1929, p. 116], instead of measuring the hardness of the altered layer on the bore surface itself, measured the hardness of the layer produced on steel cylinders placed in a 15-in. gun (Secs. 73 and 75). After the cylinders had been fired ten rounds, the Brinell hardness, measured with a 1-mm ball and 30-kg load, had increased from 209 to 547.

The scratch hardness of the altered layer was determined roughly by Bihlman [1921, p. 3]. He found that a sclerometer scratch 5.4 microns wide on the unaltered steel surface was reduced to 2.8 microns in width where it crossed the white layer. A photomicrograph of a similar scratch but without a measurement of its width, was published by de Sveshnikoff [1925, Fig. 3], who remarked (p. 796) that it "showed that this surface layer was considerably harder than the original steel."

The only indication of the hardness of the thin outer white layers are photomicrographs of a scratch across the white layers in a 75-mm gun [Kosting, 1939b, p. 15] and a Bierbaum microcharacter scratch across the white layers in a 37-mm gun [Kosting, 1940, Fig. 7(b)]. The

former photograph was said to show that "the outside of the white layer is slightly harder than the inside."

75. The altered layer considered as martensite^{74/}

Examinations of the altered layer were made first by metallurgists, who tried to explain the hardness of that layer in terms of some process already known to cause hardening of a surface layer on a piece of steel. Fay [1916] summarized the three possibilities as (i) cementation, (ii) heat treatment, and (iii) cold-working. He ruled out the presence of free cementite, because the hardened layer did not etch when treated with boiling sodium picrate. He assumed instead that the surface layer was heated considerably above A_{c1} and then chilled rapidly to martensite by the cold layers below the surface. Although no needles of martensite were found, it was concluded that the foregoing assumption was verified by the fact that the altered layer could easily be changed to troostite by tempering. As a result of experiments with pressure plugs that were locally cold-worked and then fired in a gun, it was concluded that cold-working, as by the rubbing of the projectile on the driving edge of the lands, was an essential part of the hardening process.

Fay and various later writers quoted Rosenhain and Believ [1913] in support of the view that the altered layer consisted of martensite; but these citations are of little worth because they refer simply to separate statements, made during a discussion at a scientific congress, that a distinctly martensitic structure had

^{74/} The several terms used in describing the metallographic structure of steel are defined in Table XX and the notes that accompany it.

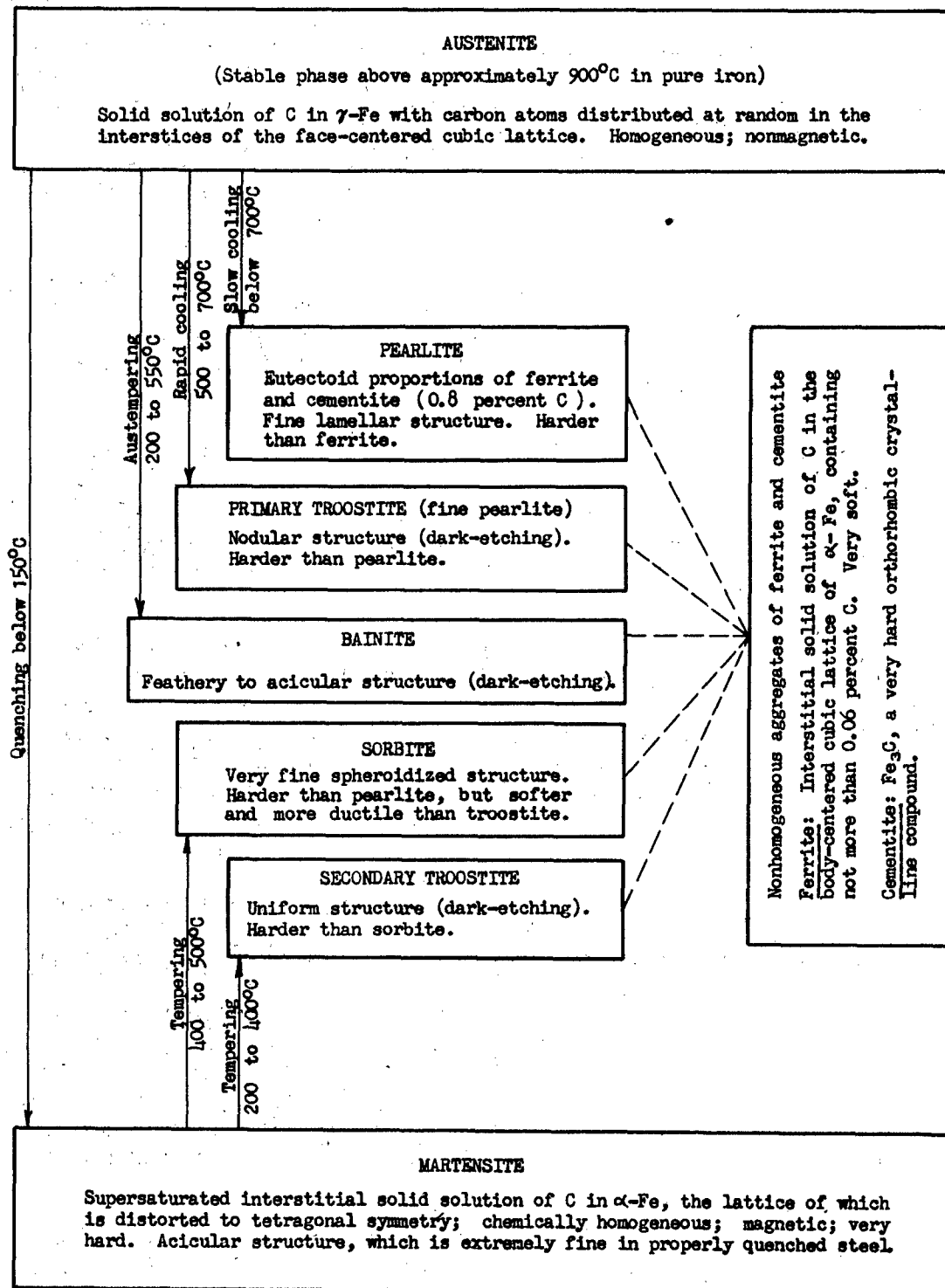
been observed. There was no opportunity at that time to support the statements by photographic evidence, and none seems to have been published since then by these investigators.

Howe [1918] followed Osmond [1901] in considering that the altered layer was either troostite or martensite, depending on the extent to which the alteration had proceeded, the troostite being an intermediate stage. Bihlman [1921, p. 3] was in general agreement with this conclusion, for he reported that photomicrographs at 250 diameters showed a structureless white layer on the surface, a dark-etching layer immediately behind it and then the original structure of the steel. "The characteristic structure of martensite was not observed in the white layer of any of the specimens examined"; but a determination of the relative scratch hardness of the altered layer (Sec. 73) was said to "bear out the suggestion of Fay that the edge structure is a martensite-troostite-pearlite one."

Greaves, Abram and Rees [1929, p. 116] adopted the same general view. They described the "hardened skin" on the surface of the cylinders that they fired in a 15-in. gun (see Secs. 72 and 73) as consisting of layers of different structure, as follows: (outside) coarse martensite, fine martensite, troostite, ferrite and troostite, narrow sorbitic region, and, finally, original structure.

As a result of his chemical, microscopic and x-ray examination of a worn 16-in. gun (see Secs. 72, 74, 77), Jones [1942] concluded that the hardness of the altered layer was caused by the formation of martensite, as evidenced by the observation that the alpha-iron lattice was distorted to an unusual extent and that this distortion

Table XX. The microstructural constituents of steel. This table is based on data obtained from Epstein [1936, Chap. VIII], Evans [1939, pp. 150-3] and a private communication from the research laboratory of the U.S. Steel Corporation.



Notes on Table XX

The allotropic transformation between the gamma and alpha forms of pure iron takes place at a slightly different temperature on heating than on cooling. The former temperature (910°C) is designated as Ac_3 and the latter as Ar_3 , which are abbreviations for the French expressions arrêt sur chauffage and arrêt sur refroidissement, respectively, in reference to the breaks on the heating and cooling curves. The Curie point of alpha-iron (about 768°C), above which the iron is paramagnetic instead of ferromagnetic, is designated as A_2 .

The gamma-alpha transformation of the iron in steel does not take place at a fixed temperature because it is accompanied by a reaction between the iron and the carbon. Thus on slowly cooling a hypoeutectoid steel -- that is, one containing less than 0.87 percent C -- from above 910°C , the transformation begins at Ar_3 . As it proceeds, ferrite is formed and the austenite solid solution is enriched in carbon until the composition of the eutectoid between ferrite, austenite and cementite is reached at 0.87 percent C. Meanwhile the temperature falls until that of the eutectoid line is reached. If equilibrium is maintained, the remaining austenite then transforms to pearlite at this temperature, which is designated as Ar_1 (723°C).

In the system Fe-C, when austenite is quenched the gamma-alpha transformation takes place; but the precipitation of the excess carbon is inhibited. The presence of this excess carbon causes the crystal lattice of the alpha-iron in the resulting martensite to be distorted to tetragonal symmetry. Certain alloying elements that may be added to steel cause the transformation as well as the precipitation to be inhibited, with the result that nonmagnetic austenite can be stabilized at ordinary temperatures.

When martensite is tempered by heating, the lattice distortion of the alpha-iron is removed by the formation of ferrite and the precipitation of the excess carbon as cementite. The secondary troostite or sorbite that is thus produced contains the same proportions of ferrite and cementite as the pearlite or primary troostite that might have been formed from the original austenite by slow cooling or rapid cooling, respectively; but they differ from it in microstructure. Bainite is a separately distinguished primary structure that is formed by the process of austempering, in which austenite is quenched to the intermediate temperature range $200\text{--}550^{\circ}\text{C}$ and then isothermally transformed.

The adjectives "primary" and "secondary" are frequently omitted in references to troostite, the context indicating which type of structure is meant. The troostite mentioned in the various papers on the altered layer is secondary. This constituent is now considered by the research laboratory of the U.S. Steel Corporation as merely a special variety of sorbite and is not separately named.

An especially useful equilibrium diagram of the system iron-carbon, containing much detailed information, was published by Sauveur [1935, p. 467

was removed by heating to 400°C in a vacuum. X-ray examination of an eroded Bren machine gun that had been fired 4000 rounds at 100 rnd/min also showed distortion of the alpha-iron lattice, but to a less extent than in the 16-in. gun.

76. Carburization as a factor in martenization

Although de Sveshnikoff [1925] agreed that the altered layer consisted of martensite and troostite, he maintained that its formation involved not only quenching but also carburization of the steel at the surface of the bore by the powder gases. Whereas Vieille [1901, p. 219], who had suggested this possibility to explain the hardening of the surface of erosion vent plugs, had been merely speculating, de Sveshnikoff based his conclusion on analyses of chips reamed from six eroded machine-gun barrels made of different steels.^{75/} Two successive cuts 0.004 or 0.005 in. deep were made for a distance of 1.5 in. forward from the origin of rifling. The samples obtained by the first cuts showed increases in carbon content ranging from 30 to 183 percent, compared with that of cores drilled from the main body of the steel. The samples obtained by the second cuts showed increases of only 14 to 33 percent.

Fay [1925], in commenting on the work of de Sveshnikoff, amplified his former theory by agreeing that absorption of nitrogen and of carbon accelerated the formation of the hard layer, since in the meantime he had found out [Fay, 1921] that "steels are nitrogenized

^{75/} These were some of the barrels made of special steels, the trial of which is described in Sec. 92.

as well as carburized in casehardening operations, the absorption of nitrogen preceding that of carbon." Graziani [1928] also supported the view that carburization is a cause of the hardening of the surface of the bore.

Piantanida [1922], on the other hand, while he admitted that the altered layer consisted of martensite, denied that it was caused by carburization, because it disappeared on annealing. Later he examined guns (caliber not stated) that had been fired to the end of life. He annealed sections of the bore by heating them to 900°C in a slow stream of hydrogen or nitrogen in an electric furnace and allowing them to cool slowly in the furnace. Whereas unannealed sections showed a distinct altered layer, the annealed ones did not. Furthermore, the number of pearlite grains was no larger near the surface of the specimens than it was at a greater depth. Hence it was concluded that the altered layer had not been caused by carburization [Piantanida, 1935].

77. The altered layer considered as a nitrided layer

An entirely different explanation of the altered layer was given by Wheeler [1922]. From a comparison of the appearance of the white layer found on the surface of steel nitrided in an atmosphere of ammonia with that found on the bore surface of a gun, he concluded that the latter was a locally cold-worked austenitic case due to penetration of nitrogen. He argued that

Since nitrogen under pressure and with heat penetrates and combines with steel as has been described, it would be strange indeed if the reaction did not occur on the bore of a gun where there is an atmosphere of from 35 to 45 percent nitrogen,

very hot and fresh from combination of another sort and therefore nascent and under a pressure of 30,000 to 45,000 lb/in². Since even molecular nitrogen is known to react at 500°C and 1500 lb/in², the reaction must occur in a gun. By assuming that the white layer on the inside of a gun is the same as that which can be artificially produced by nitrogen, most of the loose ends of previous theories are picked up.

The same samples of material from the surface of the bore of machine-gun barrels that he analyzed for carbon (Sec. 76), de Sveshnikoff also analyzed for nitrogen. Although the nitrogen content, which was of the order of a few hundredths of 1 percent, was higher than normal for these crucible steels, it was "altogether too low for assumption that the white layer consists of iron nitride." It was considered that "nitrogenization may or may not be concomitant with carburization," depending on the presence of particular alloying elements, such as chromium, that have an affinity for nitrogen. Also, it was argued, the fact that it had been possible to change the white layer to a dark-etching one by heating it to 320 or 390°C proved that it "could not be a nitride of iron because iron nitride does not readily decompose below 450°C." He did finally concede that "the probability of absorbed nitrogen remaining in the solution should not be neglected, since in such a case the layer may have a martensitic character and change at temperatures below the decomposition temperature of nitride."

In rebuttal to de Sveshnikoff, Wheeler [1925] pointed out that he had not claimed the presence of iron nitride in the altered steel but simply of a solid solution of nitrogen in steel. He remarked that the nitrogen in solid solution would not have been determined by the analytical methods used by de Sveshnikoff. After

he had suggested that the specimens analyzed might have included foreign matter containing carbon or nitrogen, he went on to argue that even if the altered layer contained more carbon than the unaltered steel, his nitrogen theory was not invalid. He considered that "whether partial carburization or decarburization takes place is a matter of no great consequence, dependent simply upon the concentration of carbon and hydrogen in the gases."

The suggestion that the altered layer might be the result of nitriding was supported by Lester [1929a] as a result of a microscopic and x-ray examination of rings from the same 12-in. gun that had been studied by Fay [1913; see Sec. 74] compared with a similar examination of an eroded caliber .50 machine-gun barrel that had been made of nitralloy and then nitrided by the usual commercial procedure [see Lester, 1929b]. Polished cross sections of the two guns showed similar structures under the microscope. The x-ray diffraction patterns of sections from both guns showed the spectrum of alpha-iron with the lines displaced to a slight extent, indicating an enlargement of the lattice of 0.5 percent. The section from the 12-in. gun showed also a spectrum of gamma-iron that was almost as strong as that of the alpha spectrum (see Sec. 79); but the section from the nitrided machine-gun barrel showed no gamma spectrum. It was concluded, therefore, that the white layer in the 12-in. gun contained about 40 percent of austenite, "caused by the alloying effect of nitrogen with consequent lowering of the A_{r1} point to such an extent that the solid-solution phase is formed on the surface," as explained by Wheeler [1925, p. 800]. The lack of a similar

austenitic phase in the case of the machine-gun barrel was explained on the ground that there had been less opportunity for quenching. The hardness of the altered layer was claimed to have been the result of the lattice distortion, which in turn was ascribed to the presence of nitrogen in solution, both in ferrite and in austenite.

Confirmation of the x-ray diffraction pattern described by Lester was reported by Snair and Wood [1939], who also found a distortion of the lattice of alpha-iron of 0.49 percent in an examination of the eroded surface of machine-gun barrels. Although they concluded that the white layer was a nitride, they had no other positive evidence than this agreement with Lester's previous determination of the lattice enlargement of a nitrided barrel. They did find that when a sample of the bore surface that showed a distinct white layer was heated for 1 hr at 400°C and cooled in the furnace to prevent quenching, the white layer remained white. They claimed that this result showed that the white layer was not martensite, because martensite would have broken down and would have appeared dark after the heat treatment, which was exactly what Bihlman [1921] and de Sveshnikoff [1925] claimed that they had observed.

The nitrogen contents of successive layers of steel 0.001 to 0.002 in. thick, removed with dilute hydrochloric acid from the bore of an eroded 16-in. gun,^{76/} were determined by chemical analysis by Jones [1942]. He found that in three sections examined the amount of nitrogen decreased gradually from a maximum of

^{76/} See footnote 66.

0.11 to 0.18 percent in the surface layer to about 0.008 percent in the core metal at a depth of 0.01 in. The maximum amount of nitrogen in the surface layer was very much less than the 9 to 10 percent that Jones and Morgan [1932] had found in the surface layers of nitrided steels and considerably less than the 1 percent they had found at a depth of 0.011 in. In x-ray diffraction photographs of successive layers of similar sections from the same 16-in. gun Jones [1942] observed a very faint set of lines which indicated the presence of a small amount ^{77/} of solid solution of nitrogen in gamma-iron; but he found no evidence whatever of Fe_4N and Fe_3N , which he claimed "give particularly strong characteristic spectra when a steel is hardened by the process of nitriding." He therefore concluded that the hardening of the altered layer was not caused by nitriding. Instead, as mentioned in Sec. 75, he attributed it to the formation of martensite.

78. Relation of cracks and inclusions to the altered layer

Photomicrographs published by Kisting [1939b, 1940] show that some of the deep cracks that penetrate into the unaltered steel are lined by the white layer along their upper surfaces. Other photomicrographs (Fig. 5(c), for example) show the birth of such a crack. To what extent the formation of the cracks was accelerated by the white layer is unknown. Inclusions, on the other hand, definitely

^{77/} In sections of an eroded Bren machine gun which he also examined by means of x-rays, Jones found relatively larger amounts of gamma-iron containing nitrogen, perhaps as Fe_6N .

seem to accelerate the deterioration of the surface of the bore. Kosting [1940, p. 8] reported that photomicrographs "show that where a radial crack and inclusion intersect, the crack branched and followed around and finally enveloped the inclusion with a marked effect on the surrounding steel." Other photomicrographs "show that inclusions to which gases had access, and which were adjacent to or within the hard layer, facilitated marked change in the steel and loss of metal at the bore."

79. Significance of the outer white layers

The work of Kosting that reveals the previously unsuspected complexity of the altered layer may represent the means of bringing together the somewhat divergent viewpoints with respect to the nature of that layer. He agrees with the early workers that most of it is martensitic and is joined to the unaltered steel by a troostitic transition zone. At the same time he considers that the two white layers which he has found on top of the martensitic band indicate the occurrence of "a chemical change on the surface that results, in the case of the present steels, not only in the formation of a friable layer that spalls off in thickness of the order of magnitude of 0.0001 in., but also in the selective attack by some agent that penetrates the steels, resulting in cracks and leading to pitting and the loss of metal in large chunks" [Kosting, 1939a]. If this chemical reaction were a nitriding one, as Kosting himself has suggested it might be,^{78/} the two principal points of

^{78/} Personal communication, August 1941.

view concerning the nature of the altered layer would be reconciled.

The identity of the two white layers is still unknown. Kosting [1939a] reported that an x-ray diffraction pattern obtained from the bore surface of a 75-mm gun showed the spectra of both alpha- and gamma-iron, and also some unidentified lines (see Sec. 76). The white layers do not seem to be constant in their properties, the two layers being less sharply separated in some cases than in others [Fig. 7(f)]. The significance of variations in the white layer that Kosting [1941, p. 19] reported he had observed in some other guns is not fully understood. It is possible that the white layer adjacent to the martensitic band represents a zone in which the reaction between the steel and some constituent of the powder gases is still incomplete, and that the easily detached outer layer represents the end product of that reaction.

CHAPTER X. EXPERIMENTAL METHODS OF STUDY OF GUN EROSION

80. The experimental study of the erosion of guns is performed most directly by actual firing under controlled conditions. Such a test is both expensive and time-consuming; therefore the need has long been felt for a means of reproducing erosion on a small scale. Erosion plug tests have been performed in the past for this purpose, but without complete correlation of the results with those of firing tests. Tests with explosives in closed vessels give little information concerning erosion. Within the past year a laboratory "gun" has been developed at Battelle Memorial Institute, and there is some hope that it may more closely reproduce service conditions.

81. General description of firing tests

A firing test for the study of erosion consists of firing a gun until erosion has proceeded so far that the gun is no longer serviceable. Usually several guns are fired in the same test, each gun (or group of guns) differing from the others in only one particular, such as the kind of steel in the tube, the type of projectile or the kind of propellant. Throughout the test, which lasts for several days with a major-caliber gun, all conditions of firing are kept as uniform as possible. At periodic intervals the velocity of the projectile is measured during a series of rounds and the accuracy of the gun during another series. In most tests the gun is cleaned periodically and the bore is star-gaged in order to obtain a record of the progress of erosion. In some tests, other measurements, such as the maximum pressure or the temperature

of the tube, are made from time to time. The final result of the test is the rating of the accuracy life of each gun. The differences among them are correlated with the variables being tested, with the help of the measurements made during the test. Frequently each variable in the test is represented by only one or two guns, in which case the interpretation of the results is somewhat uncertain, because the reproducibility of the measurements is not very high. The variation in the performances of two guns that are presumably the same may be almost as great or even greater than that between guns of different design.

82. Determination of accuracy life of guns^{79/}

The accuracy of a gun is determined by firing at a target. There is no complete agreement, however, as to the criterion to be used in measuring the accuracy. The mean deviation and the extreme deviation from the center of the target have both been used. The area of the smallest ellipse or circle that encloses all the hits gives another measure. The ellipse is preferable to the circle, because the deviations are likely to be arranged along some line as an axis.

In the firing of small arms the end of life is often considered to be indicated by the occurrence of a specified number of "keyholes" or "tips" on the target -- say three in twenty rounds. A keyhole, which is a hole of that shape in a paper target placed at fairly close range, indicates that the bullet passed sideways through the target.

^{79/} See Chap. XIV for a discussion of the life of guns under service conditions.

A tip is an ellipsoidal hole in the target that indicates that the bullet was yawing^{80/} considerably (but less than 90°) at the moment when it passed through the target. A bullet that makes a tip would make a keyhole in a target placed farther away, at a distance depending on the rapidly with which the bullet is tumbling. A bullet that makes either a keyhole or a tip in the target would, of course, be very erratic in flight at normal range. The regular occurrence of tips or keyholes is a clear indication that the bore is so badly eroded that some of the projectiles can pass through it without being properly engraved by the rifling (Secs. 8 and 18) and hence that the barrel has really reached the end of its usefulness [see Sec. 125(e)].

83. Cost of firing tests

A firing test of a special kind of tube or of some other special feature requires, in order to be reliable, a minimum of four tubes -- two regular tubes for control and two special tubes. For each additional variable at least two more tubes should be tested. The test of four tubes would require the services of about 9 men: 2 to operate the gun, 2 to measure the velocity, 3 to determine the accuracy, 1 to star-gage the guns and 1 to supervise the test. The firing of four guns would occupy 15 to 20 days; but the over-all time of the test, including the compilation of the data, would be about three months. The cost of the ammunition required

^{80/} The angle of yaw of a projectile is the angle made by its axis of symmetry with the direction of its motion.

to fire a tube to destruction by far exceeds both the cost of the tube itself and also the cost of the personnel needed to carry out the test. Estimates of this cost for four sizes of guns are given in Table XXI.

Table XXI. Estimated cost of ammunition needed for firing guns to destruction.

Gun	Estimated Life (rounds)	Projectile	Ammunition for 4 guns (complete rounds)*	Cost (dollars)
Caliber .30 MG	8,000	Ball	48,000	1600
37-mm, M3	3,000	HE	18,000	75,200
155-mm, M1	2,000	Empty for sand loading	12,000	632,000
16-in., M1919M3	175	AP, empty for sand loading	1,050	2,088,000

* The number of complete rounds required has been estimated by taking one and one-half times the figure given in the Ordnance Proof Manual for the estimated accuracy life, in order to insure that enough ammunition would be available to fire the guns to the end of life, even if some of them exceeded the nominal estimate.

84. Erosion vent plug tests

The erosion vent plug test was introduced by Noble in 1882 for the purpose of studying the relative erosibility of various steels by gunpowder. later it was used by Vieille [1901] to compare both the erosibilities of steels and the erosiveness of different smokeless powders. The method has continued to be used from time to time by other investigators. Their results will be discussed in Secs. 94 and 109.

The explosion bomb^{81/} that is commonly used for erosion vent plug tests is arranged with three openings. One is fitted with an electric connection for firing the powder by heating a wire to incandescence; a second is fitted with a pressure gage (Sec. 89); and the third is arranged so that a cylindrical test plug with a small axial hole can be inserted into it. The gases formed when a charge of powder is fired in the bomb escape through this hole with high velocity and enlarge its diameter.

The extent of this "erosion" is usually determined by measuring the loss of weight of the plug. Sometimes the loss per unit weight of powder is recorded directly; at other times it is transformed into the corresponding loss of volume of material. Greaves, Abram and Rees [1929] expressed their results in terms of the slope of the (approximately) straight line obtained when the loss of weight was plotted against the maximum pressure.

The erosive action in a vent plug test is so great that only a single firing is needed to obtain a measurable loss of weight. For a plug having a 2-mm vent 28 mm long, for instance, a charge of 3100 grains (204 gm) of cordite M.D. fired at a maximum pressure of about 2300 bars (33,000 lb/in.²) caused a loss of 5 to 13 gm, depending on the composition of the material of which the vent plug was made [Greaves, Abram and Rees, 1929, Table III].

^{81/} One such bomb and the results obtained in testing a wide variety of materials are described in a forthcoming NDRC report by O. H. Loeffler and G. Phair entitled Metals tested as erosion vent plugs.

It seems certain that much of the erosion of a vent plug occurs by reason of actual fusion of a surface layer of metal; but to what extent any other mechanism, such as the friction of the powder gases, plays a part is not known.

85. Effect of conditions of vent plug test

Vieille [1901] made a study of the effect of variation of the conditions under which an erosion vent plug test is carried out. He reached the following conclusions, which have been verified by later workers.

(a) Diameter of vent. -- A given charge of powder produces less erosion the larger the vent, except for extremely small vents. The decrease is not entirely attributable to the lowering of the maximum pressure, because there is much less erosion of a 2-mm vent than of a 1-mm one, although the maximum pressure is nearly the same. Vieille [1901] and de Bruin and de Pauw [1931] used a vent 1-mm in diameter, but Greaves, Abram and Rees [1929] used a 2-mm vent, and the plugs tested at the U.S. Naval Proving Ground had 4-mm vents [Bu. Ord., 1931].

(b) Length of vent. -- The erosion is greater the longer the vent. Thus the loss of weight of a plug having a 1-mm hole 40 mm long was two and one-half times as great as one having a hole of the same diameter only 10 mm long.

(c) Quantity of gas. -- By firing the same size of vent plug in bombs of different dimensions, it has been found that the erosion per gram of powder is greater the smaller the charge. This is explained on the ground that the increase of diameter of the vent

caused by the initial erosion slows down the rate of erosion during the later stages, so that the latter part of a large charge is less effective than the same amount of powder would be if fired as a separate charge through a new vent.

(d) Pressure. -- The erosion produced by a given mass of gas, which had been almost negligible at a pressure of 100 bars, became considerable when the pressure was increased to 2000 bars; but then it scarcely increased any more when the pressure was raised to 4000 bars.

(e) Repetition of firing. -- When the same vent plug is used for a number of successive firings, the amount of erosion decreases gradually, both because the diameter of the vent is increased and also because the maximum pressure is less.

86. Influence of turbulence on erosion of vent plugs

The experiments of de Bruin and de Pauw [1931], in addition to confirming the foregoing conclusions of Vieille, showed that turbulence of the gas stream is a very important factor in the erosion of a vent plug. They used segmented plugs made up in three sections, in order that the turbulence might be modified by varying the diameter and the length of the middle section.

In one experiment, for instance, the effect of turbulence was clearly shown by using a plug that had a middle section 5 mm long with a hole 7 mm in diameter, while the two end sections were 10 mm long and had holes only 1 mm in diameter. When this plug was fired, using a 40-percent nitroglycerin powder at a maximum pressure of about 1400 bars, the third section of the plug

eroded more than the first, even though the gas had lost some of its energy by the time it reached the third section.

They also found that if the end sections of such a segmented plug were renewed after each round, repeated firing produced a cavity in the middle section that was of the same general shape even though the initial diameter and length of the middle section were changed. The characteristic form of the cavity was an elongated ellipsoid. Thus with end sections 10 mm long having 1-mm holes, the particular charge of powder that was used created a cavity about 20 mm long and 6 or 7 mm in diameter at its widest part. It was found that after this characteristic cavity had been formed, the rate of erosion decreased considerably. Hence de Bruin and de Pauw concluded that the outline of the cavity represented the streamlines of the gas as it issued from the orifice of the first section of the segmented plug, and that once this form had been achieved, no more turbulence occurred and hence there was scarcely any erosion.

87. Applicability of erosion vent plug tests to gun erosion

Various writers have pointed out that care is necessary in drawing conclusions concerning the erosion of guns from the results of erosion vent plug tests. Thus H. F. Leary [Bur. Ord., 1931], then Inspector of Ordnance in charge of the Naval Proving Ground, although he stated that "the Proving Ground believes that erosion plug tests offer the quickest and most economical method of determining the suitability of a steel for gun use," nevertheless, on

the basis of comparative tests against standard samples, summarized a memorandum on the relationship of erosion plug tests to gun erosion in the following words:

The results of the erosion plug tests necessarily have to be considered, in relation to erosion in guns, as showing a tendency towards significance rather than as being significant in themselves. This is caused by the elements of difference between the two conditions. The period of application of heat, the fundamental significance of the pressure and the quantity of metal eroded in the two cases are radically different.

On the basis of a critical comparison of the data from erosion vent plug tests published by Greaves, Abram and Rees [1929] with those obtained at Aberdeen Proving Ground and at the Naval Proving Ground, P. R. Kosting [1934, 1938] chemical engineer at Watertown Arsenal, concluded that

This is not a sensitive test to differentiate metals. On the other hand, when used to rate gunpowders upon their erosive effects, parallelism between such tests and service tests appears to exist. Before discarding the test, its mechanism should be empirically studied, for it is believed that it has a bearing on the erosion of grooves. A metallographic study of the container, within which the explosions occurred, should be undertaken, for it is believed that more important data will be obtained than the weight loss of the plug.

Even de Bruin and de Pauw [1931] concluded the account of their extensive experiments with erosion vent plugs with the following admonition:

If one is to apply conclusions from tests of this kind to the construction of guns, he must be very careful, inasmuch as these tests differ greatly in many respects from actual firing. Hence it is recommended that only the most general conclusions be drawn, for they are the only valid ones that these tests offer.

In view of the results that have been obtained in the course of years with erosion vent plug tests, the following generalization seems to be justified; namely, that no metal which is eroded badly in an erosion vent plug test would be satisfactory for a gun tube or barrel. Hence the test may have some value in the preliminary evaluation of new materials proposed for tubes or barrels. Even if it would not distinguish the best, at least it would eliminate the worst.

88. Battelle Institute laboratory erosion gun

At Battelle Memorial Institute a gun has been developed to furnish a convenient means of producing erosion in a small test barrel, which is a cylindrical tube of whatever material is being tested, 1 in. long and 0.705 in. in inside diameter, with a wall thickness of 0.27 in. The projectile consists of two parts. One piece is a carefully machined solid cylinder about 2 in. long that fits into the barrel. The exposed end of this part of the projectile is screwed into a 19-lb cast-iron weight which slides in a frame between two vertical oak strips that act as a brake by being partially compressed by heavy coil springs. The projectile is fired by a solenoid-operated firing pin which sets off 1 gm of 37-mm powder contained in a 12-gage shotgun cartridge case that has been cut down to a length of about $3/4$ in. The powder is held in place by one of the regular shotgun wads. Under these conditions the maximum pressure is about 11,500 lb/in² and the projectile attains a muzzle velocity of 40 ft/sec. The gases are in contact with the test barrel for about 0.0036 sec.

The standard procedure adopted after preliminary experiments was as follows. The barrel and its projectile were ground until the diametral clearance was 0.005 in. They were fired a total of 400 rounds at a slow rate of fire -- 1 rnd/min or slower. After each group of 25 rounds, the barrel was cleaned, weighed and photographed on the inside. At the end of firing, measurements of the wall thickness were made at a considerable number of points, from which a contour map of the inner surface was drawn.

With this gun a wide variety of metals and of steel plated with different metals have been tested. The results have been described in a series of monthly progress reports [Russell, 1941a] which contain photographs of the eroded areas. The materials tested have been classified [Russell, 1941b] as follows, on the basis of the loss in weight of the barrel that resulted from the firing of 400 rounds in the laboratory gun:

(a) Bad materials, loss 0.23 to 0.43 gm. -- Austenitic steels, including the particular steels selected for their resistance to heat checking in hot-dye work; massive nickel; massive copper; nickel plate; copper plate; gold plate; and some chrome plate.

(b) Good materials, loss 0.10 to 0.16 gm. -- Gun steels; plain carbon steel; most alloy steels of the SAE machine grade; diffused molybdenum coating; diffused tungsten coating; and nitriding steels.

(c) Excellent materials, loss less than 0.05 gm. -- High chromium (27 percent) steel; chrome plate, when made very adherent; and diffused tantalum coating. Each of these materials, however, has some drawback to its application to gun tubes.

Some of the most recent experiments with this laboratory gun have shown that in reality it is a form of erosion vent plug in which the vent is annular in cross section. The movement of the

projectile contributes nothing, apparently, to the test of a material, for the same weight loss and heat-check pattern were obtained in an experiment in which the projectile was held in place as in one in which it moved. Consequently the test is being modified to employ a vent of rectangular cross section, formed by two opposite plane surfaces separated by a fixed distance. It is felt that this modified test will give essentially the same results as the one with the moving projectile, with much less trouble in the preparation of the specimen. It has been suggested, furthermore, that one face of the vent can be formed of the material being tested and the other of a standard material, in order to provide continuous control of the conditions of the test [Russell, 1942].

89. Pressure gages^{82/}

In test firings of guns and in closed-chamber experiments the pressure of the powder gases is frequently measured. The crusher gage has long been employed for the measurement of the maximum pressure in a gun. The piezoelectric gage, although it is more accurate, is limited in use to special investigations, because a hole has to be made into the chamber of the gun for its insertion, and also because it is a laboratory instrument that requires special care in its use.

(a) Crusher gage. -- A form of crusher gage was invented by General Thomas J. Rodman of the U.S. Army, in 1857, and then was

^{82/} The design and response characteristics of gages suitable for the measurement of the stresses generated by propellants and high explosives are discussed in detail by Goranson, Garten and Crocker [1942].

modified by Noble [1875; p. 107 in 1906 reprint] and by various later investigators [for example, Vieille, 1906; Desmazières, 1922; and Burlot, 1923]. Such a gage usually consists of a small metal cylinder at the bottom of a hole in a metal housing. The cylinder is compressed by a piston that is pushed into the hole when the pressure is applied. A gasket at the top of the piston prevents leakage of gas into the hole. The permanent change of length of the cylinder caused by compression is a measure of the maximum pressure. Annealed copper^{83/} has been the metal most frequently used for the cylinders; but lead is used in some minor-caliber gages, especially for the measurement of pressures less than 10,000 lb/in.² (700 bars). In order to prevent undesirable dynamic effects that would be produced if the travel of the piston were very great, copper cylinders intended for the measurement of pressures above 40,000 lb/in.² (2800 bars) are pre-compressed within 20,000 lb/in.² (1400 bars)* of the expected pressure. One or more of the gages are placed in the powder chamber at the base of the charge, after the several parts have been carefully cleaned and oiled.^{84/} Although copper crusher gages indicate pressures some 10 to 15 percent lower than those registered by a piezoelectric gage, their results are self-consistent, and hence they furnish a convenient means of measuring the maximum pressure in a gun without altering the gun itself.

^{83/} The maximum pressure in a gun is sometimes said to have been measured by "coppers," which means by copper crusher gages.

^{84/} Detailed directions concerning the use of these gages are given in Ord.Dept. [1915]; Ord.Dept., [1932] and Ord.Dept. [1936], No. 40-16.

A recently suggested improvement to the technic of pressure measurements with crusher gages [Hickman, 1941] is the use of 5/32- or 3/16-in. annealed copper balls instead of cylinders. Because the ball presents an increasing area with increasing compression, a much wider range of pressures may be covered. Furthermore, the balls of a given lot from a commercial source are so nearly of the same diameter that it is not necessary to measure each one of them before use. The calibration curve is essentially a straight line throughout the range 0 to 15,000 lb/in.² (0 to 1000 bars) under static load.

The use of a crusher gage in a gun slightly affects the ballistics. Thus it was found in the firing of a 37-mm gun M1A2 that a certain charge of powder would produce a velocity of 2600 ft/sec with the gages in the gun, whereas the velocity was 50 to 60 ft/sec lower when this charge was fired without the gages [Ord. Dept., 1941]. This result is naturally to be expected, because the removal of the gages decreased the density of loading.

(b) Piezoelectric gages. -- A piezoelectric pressure gage consists of several crystals of quartz or tourmaline so arranged that when they are compressed, the charges of electricity that are developed on opposite faces of each crystal are added together. This total charge is very small; the piezoelectric constant for quartz at room temperature, for instance, is $-6.90 \text{ (esu/cm}^2\text{)}/(\text{dyne/cm}^2\text{)}$ [International Critical Tables, vol. 6, p. 209]; hence a pressure of 1 kilobar produces a charge of 1 microcoulomb when exerted on a

total surface of approximately 100 cm². The charge is a linear function of the pressure above a certain limiting pressure.

The piezoelectric gage originally devised by Sir J. J. Thomson [1919; also Keys, 1921] for measuring explosion pressures used tourmaline crystals, the charge on which was measured by means of a cathode-ray oscillograph. The gage that has been developed at Aberdeen Proving Ground especially for the measurement of powder pressures [Kent, 1927] contains a stack of quartz plates. At first the charge was measured by recording the deflection of a ballistic galvanometer on moving film [Karcher, 1922]; but later measurement was made by amplifying the charge with a vacuum-tube amplifier and then recording it with a General Electric Company oscillograph and the high-speed spiraling-drum camera described by Eckhardt [1922]. In its present form [Kent, 1938b] this gage is connected through a vacuum-tube amplifier to a cathode-ray oscillograph having a fluorescent screen that is photographed by an external camera. It can be used as far away from the gun as half a mile [Kent and Hodge, 1939].

The especial merit of the piezoelectric gage is that it is capable of recording rapidly fluctuating pressures, because the response of an oscillograph, especially a cathode-ray oscillograph, is so nearly instantaneous. Another important advantage is that by a proper choice of electric circuits, it is possible to obtain directly the time derivative of the pressure as a function of either the time or the pressure (see Sec. 31, Part I).

(c) Other pressure gages. -- The spring manometer developed by Peteval [1905; also Bone, Newitt and Townsend, 1929, pp. 93-96] is slightly more accurate than a piezoelectric gage, but it is not suitable for use in a gun because its action is affected by the recoil. It has been used extensively in closed-chamber experiments.

Another form of mechanical pressure gage that can be used in a gun has been developed at the Naval Proving Ground, Dahlgren, Virginia [Webster and Thompson, 1919]. It consists of a stiff metal girder so mounted that the slight distortion caused by the pressure of the powder gases moves a contact on a variable electric resistor. The resulting change in resistance, and hence the motion of the girder, is recorded by having the resistance form part of a bridge circuit. Although this gage is not as sensitive as a piezoelectric gage, it is much more rugged.

The diaphragm pressure gage has been used for the measurement of explosion pressures amounting to a few hundred pounds per square inch, but it does not seem to have been used for measuring pressures as high as those in a gun [Bone, Newitt and Townsend, 1929, pp. 99-100; Caldwell and Flock, 1941].

A recent development is the use of a strain gage for the measurement of powder pressures, such as the one described by DuMond [1941] for measuring and recording the pressure of powder gases in rocket chambers.

CHAPTER XI. RELATION BETWEEN PROPERTIES OF
THE GUN METAL AND EROSION

90. Composition and physical properties of the gun metal

Various alloy steels have been used for gun barrels and tubes; but a quantitative comparison of the rates of erosion cannot be obtained from the ordinary service records because the guns are not fired under the same conditions. The normal variations in the rate of fire, in the amount and kind of powder, and in other conditions introduce variations of about ± 50 percent in the average life of a gun of a given model. Within these limits the variations in the properties of the gun steel do not seem to affect the rate of erosion.

91. Nickel steel

Kosting, in his review of erosion [1934], had suggested that steels containing a high percentage of nickel erode more rapidly than some other alloy steels. His conclusion was based on a comparative firing at Aberdeen Proving Ground [Lane, 1933] of two radially expanded 3-in. antiaircraft-gun tubes, one of nickel steel (C, 0.45 percent; Mn, 0.74 percent; Si, 0.245 percent; Ni, 2.41 percent; Cr, 0.13 percent) and one of carbon steel (C, 0.41 percent; Si, 0.217 percent; Mn, 0.65 percent). After 2000 rounds the increase in diameter across the lands was 0.208 in. for the nickel-steel tube and 0.170 in. for the carbon-steel tube at the origin of rifling and 0.024 in. and 0.002 in., respectively, at the muzzle. The loss of muzzle velocity, however, was about

150 ft/sec for both guns. In a letter to Watertown Arsenal commenting on this report, Rear Admiral Defrees said that Kosting's conclusion was substantiated by the experience of the U.S. Naval Gun Factory.

92. Special alloy steels in machine-gun barrels

One of the most extensive series of tests of steels for gun barrels was that conducted jointly by the Springfield Armory and the National Bureau of Standards during the five-year period from 1919 to 1924, on the effect of chemical composition and other factors on the erosion of Browning caliber .30 machine-gun barrels. Over 20 separate reports and memoranda were issued from time to time. Fortunately, a comprehensive report [Bur. Stand., 1924b] summarizes the results and gives complete references to the individual reports, some of which contain more details.

The compositions of the steels that were tested are listed in Table XXII (A). ^{85/} For steel of each composition, five full-length barrel blanks were rolled from a 4-in. square ingot that had been made by the crucible process by the Bethlehem Steel Company. The thermal expansion to 900°C and the critical temperatures, which were determined by the method of thermal analysis, were measured at the National Bureau of Standards [see Table XXII (B)], after which a heat-treatment was planned to develop a limit of proportionality

^{85/} These compositions were chosen by G. K. Burgess, then chief of the Metallurgical Division of the National Bureau of Standards, after consultation with representatives of the Technical Staff of the Ordnance Department, U.S. Army, and with other persons interested in the project.

Table XXII. Properties of special steels tested for
Browning machine-gun barrels.

(A) Chemical composition (weight percentage).

Barrel No.	C	Mn	Cr	V	P	S	Si	Other
0	0.44	0.69	--	--	0.011	0.017	0.21	
1	.43	1.22	--	--	.046	.049	.12	
2	.38	0.67	--	--	.046	.055	.07	
3	.40	.55	--	0.15	.006	.031	.13	
4	.55	.92	--	--	.020	.026	.26	
5	0.32	0.11	1.20	0.11	0.005	0.028	0.12	
6	.27	.44	0.69	.14	.005	.031	.09	
7	.10	.008	2.54	.41	.005	.033	.12	Ni 4.5
8	.21	.77	--	--	.058	.094	.05	Ni 0.49
9	.16	.08	1.14	.21	.016	.047	.11	Cu 1.88
10	0.22	0.075	--	--	0.008	0.028	0.02	
11	.14	.060	0.93	0.25	.009	.017	.13	Mo 0.60
12	.05	.030	1.38	.21	.011	.019	.91	
13	.29	.81	--	--	.013	.038	.09	Ni 3.71
14	.35	1.45	1.11	.13	.012	.056	.20	
15	0.32	0.28	0.80	0.28	0.017	0.046	0.15	Cu 2.76
16	.33	.26	--	--	.009	.057	.05	W 3.82
17	.36	1.21	--	--	.053	.077	.09	Ni 0.81
18	.40	1.30	--	--	.011	.060	1.10	Ni 3.70
19	.50	0.39	--	--	.009	.013	0.17	W 1.59
20	0.25	0.40	13.98	--	0.006	0.010	0.77	
22	.32	.66	--	--	.023	.028	.37	U 0.22
23	.19	1.05	--	--	.022	.031	.16	Ni 36.33

Table XXII. (Continued.)

(B) Thermal properties.

Barrel No.	Average expansion coefficient $\times 10^6$			Critical Temperatures	
	25° to 300°C	300° to 600°C	600° to 900°C	Ac ₁ Max. (°C)	Ar ₁ Max. (°C)
Manganese					
0	12.1	16.2	16.8	(a)	(a)
1	12.7	16.5	16.7	724	650
2	12.7	15.8	16.6	(a)	(a)
3	12.7	16.1	16.8	749	680
4	12.9	16.1	16.6	734	666
10	12.5	16.0	16.9	(a)	(a)
Manganese, chromium, vanadium					
5	12.9	16.0	16.2	764	718
6	13.1	15.9	16.8	750	692
11	12.5	15.9	16.1	---	---
12	12.7	15.2	15.8	801	734
14	13.3	15.6	16.2	753	649
Manganese, nickel					
7	12.1	14.3	---	(b)	(b)
8	12.6	16.1	16.4	731	670
13	12.1	15.3	---	(a)	(a)
17	12.9	16.1	16.4	(a)	(a)
18	12.3	15.0	---	716	---
Manganese, chromium, vanadium, copper					
9	12.7	15.7	16.7	771	688
15	12.9	16.1	16.9	749	682
Tungsten, manganese					
16	12.5	15.7	16.5	741	681
19	12.2	15.9	---	740	680
Chromium (stainless)					
20	11.0	13.3	13.7	---	---

(a) No thermal curve taken.

(b) No definite transformation.

Table XXII. (Continued.)

(C) Heat treatment and tensile properties.

Barrel No.	Temperature (°F)		Brinell Hardness	Tensile Strength (lb/in ²)	Prop. Limit (lb/in ²)	Elongation (percent)	Reduction in Area of Cross Section (percent)
	Quench ^a	Temper ^b					
Manganese							
0	1600-O	900-N	241	124,650	75,000	20	46
1	1500-O	1250-F	244	114,650	85,000	23	59
2	1600-O	950-N	228	112,800	70,000	20	46
3	1575-W	1200-F	217	103,100	80,000	26	65
4	1500-O	1250-F	223	110,750	67,000	24	58
10	1650-W	500-O	177	81,100	55,000	25	64
Manganese, chromium, vanadium							
5	1600-W	1200-F	196	96,200	60,000	26	65
6	1600-W	1250-F	196	95,100	73,000	26	69
11	1650-W	1325-F	286	124,050	105,000	23	66
12	1750-W	500-O	235	110,000	53,000	19	42
14	1625-O	1250-F	241	115,600	100,000	23	58
Manganese, nickel							
7	1650-W	1175-F	242	118,100	80,000	20	66
8	1550-W	700-N	185	90,400	63,000	28	68
13	1475-O	1125-F	235	112,300	92,000	26	66
17	1525-O	900-N	225	113,500	90,000	24	54
18	1600-O	1150-F	277	142,500	65,000	27	46
Manganese, chromium, vanadium, copper							
9	1650-W	1300-F	235	108,100	98,400	23	64
15	1650-W	1125-F	241	107,450	70,000	24	66
Tungsten							
16	1550-W	1100-F	241	94,500	70,000	28	61
19	1550-W	1250-F	248	104,850	90,000	29	56
Chromium (stainless)							
20	1800-O	1250-F ^c	269	120,600	75,000	22	60
Nickel (invar)							
23	None	None	149	94,000	61,250	33	63

^aO, oil; W, water.

^bF, open flame; N, nitrate bath; O, oil.

^cHeat-treated after machining.

Table XXIII. Firing tests of Browning machine-gun barrels made of special steels.

First Test			Second Test					
No.	Accuracy Life (rds)	Condition	No.	Order of Accuracy			Muzzle Velocity	
				2000 rds	6000 rds	7000 rds	Initial (ft/sec)	Loss, 6000 rds (percent)
Manganese								
0	6000	Bulged						
1	8000	Bulged	1B	8	*	-	2618	4.04
			1C	8	7	-	2622	3.05
2	8000	Bulged	2B	1	*	-	2654	5.06
			2C	3	*	-	2640	3.30
3	10000		3B	6	*	-	2655	3.14
			3C	1	11	6	2644	4.34
4	7000	Bulged	4B	5	*	-	2618	2.93
			4C	5	*	-	2616	3.60
10	2317							
Manganese, chromium, vanadium								
5	9000	Bulged	5B	9	5	-	2612	2.75
			5C	4	6	1	2629	2.62
6	6000	Bulged	6B	13	7	-	2623	3.16
11	4000	Bent						
12	8000		12B	11	2	-	2601	1.97
			12C	6	10	-	2660	3.31
Manganese, nickel								
7	8000							
8	8000		8B	2	10	-	2635	3.32
			8C	10	13	-	2665	4.70
13	9000		13B	10	8	-	2605	2.10
			13C	7	12	-	2613	1.64
17	8000		17B	7	3	-	2612	3.95
			17C	2	5	4	2622	3.00
Manganese, chromium, vanadium, copper								
9	8000		9B	12	2	-	2668	5.19
			9C	9	8	-	2665	4.62
15	1705	Bulged						
Tungsten, manganese								
16	8000		16B	15	11	-	2620	2.71
19	9000		19B	3	1	-	2609	2.53
			19C	11	4	2	2640	2.65
Chromium (stainless)								
20	Barrels spoiled in machining operations		20B	14	12	1	2632	3.18
			20C	9	2	5	2643	5.15
Uranium								
22			22B	4	13	-	2620	2.79
			22C	6	9	3	2631	2.70

* Not rated.

of at least 75,000 lb/in.², coupled with a minimum elongation of 20 percent in a 2-in. gage length. After some trial quenchings, each group of barrel blanks was given the heat-treatment best adapted to it, and then the microstructure was examined. The heat-treatment and resulting thermal properties of each steel are listed in Table XXII(C).

One barrel was made from each group of blanks and fired for erosion at Springfield Armory. The rate of fire was not stated, except that 50-round bursts were used for the targets. All barrels were fired 11,000 rounds regardless of their accuracy life, except for several barrels that became unserviceable because of bulging. The end of life of the barrels, which is listed in the second column of Table XXIII, was taken as the point at which keyholing (Sec. 82) occurred on a screen 100 ft from the muzzle.

Two more barrels were made up from each of most of the remaining, original ingots. These barrels were fired for erosion, and the accuracy was measured after each 2000 rounds. The order of accuracy that is listed in columns 5, 6 and 7 of Table XXIII was determined by the relative degree of clustering of the shots. It should be noted that the order after 6000 rounds was considerably different from that after 2000 rounds. Part of the reason for this variation was the smallness of the differences among the various barrels, but part of it also reflects the general order of uncertainty of such a test. As mentioned by Hatcher [1920a], "experience with service machine-gun barrels has shown that several barrels of identical heat-treatment and material will vary in accuracy life from 4000 to 8000 rounds."

The conclusions [Bur.Stand.,1924b] were as follows:

It is very evident from the results obtained that there are noticeable differences in the behavior of the different barrels. Just how much is to be attributed to the different variables in composition is somewhat problematical. The results available are entirely too few to permit any very definite or wide-sweeping conclusions being drawn. The wide discrepancies found in some cases for barrels of the same steel in the two firing tests or even between two barrels of the same steel in the second firing series emphasizes this fact.

In ranking the barrels with respect to erosion, it is most convenient to compare them with barrel No. 1 [the nominal composition of which was essentially that of the "standard" used for machine gun barrels]. Of the barrels tested, Nos. 22, 20, 5, 3 and 17 are superior to the "standard barrel," the first two being distinctly so. They all showed less wear on the lands and grooves at the breech section of the bore. For many of the others, including the "standard," the rifling was completely worn away for a distance of several inches at the breech end with a considerably smaller number of rounds fired. In accuracy all the barrels listed above surpassed the standard, the comparison being based upon the order in the arrangement of the targets. The depth of penetration of the erosion cracks was also considerably less in most cases and the decrease in velocity noticeably less. In this respect, the conclusions expressed here are not in complete agreement with that reached in the final report from the Springfield Armory which was to the effect that "none of these barrels have shown any marked improvement over the regular service barrel in regard to accuracy life." The magnitude of the difference between these conclusions depends, of course, upon how "marked" the improvement must be in order to receive recognition.

While it is evident from the tests that superiority of the different steels over the standard is associated with differences in composition, no definite statements can be made upon this point. However, concerning the correlation of "erosion" and mechanical properties, it appears from the results available for comparison that erosion resistance cannot be predicted, a priori, by a determination of the mechanical properties, at least as carried out ordinarily at room temperatures. By way of example, steel No. 5 (chromium-vanadium), which is here ranked as superior to the "standard," showed in the mechanical tests a proportional limit of only 60,000 and an ultimate tensile strength of 96,200 lb/in², whereas another chromium-vanadium steel No. 9 (containing copper), which did not show superiority to any extent in the firing tests, had a proportional limit of 98,400 and an ultimate tensile strength of 108,100 lb/in², the ductility

in the two cases being not materially different (No. 5, elongation, 2 in. or 26 percent, reduction of area, 65 percent; No. 9, 22.5 and 63.5 percent, respectively).

The malfunctioning of a gun on account of bulging or similar causes appears to be more closely related to the mechanical properties of the steel than is the erosion resistance. Although bulging was not experienced with all the steels having the lower tensile properties, the cases which did occur were confined, for the greater part, to such steels. However, it should be borne in mind that the results of these tests indicate that one cannot predict with any degree of assurance the malfunctioning of a gun by reason of bulging or similar causes on the basis of the low tensile properties of the steel.

Three barrels that were made of invar steel were tested as a supplement to the Springfield firings just described. They have been listed as No. 23 in Table XXII(A). The metal was so tough that drilling was difficult [Ames, 1921]. The three barrels were fired until pronounced keyholing of the target occurred at 100 ft. The numbers of rounds fired were: barrel No. 1, 3500; No. 2, 1700; No. 3, 4000. The lands were entirely removed for a distance of 6 to 12 in. from the origin of rifling [Hatcher, 1920b].

In addition to the conclusions already quoted, it was suggested [Bur. Stand., 1924b] that the steels that had superior erosion resistance showed very small permanent dimensional changes as a result of thermal transformation. It was admitted, however, that not all steels which showed small change were erosion resistant.

93. Nonferrous metals used for gun barrels

Metals other than steel that have been tried for machine-gun barrels have included beryllium-copper, monel and molybdenum. The

barrels of beryllium-copper, which were tested at Springfield Armory about 1938, had extremely short lives.^{86/}

The U.S. Navy has tried some monel-metal guns in an effort to reduce sea-water corrosion. The erosion^{87/} of a 3-in./50-caliber unplated monel gun (No. 5533) was 0.061 in. at the origin after 641 E.S.R.,^{88/} which was about the same as that of a standard 3-in./50-caliber Mk. 20, unplated steel gun (No. 2956) firing the same ammunition at a muzzle velocity of 2700 ft/sec. After 1255 E.S.R. the erosion of the monel gun had increased to 0.085 in.

A molybdenum liner was tested in a caliber .30 machine gun at Aberdeen Proving Ground in 1936 [Lane, 1936]. The liner, which was 6 in. long, was shrunk into a caliber .30 barrel blank and then bored, chambered and rifled. Because the liner was pushed backwards by the powder gases while the bullet was in the forward part of the barrel, the barrel had to be cut off $\frac{1}{2}$ in. in front of the liner. For comparison a standard M2 barrel was similarly altered. Each barrel was fired 4649 rounds at such a rate that a thermocouple placed on the barrel registered a temperature of 900°C. Although the molybdenum liner did not have a homogeneous structure and had not had a smooth inner surface because of difficulty in machining it, the lands of this liner eroded less than those of the steel barrel -- 0.007 in. and 0.011 in., respectively, after

^{86/} Capt. C. E. Balleisen, U.S. Army, personal communication.

^{87/} Lt. B. D. Mills, U.S. Navy, personal communication.

^{88/} Equivalent service rounds; see Sec. 124.

4000 rounds -- and the grooves did not erode at all. Microscopic examination of a longitudinal section of the molybdenum liner showed that there were no heat checks in front of the chamber, whereas the standard steel barrel had the customary heat checks. These results were considered to support the gas-washing theory of erosion advocated by Greaves, Abram and Rees [1929], the erosion of the lands having been ascribed to the abrasion of the bullet and the lack of erosion of the grooves having been explained by the high melting point of molybdenum (2600°C).

94. Erosion vent plug tests

(a) Pure metals. -- Other investigations of the erosion resistance of metals have been made by means of erosion vent plugs. Vieille [1901], for instance, measured the erosion of a number of pure metals and alloys in the form of vent plugs fitted to a closed chamber that had a volume of 17.8 cm³ and in which was fired a charge of 3.55 gm of ballistite containing 50 percent nitroglycerin. Vieille claimed that for pure metals the erosion increases in inverse proportion to the melting temperature. This conclusion is only partially substantiated by the data that he gave, which is reproduced in Table XXIV. In terms of volume, which was the basis of comparison that Vieille used, zinc eroded less than aluminum, and one sample of copper eroded less than iron or platinum.

(b) Alloy steels (U.S. Army). -- The effect of alloying elements on the erosion resistance of steel was investigated by Ritchie [1928] by means of erosion vent plugs. He made up a series

Table XXIV. Erosion of pure metals as a function of melting point.*

Metal	Melting Point ^a (°C)	Specific Gravity ^b	Erosion ^c	
			Volume (mm ³)	Mass (gm)
Platinum	1755	21.5	59	1.27
Iron	1535	7.8	68	0.53
Copper	1083	8.9	99 ^d	.88
Silver	960	10.53	231	2.45
Aluminum	660	2.60	2238	5.82
Zinc	419	7.15	1018	7.28

*After Vieille [1901].

^aThe melting point given is that listed in the International Critical Tables. The values given by Vieille had differed somewhat from them.

^bThe specific gravity is that given by Vieille, which does not differ much from current values.

^cThe mass of metal eroded has been computed for this table from the volume eroded and the specific gravity given by Vieille.

^dThe value given is the mean of two for "red copper for crusher-gage cylinders." Vieille also listed four values for commercial red copper, ranging from 48.7 mm³ (0.43 gm) to 90.8 mm³ (0.81 gm). This wide variation was perhaps due to impurities.

of 41 alloy steels and subjected them to the following tests: (i) proportional limit, (ii) tensile strength, (iii) elongation, (iv) reduction, (v) Charpy impact. These tests were conducted at 70°, 600° and 1000°F on annealed and heat-treated specimens and also at 70°F on both annealed and heat-treated specimens (a) after cold-working and (b) after cold-working followed by soaking at 480°F. The cold-working was obtained by cold-drawing to a 6-percent increase in length. Photomicrographs were taken of all specimens, both annealed and heat-treated. The two steels which had the most all-round

desirable physical properties were one containing 0.25-0.30 percent C, 1.25 percent Mn and 0.35 percent Mo, and another containing 0.25-0.30 percent C, 1.50 percent Mn, 0.35 percent Mo and 0.075 percent Zr.

Specimens of the annealed and heat-treated bars (not cold-worked) in the form of vent plugs were tested for erosion at Aberdeen Proving Ground [Kent, 1926]. Each erosion test bar, which weighed 19.4 oz, had a vent 0.156 in. in diameter. It was fitted to a closed chamber having a volume of 1000 cm³, which had been constructed from a 5-in. gun. A charge of 7 lb 15 oz of powder was fired, all the gas from which escaped through the vent in slightly over $\frac{1}{2}$ sec. After erosion the hole ranged in diameter at the breech end from 0.35 to 0.53 in. and at the muzzle end from 0.32 to 0.44 in. The enlargement at the breech end was always the greater. The maximum, minimum and average losses in weight for the three classes of steel^{89/} are given in Table XXV(A). Each chrome or chrome-vanadium steel was tested in both the annealed and the heat-treated conditions; and the same was true of all but three of the manganese steels. Three of the stainless steels were annealed, the fourth was heat-treated.

^{89/} P. R. Kosting (personal communication, Aug. 22, 1942) has suggested that "the data collected by the Army by means of the erosion vent plug can be divided into two subgroups; one of low-alloy steel and the other of high-alloy steel, such as 12 percent Cr stainless alloy. When sensitivity and reproducibility of the results are taken into consideration it is believed that Greaves, Abram and Rees' conclusions that low-alloy steels have the same erosion rate in vent plugs will be substantiated."

Table XXV(A). Loss of weight of erosion vent plugs.*

Type of Steel	No. of Specimens ^a	Loss in Weight (percent)		
		Max.	Min.	Avg.
Manganese	51 (27)	30.7	20.8	27.3
Chrome and Cr-V	22 (11)	43.1	21.7	28.9
Stainless 12 percent Cr, 0.4 percent Ni	4 (4)	41.5	36.2	38.2

*After Ritchie [1928].

^aThe number in parentheses indicates the number of different compositions of each type of steel, some of which were tested in duplicate.

It was observed that heat-treatment seemed to have little effect on erosion, and that "the apparent average depth of change in structure from the bore outward on the manganese steels was 0.031 in. as against 0.025 in. for the chrome and chrome-vanadium steels. In other words the depth effect on the manganese steels is greater while at the same time they suffer slightly less erosion than do the other steels"[Ritchie, 1928] (see Sec. 73).

(c) Alloy steels (U.S. Navy). -- The Naval Proving Ground has also tested a large number of erosion vent plugs. A summary [Bur. Ord., 1931] of one series of these tests was enlarged [Bur. Ord., 1938a] to include subsequent results. Each plug was tested by fitting it in the base of a 12-in. armor-piercing projectile, volume 249 in.³ and firing a charge of 2.25 lb of pyro powder through its orifice, after which the loss of weight was measured. The wires attached to the electric primer ("squib") that was used to set off

the powder passed through the hole in the plug, the diameter of which was not stated. The tungsten steels, nitralloys, stainless steels and monel were all inferior to gun steels, as is shown in Table XXV(B). Both the plain carbon and the nickel gun steels

Table XXV(B). Loss of weight of erosion vent plugs.*

Type	No.	Loss of Weight (percent)
Gun steels, chrome plated ^a	10	9.7 - 11.7
Gun steels, unplated ^a	38	10.1 - 12.3
Tungsten steels (0.6, 1.1, and 2.3 percent W)	3	11.8 - 12.5
Nitralloys, nitrided	4	12.6 - 13.4
Stainless steels (12.2 to 20.6 percent Cr)	7	13.1 - 16.4
Inconel (79.6 percent Ni, 13.5 percent Cr, 5.7 percent Fe)	1	13.7
Monel (66.9 percent Ni, 1.4 percent Fe)	1	20.0
K-Monel (65.6 percent Ni, 3.5 percent Al, 29.1 percent Cu, 1.3 percent Fe)	1	22.3

*After Bur. Ord. [1938a]

^aGun steels include carbon steels, nickel steels (2.2 to 3.3 percent Ni) and low alloy steels containing 1 percent or less of Ni, Cr, V and Mo.

that were chrome plated eroded less than the unplated plugs of the same steel; and in both cases the least loss was suffered by the plug plated with the thinnest coating (0.0005 in.)

95. Effect of structure of steel on erosion

The structure of the steel may also affect its erosion resistance. Rockwell [1919], for instance, suggested that slag in

the steel may accelerate erosion. Photomicrographs made by Kosting [1940] support this conclusion (see Sec. 78). Kosting [1934, p. 1] also suggested that in guns, "steels of uniform sorbitic micro-structure with absence of much free ferrite tend to have longer life than steel not treated for uniformity of structure."

96. Effect of radial expansion (cold-working) on erosion

The effect of radial expansion on the erosion of a nickel-steel gun was investigated in the case of a 3-in. gun [No. 1(B-1)] that was compared with a built-up gun (No. 91). After having summarized the results, Lane [1933] concluded that the radially expanded gun was superior to the built-up gun; but the reason for this conclusion was not stated except by reference to the curves showing the enlargement of the bore as a function of the number of rounds. These curves, however, do not substantiate the conclusion, for the enlargement at the origin after 2000 rounds was 0.15 in. on the lands and 0.08 in. in the grooves for the built-up guns, whereas it was 0.21 and 0.15 in., respectively, on lands and grooves of the radially expanded gun. The star-gage records show also that after 2000 rounds the lands of the radially expanded gun had been enlarged 0.024 in. at the muzzle, whereas those of the built-up gun had been enlarged 0.014 in. On the other hand, the accuracy life of the radially expanded gun was 10 percent greater than that of the built-up gun -- 2220 rounds instead of 1990 -- and the loss of muzzle velocity was only 95 ft/sec for the radially expanded gun after 2000 rounds compared with 165 ft/sec for the built-up gun. Also the mean deviations in velocity were somewhat less and much more regular for the radially

expanded gun than for the built-up one. The comparison was complicated by the fact that several different kinds of projectile were used in the firings of the built-up gun. Also the gun steels, made by different manufacturers, were different in chemical composition and heat treatment. All in all, therefore, the comparison was inconclusive.

97. Effect of condition of bore surface on erosion

The nature of the surface of the bore in a mechanical sense may also influence erosion. Thus both Fleming [1919] and de Sveshnikoff [1922] considered that tool marks represent "incipient erosion," for the reason that the powder gases would be expected to react more quickly with a roughened surface than with a smooth one. Also recent researches in connection with such processes as Chrysler's "Super-finish" have shown that the deformation of the surface of steel during finishing varies with the type or process used [Wulff, 1941]; therefore it might be expected that the surface of a gun bore finished by machining would have been deformed more than one finished by a less drastic process, and would consequently be more reactive to the powder gases. The bores of some guns are now being honed,^{90/} but records are not yet available to show whether such a surface resists erosion any better than the usual machined surface. If any improvement did occur it would only apply to the lands, because the grooves are cut after the honing operation.

^{90/} Personal observation, Watervliet Arsenal, 1941.

98. Chrome-plated Navy guns

Since the middle thirties U.S. Navy guns have been chrome plated to protect them against sea-water corrosion. After such plated guns had been in use, it was discovered that they eroded less than unplated guns fired under the same conditions -- especially at the muzzle. A quantitative comparison of a plated gun with unplated guns was made during the experimental firing of 14-in./50-caliber guns in 1938. Gun No. 110L2, Mark C, was fired 207 equivalent service rounds during 209 actual rounds, which was somewhat beyond the end of effective life.

The behavior of the chrome plating was markedly different at the two ends of the gun. At the muzzle,

... flaking was first noticed at 52 E.S.R.^{91/} but no appreciable amount of plating was gone until 62 E.S.R., when plating had worn rapidly on top of the lands (60 percent gone for 5 ft at 62 E.S.R.) so that at 73 E.S.R. plating was gone from on top of the lands for 6 ft aft. From then on the plating wore off farther aft slowly until at 124 E.S.R. it was worn off for 18 ft aft of the muzzle. Wear on the side of the lands and in the grooves was first noticed at 83 E.S.R. (15 percent gone), but wear here was slow and at 124 E.S.R. amounted only to 30 percent for 18 ft aft (wear on driving sides being greatest). [Bur. Ord., 1938b, par.11.]

At the breech end, on the other hand, erosion was scarcely affected by the chromium plating.

The plating on the slope of the origin was gone after 15 E.S.R.; the plating from the origin to 18 in. forward of the origin wore rapidly and at 36 E.S.R. was 65 percent gone. At 41 E.S.R. the plating at the origin was all gone, decreasing to 55 percent gone 4 ft forward, then to 1 percent gone 8 ft forward. The plating then wore with regularity to 73 E.S.R., when it was 90 percent gone 6 ft forward,

^{91/} Equivalent service rounds; see Sec. 124 for method of computation.

decreasing to 1 percent gone 9 ft forward. From then on the wear was slow until at 12½ E.S.R. the plating was 90 percent gone 8 ft forward and 1 percent gone 11 ft forward. [Bur. Ord., 1938b, par. 11.]

In the intermediate section of the gun, from 11 ft forward of the origin to 18 ft aft of the muzzle, a distance of $21\frac{1}{2}$ ft, the plating appeared intact at 12½ E.S.R. [Bur. Ord., 1938b, par. 11].

The life of a 1¼-in./50-caliber gun was considered as the number of rounds at which enlargement at the origin, ΔD , reached 0.4 in., or enlargement at the muzzle, ΔM , reached 0.1 in., or at which [Bur. Ord., 1939a, par. 6]

$$Z [\pm \frac{1}{2} (\Delta D/0.4) + \frac{1}{2} (\Delta M/0.1)] \approx 1.$$

Inasmuch as ΔM reaches 0.1 in. before ΔD reaches 0.4 in. in unplated 1¼-in. guns, the end of life is caused by muzzle erosion. Therefore the retardation of muzzle erosion by chrome plating increased the life of gun No. 110L2 about 40 equivalent service rounds, from 115 to 155 E.S.R. [Bur. Ord., 1939a, par. 4b]. The enlargement at the origin of chrome-plated gun No. 110L2 after 207 E.S.R. was 0.038 in. more than the average for unplated guns; but inasmuch as the total enlargement amounted to only 0.348 in., it was not enough to decrease the life of the gun [Bur. Ord., 1939a, encl. C]. A slight decrease in the loss of velocity of chrome-plated gun No. 110L2 up to 80 E.S.R. was attributed to decreased erosion forward of the origin of rifling [Bur. Ord., 1939a, par. 4e]. This decrease was manifest at first, but then the rate of erosion at a point 1 in. forward of the origin increased

with respect to the rate for unplated guns, so that at about 130 E.S.R. the total erosion at this point was the same as for unplated guns, and after 207 E.S.R. it was 0.028 in. greater.

99. Experimental chrome-plated Army guns

The interest of the Ordnance Department of the Army in chrome plating^{92/} was originally directed toward small arms. The first experiments with chrome-plated rifle barrels at Frankford Arsenal in 1927-28 indicated that a 50-percent increase in accuracy life was obtained, but that the process cost 40 percent of the price of a new barrel. More extensive tests of rifle, pistol and caliber .30 machine guns confirmed the conclusion "that chromium plating very materially increases the resistance of small bores to both erosion and corrosion." [Ord. Dept., 1929.] As a result of subsequent erosion tests of caliber .30 plated machine-gun barrels at Springfield Armory, it was reported that plating had doubled the life [Whelen, 1930].

A microscopic examination at Watertown Arsenal [Lester, 1929c] of two of the rifle barrels plated at Frankford Arsenal showed that the plating adhered strongly, and "was found on the most eroded sections even after the firing tests." However, it was observed that some particles of chromium torn from the plating had been driven into the softer base metal, which may have accounted for the presence of the chromium in the heavily eroded sections.

^{92/} A résumé of this subject, including extracts from the original reports, was prepared by Vincent [1937]. His report was the source of the information in Sec. 99 unless otherwise credited.

During antiaircraft firings in the fall of 1928, two chrome-plated 37-mm Browning automatic guns M1 and two chrome-plated liners for 3-in. AA guns M1 were tested. The plating, which was 0.0005 in. thick in the 3-in. liners and of unknown thickness in the 37-mm guns, began to flake off after a few rounds. No difference was observed in the increase of diameter at the origin of rifling of these guns compared with unplated ones; but in neither case did erosion extend as far forward in the plated as in the unplated guns. It was recommended that plated guns be retested after the technic of plating had been improved.

The guns subsequently tested comprised a 3-in. liner plated to a thickness of 0.001 in., fired in 1929, and four 3-in. liners plated to thicknesses of 0.0015, 0.0020 (2), and 0.0030 in., fired in 1930. The plating also flaked off the surface of these guns, but not as quickly as from the earlier ones. It was again observed in the plated guns that, although erosion at the origin of rifling was not affected very much, the forward extent of erosion was markedly decreased. Because none of these guns was fired to the end of life, the effect on accuracy life is not known. It was observed further that the thicker coatings seemed less satisfactory than the thin one. Exact comparison of the plated and unplated guns was not possible, because the stargaging was not done systematically.

The next trial of a chrome-plated gun was that of liner No. 138 for a 3-in. AA gun M3, in 1936. This liner, after having been machined at Watervliet Arsenal, was chrome plated to a thickness of approximately 0.0005 in. at the Naval Gun Factory according to the standard procedure used there.

The gun was fired in conjunction with tests of pressure gages. Star-gage records were made frequently. The first evidence of erosion was noted after 247 rounds, at which time the diameter of the lands had increased 0.002 in. at the origin of rifling. By the time the gun had been fired 640 rounds the increase in diameter of the lands at the origin amounted to 0.060 in., and the increase across the grooves was 0.019 in. (In the other chrome-plated 3-in. liners tested in 1929-30 the increase in diameter at the origin had been only 0.03 to 0.04 in. at 700 rounds.) The eroded region extended about 5 in. forward of the origin. Beyond that point the chromium plating remained intact.

Measurements of muzzle velocity and of pressure made at intervals with a standard charge showed a steady decrease. By round 677 the muzzle velocity had changed from the original value of 2850 ft/sec to 2743 ft/sec and the pressure had dropped from about 35,000 lb/in.² to 31,600 lb/in.² In view of these changes, according to Vincent [1937, p.36], "it was decided that the cost of chromium-plating liners was not warranted inasmuch as increased accuracy life was not obtained."^{93/}

At any rate, as Vincent reported, a project for the testing of 8 additional liners was abandoned, and on March 12, 1936 the

^{93/} The justification for this conclusion is not clear, inasmuch as an unplated 3-in. antiaircraft gun liner (No. 1183) fired at a different time showed an increase of 0.064 in. at the origin after only 326 rounds, as contrasted with 640 rounds. A careful comparison of the conditions of firing of these two guns and of other unplated ones needs to be made; but unfortunately the writer has not been able to find the records.

Ordnance Committee directed "that the development of chromium-plating technic be closely followed by the Ordnance Department, with a view to its possible consideration for gun-bore treatment when the progress of the art appears to warrant such consideration." Up to the time of writing, no new trials of chrome-plated cannon have been made, although early in 1942 Watervliet Arsenal furnished three oversize 37-mm tubes to the Van der Horst Corporation of America for experimental plating. Also, recent experiments at the Battelle Memorial Institute have indicated considerable improvement in the technic of chrome plating [Russell, 1942], tests of which were made with their laboratory erosion gun (Sec. 88).

100. Partially chrome-plated machine-gun barrels

A new idea in chrome-plating was developed during 1941 at Springfield Armory, namely, to plate only the breech end of the bore where most erosion occurs. Use of a short anode for plating only the first 7 in. of the bore of a caliber .30 machine gun permits better control of the plating, and it also decreases the cost. The plating is only 0.00025 in. thick. One interesting result of these experiments is that not only is the erosion reduced, but also the muzzle velocity is increased, in one case from 2610 to 2747 ft/sec [Benson, 1941].

101. British nickel-plated guns

As an economy measure, eroded gun tubes are now being plated with nickel and then rerifled. This process, which originally had been suggested by de Sveshnikoff and Haring [1924],

has been developed by the Research Department of Woolwich Arsenal [A.C., 1942a]. The process, which involves the deposition of a layer of nickel 0.1 in. or more thick at the breech end of the bore, has about reached the stage at which it can be used on a production basis for 3.7- and 4.5-in. antiaircraft guns [A.C. 1942b]. One of the plated 3.7-in. guns has been found to have an accuracy life as long as that of a similar steel gun. After 750 rounds, nearly one-third of which were bursts of 25 rounds each, the increase of diameter at 1 in. from the origin of rifling was 0.154 in. as compared with 0.191 in. for the average of normal service guns. Some flaking of the nickel plating had occurred. Ranging was normal and accuracy was still satisfactory. The loss of muzzle velocity, however, was greater than with a service gun [O.B.P., 1942a]. A subsequent trial of two more barrels gave less favorable results. One barrel showed poor accuracy after 100 E.F.C.^{94/} and definitely bad results after 450 E.F.C. The accuracy of the other was fair up to about 400 E.F.C. It was reported that "the complete trial shows that satisfactory results may be achieved by this method of repair, but that it is not yet reliable" [O.B.P. 1942e].

^{94/} E.F.C. = equivalent full charge, which is the British term corresponding to equiv-alent service round (see Sec. 124).

CHAPTER XII. CONDITIONS OF FIRING THAT INFLUENCE

THE RATE OF EROSION

102. In previous sections^{95/} the effect of various features of the design of parts of the gun on the rate of erosion have been considered. Of equal or even greater importance are the conditions under which the gun is fired. Although the records of the erosion of guns under varying conditions are not complete enough to evaluate all the factors that conceivably might be suggested,^{96/} they do indicate qualitatively the effect of some of them. The present chapter gives a resume of the influence of a number of the conditions of firing, illustrated by examples of data concerning the rates of erosion of actual guns.

103. Rate of fire

It has long been known among artillerists that a rapid rate of fire wears out a gun faster than a slow rate. This conclusion has been confirmed frequently in proving-ground tests. Thus Tolch [1936a, p. 4] reported that the erosion produced in a

^{95/} In Sec. 9 Part I, on Effect of design of rifling on erosion, mention should have been made of the work of Jeansen [1936], in which the results of calculations of the pressure on the sides of the lands are given for different riflings in a 12-in./50-caliber gun. They show that although much of the pressure on the lands at the origin of rifling can be eliminated by the use of a rifling that starts with zero twist and then increases, a very large pressure is then exerted on the lands during the forward two-thirds of the travel of the projectile.

^{96/} Both Cranz [1926, vol. 2, p. 158] and Schwinning [1934, Chap. IV] have given extensive lists of such factors.

105-mm antiaircraft gun by 169 rounds of rapid fire was much greater than that produced by 770 rounds of prior routine firing. The rate of erosion at the origin of rifling during the first 770 rounds was 0.00018 in./rnd, whereas during the next 169 rounds it was 0.00025 in./rnd. The increase in erosion in the forward half of the tube was even more marked. This gun was fired at its normal muzzle velocity of about 2775 ft/sec in four bursts, three of which were at the rate of 8 to 9 rnd/min and the fourth at half this rate.

A recent test, in which eight 13-lb barrels and three $9\frac{1}{2}$ -lb barrels were fired under different conditions, resulted in the conclusion [Grant, 1941] "that the erosion in the bore of a caliber .50 machine-gun barrel varies directly as: (a) length of the burst; (b) number of bursts; (c) cyclic rates; (d) lightness of the barrel; and (e) velocity of the ammunition." This conclusion is in agreement with those of earlier tests [Fleming, 1918]. One of these tests illustrated the effect of continuous fire. Two caliber .30 Lewis aircraft automatic-rifle barrels were fired in bursts of approximately 500 rounds. At the end of the first 500 rounds erosion was slight; but after 1500 rounds the rifling wore away rapidly. The barrels became a bright cherry red, and the temperature of the outside of the chamber as measured with an optical pyrometer was 978°C. The two barrels bulged just beyond the chamber after 2425 and 2885 rounds, respectively, and a bullet passed through the wall of one of them at the bulge. The steel used in these barrels had the following composition: C, 0.20 percent; S, 0.91 percent; Mn, 0.44 percent; Cr, 1.47 percent; and V, 0.15 percent. Its tensile strength was 110,000 lb/in.², and its elastic limit was 75,000 lb/in.²

104. Temperature of the barrel

The increase in rate of erosion with an increase in the rate of fire is usually considered to be a result of the correspondingly higher temperature of the surface of the barrel. A direct measurement of this factor was made by Tolch [1935] who fired six caliber .30 M1919 Browning machine-gun barrels to destruction at different temperatures, using two lots of single-base and two lots of double-base powder. The temperature of the barrel was measured at first by resistance thermometers and later by thermocouples welded 3.7 and 11.2 in. from the muzzle. After 100 to 200 warming rounds, during which the temperature rose 1.3° to 1.9°C per round, 500 (or 1000) rounds were fired in bursts of 10 rounds at such frequency as to maintain a predetermined temperature at 11.2 in. from the muzzle. The accuracy life -- corrected for warming and velocity rounds -- which was determined on the basis of the extreme spread on targets at 1000 yards (see Chap. XIV, as given in Table XXVI.

Table XXVI. Accuracy life of machine-gun barrels fired at different temperatures.

Temperature (°C)	Accuracy Life (rounds)	
	Single-base Powder	Double-base Powder
200	19 050	21 000
300	12 180	10 830
400	9 060	6 650

Although with the same ammunition there was considerable variation in the heat effects of the different barrels, the conclusion is

unmistakable that the life of the barrels fired at a high temperature was shorter than that of the barrels fired at a lower temperature.

105. Muzzle velocity

The muzzle velocity of a gun is not an independent factor in the rate of erosion, for it is dependent on the weight of the powder charge, the weight of the projectile, the length of the gun and the maximum pressure. Data are not available for an evaluation of the separate influences of the length of the gun and the weight of the projectile. For a given gun firing the same projectiles, of course, these factors are eliminated, and any increase in the rate of erosion caused by an increase in muzzle velocity is due to the combined effect of the increased powder charge and the resulting increased pressure. It is convenient, therefore, to refer comparison of the rates of erosion to this combined effect as expressed by the muzzle velocity, although actually most of the increased erosion is probably due to the increased charge, for the pressure itself, which is discussed in Sec. 110, apparently has little effect on the rate of erosion. Even for different guns, such as the three listed in Table XXVII, the apparent inverse relation between the life of the gun and its muzzle velocity probably is merely a reflection of the corresponding variation of the weight of charge. The interpretation of this comparison is complicated by the fact that the three guns were not fired at the same pressures or with the same charge.

(a) 3-in. antiaircraft guns. -- In a comparison of two nickel-steel radially expanded 3-in. antiaircraft guns, one gun, No. 1(B-1),

Table XXVII. Comparison of life of guns and muzzle velocity.

Gun	Length (calibers)	Wt. of Charge (lb)	Pressure (lb/in ²)	Proj. Wt. (lb)	Muzzle Vel. (ft/sec)	Est. Life* (rounds)
75-mm pack howitzer	15.93	1.0	26 000	15.0	1270	12 000
75-mm M1897A2	34.5	2.0	36 000	14.7	1950	10 000
3-in. AA gun M2	55.0	6.0	41 000	12.8	3000	2 500

*Ord. Dept., 1936, 40-15, Table I, pp. 2-4.

was fired initially at 2600 ft/sec with an average "copper pressure"^{97/} for 5 rounds of 26,800 lb/in.² and the other gun, No. 2(B-2), was fired initially at 3000 ft/sec with an average copper pressure for 5 rounds of 38,200 lb/in.² The two guns were fired with the same powder charges, whereupon the pressures and velocities decreased gradually. After 631 rounds, gun No. 2(B-2), which had been fired with 6.5 lb of powder, had a velocity of only 2760 ft/sec at a pressure of 31,000 lb/in.² The charge in this gun was increased progressively during the next 12 rounds, until it blew up at a pressure of 113,200 lb/in.² The corresponding decrease of velocity and pressure in gun No. 1(B-1), which had been fired with 5.45 lb of powder, resulted in a velocity of 2426 ft/sec at an average pressure of 23,700 lb/in.² during rounds 723-727.

The increase in diameter at the origin of rifling of the gun fired at higher velocity amounted to 0.181 in. on the lands and

^{97/} See Sec. 89(a).

0.126 in. in the grooves after 640 rounds. The corresponding enlargements of the lower-powered gun after 640 rounds were 0.087 and 0.056 in. It required 1530 rounds to enlarge it to the same extent as the higher-powered one had been enlarged after only 640 rounds. At the muzzle after 640 rounds the higher-powered gun had increased 0.050 in. in diameter on the lands; the other not at all. Even after 2200 rounds it had increased only 0.030 in. The rate of loss of velocity was 0.32 ft/sec per round for the higher-powered gun and only 0.05 ft/sec per round for the other [Lane, 1933].

(b) 4.7-in. guns. -- The report of a recent endurance firing of an experimental model of the U.S. Army's new 4.7-in. antiaircraft gun not only illustrates the rapid erosion that occurs at a muzzle velocity of about 3000 ft/sec but also furnishes an opportunity to compare this rate of erosion with that of another gun of the same caliber fired at almost the same pressure with different charges and hence different muzzle velocities. The muzzle velocity of the 50-lb projectile of this 4.7-in. gun, T2, when the tube was new (rounds 16-20, inclusive) was 3142 ft/sec with a charge of 23.5 lb of single-base powder, which gave an average maximum copper pressure of 37,220 lb/in.²; but with this same charge the muzzle velocity decreased, rapidly at first and then more gradually, to 2975 ft/sec at the end of 400 rounds. The maximum pressure had dropped correspondingly to 29,000 lb/in.². The erosion that had caused these changes in pressure and muzzle velocity had been such as to increase the diameter across the lands at the origin of rifling by 0.175 in. at the end of 418 rounds. The erosion of the grooves had been about

half as great and, consequently, the distinction between the lands and the grooves was lost at the origin of rifling. From an extrapolation of the behavior of the gun for 463 rounds, the "economic accuracy life" [Sec. 125(f)], calculated on the basis of the probability of hitting an airplane under certain specified conditions, was 1400 rounds. However, it was admitted in the report of this calculation [Altschuler, 1941] that, although no stripping of the rotating band had been observed during the rounds fired, it is probable "that the rotating bands of the projectile would be stripped before the predicted accuracy life would be reached and, therefore, that the stripping of the rotating band would determine the actual life of the gun."

In contrast to the rapid erosion of this high-velocity 4.7-in. gun is the record of an earlier model, the 4.7-in. gun M1906. The complete history of one of these guns is not available, but a record [Ord. Dept., 1922c] has been found of the charges and copper pressures during one period of the life of gun No. 808. Between rounds 2244 and 2312, inclusive, 41 rounds were fired with a charge of 6.5 lb of powder at a mean pressure of 30,050 lb/in². The mean velocity was 1703 ft/sec. The remaining 28 rounds were fired at lower velocities, in the range 1529 to 1700 ft/sec. Thus, if this sequence of firings may be considered representative, the pressures in this gun were just about the same as in the 4.7-in. gun T2, but the powder charges were only about 30 percent as large. The muzzle velocities were correspondingly some 1400 ft/sec lower. The erosion of the lower-powered gun was so slight that a star-gaging after

3386 rounds showed an increase in diameter at the origin of rifling of only 0.023 in. on the lands and 0.002 in. in the grooves.

(c) 3-in./105-caliber gun. -- A striking example of the extremely short life of a hypervelocity gun was furnished by the 3-in./105-caliber gun, Mark XVI, No. 61-L, tested by the U.S. Navy in 1922. This gun was fired 46 actual rounds, in nearly all of which a charge of 17 lb of nitrocellulose powder was used. With the 10-lb projectile that was used in most of the rounds, the average muzzle velocity was 4750 ft/sec at an average maximum pressure of about 48,000 lb/in². The increase of diameter at the origin of rifling amounted to 0.140 in. in this gun after 46 rounds, whereas in 82 3-in./50-caliber guns fired at a muzzle velocity of 2700 ft/sec, the average increase was only 0.028 in. after 454 rounds; that is to say, the erosion of the higher-velocity gun was five times as great after only one-tenth as many rounds [Naval Ord., 1926].

(d) The Paris gun. -- The German long-range guns that were used to bombard Paris during World War I were 21-cm guns -- one was rebored later to 24 cm -- made by inserting a lining in a 38-cm gun and having it extend beyond the muzzle of the original tube. The total length was 36 meters (174 calibers). The muzzle velocity was 1500 to 1600 meters/sec (4920 to 5248 ft/sec) at a maximum pressure of 44,000 lb/in². The probable life of one of these guns was not more than 50 rounds [Miller, 1921].

106. Type of propellant

The effect on erosion of difference in the kind of propellant was early recognized, for it was the change from black powder to

smokeless powder that made the erosion of guns a serious problem. After the experience of the Boer War, the British decreased the proportion of nitroglycerin in cordite in order to reduce erosion [Marshall, 1917, p. 304]. According to Greaves, Abram and Rees [1929, p. 122], "the change from cordite Mark I (calorific value, 1150 cal) to cordite M.D. (950 cal) trebled the life of big guns. Similarly the use of nitrocellulose (810 cal) in place of cordite M.D. leads to increased life."^{98/}

107. Double-base versus single-base powder

The comparison between double-base and single-base powder is illustrated by some recent data obtained in the endurance tests of the 37-mm gun M1A2. For the first 500 rounds the increase in diameter of the lands at the origin of rifling was the same (0.004 in.) for a gun fired with du Pont single-base powder as for another gun fired with Hercules double-base powder. Then the erosion of the gun fired with double-base powder began to increase rapidly, so that after 800 rounds, the lands had increased in diameter a total of 0.014 in. while the lands of the other gun had increased only 0.005 in. The increase in diameter of the grooves was 0.009 in. after 800 rounds for the gun firing double-base powder and only 0.001 in. for the other gun. The expected life of the gun that had fired double-base powder was only 1800 rounds [Ord. Dept., 1941, Report 13] compared with 3000 to 3500 rounds for the one

^{98/} See the quotation from O.B.P. [1942d] in Sec. 108.

firing single-base powder in bursts of 50 rounds each with external cooling between rounds [Ord. Dept., 1941, Report 11].

In the test of machine-gun barrels already referred to (Sec. 104), half of the barrels were fired with single-base and half with double-base powder. As is shown in Table XXVI, those fired with single-base powder at 300° and 400°C had the longer accuracy lives. The comparison at 200°C was complicated by the fact that one barrel was fired with both single-base and double-base powder and had an actual accuracy life of 27,770 rounds. The life of 21,000 rounds listed in the table was an estimate of what would have been expected if the barrel had been fired only with double-base powder. Furthermore, a lower rate of fire was required with the double-base powder for the maintenance of a given barrel temperature. Hence, as Tolch [1935, p. 20] pointed out in his report on the test, "if the barrels had been tested at constant rates of fire, the differences in accuracy life would have been considerably greater, other conditions being equal, because of the greater heating effect of nitroglycerin-type powder."

An important observation reported by Greaves, Abram and Rees [1929, p. 123] was that cordite and tubular nitrocellulose (NCT) powders produced the same sort of eroded surface. Two 4.5-in. howitzers of nickel-steel and two 6-in. howitzers of nickel-chromium-steel that had been worn out by firing one of each type with cordite and one with NCT were examined. "There was no characteristic difference in the type of crack produced by either propellant. The cracks in all instances were sharp at the bottom. Their maximum

depth was about 0.05 in. in the tubes worn out with NCT and 0.03 in. in those worn out with cordite, the apparent depth of the crack being reduced by the more rapid erosion of the surface of the tubes worn out with cordite. The character of the hardened skins and of the surface cracking was the same in each case, the difference between cordite and NCT being confined to the more rapid removal of steel from the surface by cordite."

108. Picrite powders

The only information at hand concerning the erosion produced by picrite powders is the statement that "the erosion produced by cordite N is about one-half that produced by American nitrocellulose cannon powders. The erosion caused by cordite NQ is about equal to that produced by American nitrocellulose powders." [O.B.P. 1941a.] No quantitative data were included. Another report [O.B.P. 1942c] suggests that in Q.F. 40-mm (Bofors) guns "the use of NH propellant may be expected approximately to quadruple the life of the gun," compared with its life when firing cordite W.T. In a later action the Ordnance Board recommended "that in all guns one cordite full charge (M.D., S.C., W or W.M.) should be reckoned as one E.F.C.,^{99/} nitrocellulose full charges (NH or FNH) and cordite NQ as half E.F.C. and cordite N as quarter E.F.C." [O.B.P. 1942d].

^{99/} See footnote 94.

109. Erosion vent plug tests

The relation between the adiabatic explosion temperature (Sec. 36) of the propellant and the rate of erosion was investigated by de Bruin and de Pauw [1931]. In two series of experiments at pressures of 15,500 and 20,000 lb/in², erosion vent plugs of "Silberstahl" (C, 1.28 percent; Mn, 0.31 percent; Si, 0.20 percent; P, traces; S, 0.029 percent), having axial holes 1 mm in diameter and 25 mm long, showed losses of weight that were linear functions of the temperatures of combustion as computed from the composition of the smokeless powder. These computations were based on the authors' previous measurements [de Bruin and de Pauw, 1928] of such temperatures as a function of composition. The temperatures ranged from 2675° to 3575°C. It was also found that two powders of very different composition but having the same combustion temperatures produced the same amount of erosion.

110. Pressure

The effect of pressure on erosion is difficult to evaluate, because in guns of the same design any marked increase of pressure must be obtained by an increase of charge. Hence any variation of the rate of erosion may be ascribed to either cause. Vieille [1901] suggested that the pressure affects erosion indirectly by determining the amount of gas that flows through a crack. This suggestion, which is bound up with Vieille's theory of the mechanism of erosion (see Sec. 114), has been neither proved nor disproved.

(a) 6-pounder guns. -- One occasion on which two guns of the same caliber were fired at different pressures with the same charge

of powder was when two new 6-pdr. guns -- Mark III, No. 18, American Ordnance Co., and Model 1900, No. 34, Driggs Seabury R. F. -- were fired a total of 995 rounds each, in two series, at a muzzle velocity of approximately 2400 ft/sec. During the first series of 600 rounds, gun No. 34 was fired with slow-burning powder and gun No. 18 with quick-burning, and during the second series of 395 rounds, the powders were interchanged. The slow-burning powder was U.S. Navy 6-pdr. S. P. 592, web 0.034 in., and the quick-burning powder was U.S. Navy 3-pdr. S. P. 534, web 0.023 in. The mean pressures were about 32,500 lb/in.² with the former and 37,000 to 38,000 lb/in.² with the latter. After 600 rounds the erosion in the rear portion of the rifled bore of the gun firing the quick powder was very slightly greater than that of the other gun. The difference was described as "inconsiderable." After 995 rounds the wear on both guns, which was not near the limit of endurance, had been approximately equalized by the interchange of powder [Ord. Dept., 1907]. From this experiment we may judge that the difference of 15 percent in the maximum pressure had practically no effect on the rate of erosion of these guns.

(b) 4.7-in. guns. -- The comparison of the erosions of a 4.7-in. gun and a 4.7-in. howitzer, already cited in Sec. 105(b), shows clearly how little influence the maximum pressure per se has on the rate of erosion. It seems that only with reference to a particular gun, firing a certain kind of powder, is the maximum pressure related to the rate of erosion, and then only as an index of the amount of charge.

(c) Erosion vent plug tests of propellants. -- The corresponding effect in the case of erosion vent plugs is shown by the results of two series of experiments at pressures of 1050 and 1350 atmos and at different temperatures ranging from 2675° to 3575°C, made by de Bruin and de Pauw [1931]. The extent of the erosion of the plug was a linear function of the temperature for each pressure, that is, the extent of the erosion was increased by the same absolute amount at all temperatures; and hence at the low temperatures, where the erosion was slight, the proportional effect of the increase in pressure was much greater than at the higher temperatures.

111. Lubrication of the bore

Lubrication of the bore of a rifle or handgun firing plain lead-alloy bullets is essential to prevent the barrel from becoming "lead-ed," as described by Sharpe [1942, p. 81]. The lubricant ordinarily is applied to the bore by putting it in the cannellures cut in the body of the bullet. It consists of a mixture of several of the following constituents, the proportions of which vary according to the whim of the handloader: carnauba wax, "Japan" wax, beeswax, tallow, ozocerite, mineral oil, castor oil, graphite, and sodium aluminum stearate (dictaphone-records shavings).

112. Lubrication of bullet by base wad

Another method of lubricating a rifle bore that was in vogue in the days of black powder was to place a wax wad on the base of the bullet before inserting it into the cartridge case. The wad

was cut from a thin sheet of wax of the desired composition. This practice, which is still used by some riflemen when firing lead bullets, has been extended recently to the firing of high-velocity metal-case bullets. Sharpe [1942, p. 84] claims that the wax wads he has used with both the .220 Swift and the .257 Roberts cartridges "not only improve accuracy, but practically eliminate erosion when light bullets are driven at velocities above 4000 ft/sec." He goes on to quote [Sharpe, 1942, p. 85] J. B. Sweany, one of the originators of the .220 Swift cartridge, as having stated that "all Swift loads require grease wads for best results, both in reducing erosion and producing maximum accuracy." A wax wad especially recommended by Sharpe for this use contains colloidal graphite in the form of Oildag, which he claims [Sharpe, 1942, p. 85] penetrates "the pores of the barrel metal under the pressures developed during firing, thus sealing these pores and greatly reducing wear on the barrel." Lubrication of small arms bullets for military use has never been adopted by the Ordnance Department of the U.S. Army on the grounds that it would be a useless practice.

113. Lubrication of artillery projectiles

Artillery projectiles have been lubricated at times. Thus during World War I the Italian army used an asbestos band impregnated with wax and tallow. The French greased the outside of shells; and instructions were issued to the A.E.F. to grease the 155-mm howitzer projectiles, apparently in acceptance of the current French practice. The Ordnance Committee in 1922, however, approved a report by a subcommittee recommending that this practice

be not followed on the grounds that the grease may cause the introduction of dirt into the bore, that the use of grease is an unnecessary expense and inconvenience, and that tests at Aberdeen Proving Ground with greased projectiles in 75-mm guns had shown no decrease in erosion. Details concerning these tests have not been located. Limited trials by the U.S. Navy of experimental projectiles having cannellures filled with graphite and grease did not indicate any improvement with respect to either erosion or coppering.^{100/}

Similarly, Greaves, Abram and Rees [1929, p. 123] reported that "a comparative examination was made of two 60-pdr. guns, each of which had fired about 4500 equivalent full charges of cordite M.D. One had been lubricated with wool grease throughout the last two-thirds of its life and the other had been worn out dry. The main differences observed were a slightly greater maximum depth of scoring in the nonlubricated gun, and rather more coppering in the lubricated gun. The character of the surface cracking was almost identical at similar positions throughout the tubes."

In spite of these negative results, the use of a bore lubricant as a cure for erosion is suggested probably more often than any other remedy. The a priori reasoning is sound, being based on the proven value of a lubricant such as graphite in reducing wear on metal dies. The lack of similar success with the use of a lubricant in the bore of gun may be due either to the operation of other more powerful causes of erosion or else to improper

^{100/} Lt. B. D. Mills, personal communication.

application of the lubricant. In this latter respect the "J" band having cannellures at the front end, which is discussed in Sec. 122, would seem to represent about the best means of applying a lubricant to the bore surface at the point of contact between the rifling and the rotating band.

CHAPTER XIII. EFFECT ON EROSION OF
LEAKAGE OF GAS PAST THE PROJECTILE

114. Theory of gas leakage

Although doubts have often been expressed as to how well the rotating band performs its function of obturating the bore, there seems to have been no systematic experimentation to determine whether it does or does not. Consequently, most of the writings concerning the influence of gas leakage on erosion have been speculative. Lanfroy [1885] and Bourgoin [1913] supposed that this leakage takes place through a crescent-shaped opening between the projectile and the bore, caused by dilation of the bore by the pressure of the powder gases. Vieille [1901], who was the leading exponent of the theory of gas leakage, supposed that it takes place principally through the small openings that result from failure of the rotating band to mold itself into the fine cracks on the surface of the bore (Sec. 70). He argued that the particular openings through which leakage occurs change from moment to moment as the rotating band moves forward; and that therefore it is only at the breech end of the bore that the rotating band is moving slowly enough for a given set of cracks to remain in action long enough to cause much erosion.

Charbonnier [1922, pp. 1004-1005], on the other hand, who opposed Vieille's theory, stated that projectiles fired without rotating bands gave the same velocity and pressure as was obtained with the same kind of projectile fired with bands. He claimed that

the same was true of a tubular projectile. He suggested that these phenomena indicated that as the projectile moves forward it carries with it an annulus of gas that acts as an obturator.

The best exposition of the objections to the theory of gas leakage was given by Alger [1910] in a paper written in reply to the one by Yarnell [1910] mentioned in the next section. He pointed out five objections to the theory, which may be summarized as follows: (i) the rate of wear of the smooth bore just at the rear of the rotating band is the same as that of the bottoms of the grooves at the origin of rifling; (ii) the lands erode twice as rapidly as the grooves; (iii) the opportunity for gas leakage should be greater halfway down the bore, because of wearing of the copper rotating band, than at the beginning of travel; (iv) the erosive effect of the gas that escapes past the projectile depends solely on the temperature and pressure of that gas, which conditions are the same in low-powered and high-powered guns firing the same kind of powder at the same maximum pressure, although these guns erode at different rates; and (v) the rotating bands of fired projectiles show no erosion.

115. Vent plug experiments

The erosion vent plug experiments performed by Vieille [Sec. 94(a)] were offered as evidence of the erosive effects of hot powder gases rushing through a small opening with a high velocity. Neither he nor Yarnell [1910], who espoused Vieille's theory and who reported additional erosion vent plug experiments, performed

any other experiments that more closely simulated the conditions in a gun.

A special vent plug experiment reported by Yarnell consisted of placing a can containing water on the inside of the chamber in such a manner that the water was forced out through two pinholes into the top of the chamber near the vent. He found that in this way the erosion of the vent plug was reduced to a third of its former value. He suggested that in a gun, erosion similarly might be reduced by having a circular receptacle containing water -- or other liquid -- at the rear of the projectile so that it would burst upon the shock of firing and would permit the water to seal the bore before and shortly after the projectile begins to move. Yarnell suggested that "as the necessity for such a seal exists for an exceedingly small fraction of a second, not much liquid would be required, and its high latent heat would effectively cool such small percentage of the total volume of gas as would escape past the projectile." There is no record that Yarnell's suggestion has ever been tried.

116. Photography of gas leakage^{101/}

High-speed photographs of a large projectile coming out of the muzzle of a gun were cited by Dr. L. T. E. Thompson^{102/} as supporting evidence that leakage of gas is not an important factor in

^{101/} Photographs of the gas that leaks past a rifle bullet when fired into a vacuum are being taken at the Geophysical Laboratory.

^{102/} Personal communication, September 1941.

erosion. These photographs show that only a "small" amount of gas escapes ahead of the projectile in comparison with what comes out behind it; but inasmuch as there is no way to estimate the actual quantity of this gas, the evidence is not convincing.

117. Escape of gas through holes drilled in the shot

Greaves, Abram and Rees [1929, p. 119] described an experiment that caused them to conclude that leakage of gas past the projectile was a negligible factor in erosion. Inasmuch as it represents about the most thorough investigation of the subject that has been made, their description is quoted in full:

It has been suggested by Vieille that not only is scoring due to escape of gas past the driving band, but that normal erosion is also due to such escape through the minute channels existing in the cracked surface layer. It is a matter of importance to determine the minimum size of orifice through which gas can pass without undergoing sufficient cooling to render it inactive as an erosive agent. Two 18-pdr. proof shot were drilled longitudinally, one with a central axial hole 0.5 in. in diameter, and the other with four holes each 0.25 in. in diameter, spaced symmetrically relative to the axis of the shot and to each other. The two shot were then fired under the normal conditions adopted for solid 18-pdr. proof shot, with the following results:

18-pdr. Proof Shot	Weight of Projectile	Muzzle Velocity (ft/sec)	Maximum Pressure (tons/in. ²)
Solid	18 lb, 8 oz	1677	13.65
Drilled with hole 0.5 in. in diam.	18 lb, 1 $\frac{1}{2}$ oz	1602	12.35
Drilled with 4 holes 0.25 in. in diam.	18 lb, 1 $\frac{1}{2}$ oz	1607	12.65

There was thus a decrease in recorded pressures and muzzle velocities relative to those obtained for solid shot.

The fired shot was sectioned. Microscopical examination of the metal in the neighborhood of the holes showed the presence of a hardened slowly-etching surface layer. The structure at a position near the nose of the shot drilled with four holes is shown in Fig. 16 (Plate IV). The depth of this hardened skin appeared to be constant throughout the length of the shot, and was 0.0034 in. for each shot. Brinell hardness measurements made with a 1-mm ball and 30-kg load on the bore surface of the drilled holes gave 341 in comparison to 220, the normal hardness of the material of the proof shot.

It was thought desirable to employ a smaller orifice, but a hole much less than 0.25 in. in diameter could not be bored through the full length of a proof shot. Two 18-pdr. proof shot were therefore drilled with axial holes 0.5 in. in diameter. The forward end of these holes was then fitted with a plug of annealed 0.8-percent carbon steel. This steel (the same type as was used for the cylinders subjected to chamber conditions during firing) was chosen because it is sensitive to the formation of a hardened skin and has poor resistance to erosion. The plug in one shot was drilled with an axial hole 2 mm in diameter, while the other was drilled longitudinally with 4 holes each 2 mm in diameter:

18-pdr. Proof Shot	Weight of Projectile	Muzzle Velocity (ft/sec)	Maximum Pressure (tons/in ²)
Solid shot	18 lb, 8 oz	1672	13.40
Shot fitted with plug with 1 hole, 2 mm in diam.	18 lb, 4 oz	1668	13.35
Shot fitted with plug with 4 holes, 2 mm in diam.	18 lb, 3 $\frac{1}{2}$ oz	1659	13.45

There was thus no diminution in maximum pressure, and only a slight loss in muzzle velocity.

The plugs were weighed before and after the proof shot had been fired; the loss of weight on firing was 0.180 gm for the plug containing one hole, and 0.233 gm for that with four holes. As the plugs suffered some slight abrasion in the sand bay, these figures may be rather too high, but evidence of the passage of propellant gases through the plugs was afforded by the fact

that along all the holes there was a slowly-etching hardened layer, which appeared to be of a constant depth of 0.0022 in. throughout the length of the plugs.

In order to ascertain whether there had been any escape of gas past the driving band, the surface of the shot was examined by etching, but there was no trace of a hardened skin due to gas-washing. Thus, these experiments, while they show that gas passes through a 2-mm orifice in the proof shot at some time during its passage down the bore, fail to indicate (in the case of a new 18-pdr. gun, at least) that there is any escape of propellant gases past the driving band during the initial stages of motion.

118. Gas leakage in a worn gun

As a continuation of the experiment just described, Greaves, Abram and Rees sought for evidence of gas leakage in a worn gun.

They reported as follows:

Some 4-in. proof shot fired in a worn 4-in. Mark V gun (mean wear at 1 in. from commencement of rifling, 0.039 in.) were examined. One of these showed a hardened skin (maximum thickness, 0.0010 in.) produced by gas-washing forward of the driving band. The driving band itself showed some signs of gas-washing. Four other shot fired in the same gun showed no hardened skin on the side of the shot. It seems, therefore, that the formation of a hardened skin, indicating gas-washing, on the projectile forward of the driving band, is not a necessary consequence of the worn condition of the bore (except possibly when scoring is already very pronounced), but is fortuitous and due to occasional faulty ramming or bad centering of the projectile in the gun. In a worn quick-firing gun firing fixed ammunition, however, the same efficiency of obturation could not be obtained.

119. Undersize rotating bands

In a recent experiment with rotating bands, projectiles having bands that differed in diameter were fired with single-base powder from two new 37-mm guns. After 800 rounds, each gun had eroded only very slightly; there was an increase in diameter of 0.005 in.

across the lands at the origin. The advance of the forcing cone was also essentially the same -- 0.035 in. for the large bands and 0.045 in. for the small ones. This result, which by itself would have been inconclusive, assumes new significance upon comparison with the result obtained when some of the same projectiles having rotating bands of normal diameter were fired from another new gun with double-base instead of single-base powder. At the end of 800 rounds this gun had eroded 0.014 in. at the origin and the forcing cone had advanced 0.20 in. Hence it may be concluded that the use of the small-diameter rotating bands, the diameters of which were slightly less than that of the grooves, had far less effect on the erosion of one of these 37-mm guns than the use of double-base powder compared with single-base [Ord. Dept., 1941].

120. Obturation by bullets

The obturating action of a small arms bullet is different from that of a banded projectile, for the whole jacket of the bullet acts as the rotating band. In the case of a lead-core bullet, obturation is aided by the "upsetting" of the bullet, that is, the increase of diameter caused by the sudden application of the accelerating force of the powder gases. The increased erosion that armor-piercing bullets are supposed to cause may be due to the lack of upsetting and hence to poorer obturation.

The use of a bullet that is a force-fit in the throat of a rifle just behind the forcing cone is reputed to eliminate erosion.

Mr. Niedner, of the Niedner Rifle Manufacturing Company, once told Mr. J. C. Gray, Ordnance Engineer of the Ordnance Department, that Mr. Mann, the amateur rifle expert, fired such bullets about 1915, and found no erosion of a caliber .25 rifle after 15,000 rounds.^{103/} It is not known whether a control test was made with normal bullets, and so it is questionable whether the erosion of a rifle of this small caliber could have been detected after that number of rounds.

121. Gas checks

Some experimental firings have been made with projectiles having special obturators or gas checks attached to them. Thus different modifications of a device invented by J. H. Brown were tested at Aberdeen Proving Ground from 1907 to 1911, without any marked decrease in erosion having been noted. Another obturator that was tested at Aberdeen was reported [Feltman, 1929] to have increased rather than decreased the erosion. The exact design of the device was not given in the report of the firing, but it seems to have consisted of some sort of cardboard wad at the base of a 3-in. projectile. The increased erosion was ascribed to the "sandpapering effect" of the bits of cardboard that were blown down the bore.

122. Rotating band with forward gas seal

If obturation by the rotating band is important, then a very sensible suggestion concerning the position of the gas seal is

^{103/} J. C. Gray, personal communication, 1941.

that made recently by Commander F. G. L. Johnson, (British) Royal Navy (retired). In the "J" band that he has patented, Johnson [1942] claims that the lubricated seal formed by the front end of the rotating band is unaffected by the dilation of the bore of the gun by the gas pressure. This seal is obtained by having several narrow cannellures which are cut in the front end of the band filled with a heavy grease ("Tropilene E," melting point 320°F). The cannellures are close together, so that "when the shell is loaded, the front two or three ribs [of copper that separate the cannellures] are deformed to the rear due to contact with the band seating, and grease is extruded, thus creating a gas-tight joint. As the lands cut through the ribs and grooves during engraving, they force the grease in a circumferential direction, which action has the beneficial effect of forcing the portions of ribs located in the rifling grooves to the front, thus keeping them in close contact with the bottom of the groove to maintain the seal." Commander Johnson stated that firing tests, of which he gave no details, have substantiated his claims, and that the British Ordnance authorities are giving serious consideration to his proposal.

Somewhat the same end is achieved by certain features of the so-called "R. D. System of Rifling" (Sec. 126), which has been developed recently by Colonel G. O. C. Probert and others in the Research Department of Woolwich Arsenal. A projectile having two bands is used and the forcing cone is moved forward slightly. The rear band, which fits tightly in the smooth cylindrical throat of the gun, is supposed to seal the bore while the front band is being

engraved. Then, after the rear band has been engraved, the front band can continue to make the gas seal even if the bore is dilated at the rear band. The R. D. System of Rifling has been tried recently with considerable success in the reduction of erosion. Thus, in two quick-firing 3.7-in. antiaircraft guns with muzzle velocities of about 3400 ft/sec the maximum erosion in the one of conventional design after 80 rounds was 0.073 in., whereas in the modified gun it was only 0.048 in. after 80 rounds. The other feature of this design, as will be described in Sec. 125(d), is that the effect of erosion on ballistic performance is minimized [Naval Intell., 1942].

CHAPTER XIV. LIFE OF GUNS

123. The life of a gun is not a fixed mathematical quantity but is a statistical average, analogous to a life expectancy for a human being. Because of variations in the manner of their use, several guns of the same kind will have widely different lives. Some of these variations, such as rate of fire, amount of charge and kind of powder, have already been discussed in Chap. XII, but it is likely that there are other less well-defined conditions that also affect the life of guns in service.

124. Formula for equivalent service rounds

One of the most important variations of firing conditions is the amount of charge, because scarcely any erosion occurs when a gun is fired with a charge considerably below the "service charge" for which it was designed. Sometimes at the beginning of a firing a reduced charge is used for the first round or two, just for the purpose of warming the gun. In the U.S. Navy, for the purpose of tabulation, such warming rounds or any other round fired at other than the standard charge are converted into equivalent service rounds -- E.S.R. -- by means of the formula,

$$\text{E.S.R.} = (W/W_s)^6, \quad (\text{XIV-1a})$$

where W is the weight of the charge actually used and W_s is the weight of the service charge.

Another formula for the same purpose was developed by Feltman^{104/} empirically on the basis of the values of E.S.R. for various charges of nitrocellulose powders as given in various British firing tables and then checked against the values of E.S.R. used in the U.S. Navy. This formula, which is intended to take into account the effect of the reduced pressure that accompanies the decrease in weight of charge, is

$$\text{E.S.R.} = (V/V_s)^p, \quad (\text{XIV-1b})$$

where V is the muzzle velocity at which the gun was fired, V_s is the standard muzzle velocity, and p is an empirical constant taken equal to 7 when $V/V_s \geq 0.6$ and equal to 5.5 when $V/V_s < 0.6$. Both these formulas indicate a large increase in the life of a gun when it is fired with reduced charges. For example, during the acceptance test of some 37-mm powder a charge of 4.00 oz gave a maximum pressure of 21,500 lb/in² and a muzzle velocity of 2339 ft/sec, whereas a service round required 4.70 oz of the same powder to give the standard velocity of 2596 ft/sec (nominally 2600 ft/sec) with a maximum pressure of 28,600 lb/in². The round fired at reduced charge, therefore, was 0.4 E.S.R. according to Eq. (XIV-1a) and 0.5 E.S.R. according to Eq. (XIV-1b). Correspondingly, a round fired in the same gun with a charge of 4.94 oz of the same powder, which gave a muzzle velocity of 2684 ft/sec at a maximum pressure of 31,450 lb/in², was equivalent to 1.35 E.S.R. according to

^{104/} S. Feltman, Ballistics Section, Ordnance Department, personal communication.

Eq. (XIV-1a) and to 1.26 E.S.R. according to Eq. (XIV-1b). Thus Eq. (XIV-1b) indicates less of a variation from unity than does Eq. (XIV-1a), for charges either more or less than standard.

125. Criteria for end of life

Another complication in considering the life of a gun is that there is no unambiguous point in its history that is considered the end of its life. As erosion proceeds during use, the muzzle velocity gradually decreases, because of the advance of the forcing cone [see Sec. 125(d)], and also the dispersion of the shots at a given target increases. However, the decision as to just how much of a decrease in muzzle velocity or how large a dispersion can be tolerated is purely arbitrary. Moreover, this decision depends to a certain extent on the tactical purpose of the gun.

(a) Loss of muzzle velocity. -- Some writers have suggested that the time when a gun has lost 10 percent of its initial muzzle velocity should be considered the end of its life. This criterion, according to Lintès [1935] corresponds to a loss of 50 percent in precision and an appreciable diminution of range. A somewhat more severe criterion^{104a/} is actually used now by the Small Arms Division of the Ordnance Department with respect to the caliber .50 machine gun. When the muzzle velocity of this gun -- which is 2800 ft/sec when the gun is new -- has decreased 200 ft/sec, the gun is considered to be at the end of its accuracy life. This usually occurs

^{104a/} Capt. C. E. Balleisen, personal communication, August 1942.

after about 8000 rounds. Further firing would be possible, but the sights would have to be adjusted for the decreased velocity, which causes the gun to hit below the target.

(b) Dispersion in range. -- In the U.S. Navy the mean dispersion of five successive shots fired at a target at a given range is usually used as the basis of the criterion^{105/} for determining the end of life of a gun. When this mean dispersion exceeds 0.5 percent of the range for a major-caliber gun -- 8 in. and larger -- or 1 percent for a smaller gun, the end of accuracy life is usually considered to have been reached. There is no regulation, however, on this question, and not all guns are rated in this way.

(c) Enlargement of the bore. -- The loss of muzzle velocity, and hence the life of a gun, has frequently been correlated with the extent of erosion as expressed by the increase in diameter of the lands at the "origin of rifling" (really at the front end of the forcing cone) or at a point 1 in. in front of the true origin of rifling. The decrease in muzzle velocity for most guns is a linear function of the increase in diameter, the constant of proportionality being a function of the caliber and muzzle energy of the gun. Manning [1919], for instance, found that in the expression,

$$\Delta V = 100 Ky, \quad (\text{XIV-2})$$

where ΔV is the loss of muzzle velocity in feet per second and y is

^{105/} Lt. B. D. Mills, personal communication, August 1942.

the increase in diameter of the lands in inches at a point 1 in. in front of the origin, the empirical constant K varied from 2.3 to 12.1 for eight guns of different calibers, being larger for small calibers.

Practical use is made of this relation at proving grounds in connection with so-called "work guns," which are used for acceptance tests of powder. The end result desired is the relation between muzzle velocity and weight of charge when the powder is fired in a new gun. A given weight of charge fired in an eroded work gun gives a somewhat lower muzzle velocity than would have been obtained in a new gun. The muzzle velocity characteristic of a new gun is obtained by an extrapolation based on the measured erosion of the work gun and the relation between muzzle velocity and the increase in diameter at the origin.

The end of life of some U.S. Navy guns is considered to be reached when the enlargement at 1 in. in front of the origin of rifling has reached a certain magnitude. For 14-in./50-caliber guns the permissible maximum enlargement is 0.4 in. For such high-powered guns the application of this criterion is complicated by the fact that they are subject to considerable muzzle erosion, which also affects the accuracy life; and therefore, as already mentioned in Sec. 98, a duplex criterion involving erosion at both ends of the bore is used.

(d) Advance of the forcing cone. -- Another direct measure of erosion that has been correlated with gun performance is the advance of the forcing cone (Sec. 10) as measured with a plug gage. This

measurement is much simpler than that of the increase in diameter across the lands and therefore is more readily performed in the field. The 40-mm Bofors gun now being used by the U.S. Services, for instance, is supplied with such a gage.

The advance of the forcing cone is reflected in the performance of the gun. In an eroded gun using separate-loading ammunition the projectile can be seated correspondingly farther forward in the bore. Thus for some worn 155-mm guns, G.P.F., when the forcing cone had advanced 4.0 in., the seating had advanced about 2.5 in., and when the forcing cone had advanced 8.0 in., the seating had advanced 6.75 in. [Weyher, 1939]. The decrease in the density of loading that results from the advance of the seating of a separately loaded projectile causes a decrease in the pressure and velocity. The reduced travel of the projectile also decreases the velocity slightly. In a case gun the projectile remains in the cartridge case until the powder is ignited; but as soon as a little pressure is developed, the projectile is able to move forward nearly the whole distance that the forcing cone is advanced. This free run-up has about the same effect on the maximum pressure and the muzzle velocity as the advance of seating in a bag gun. In addition, it tends to cause stripping of the rotating band [Sec. 125(e)].

The relation between loss of muzzle velocity and advance of the forcing cone is nonlinear for most guns; but in spite of this, the advance of the forcing cone can be used as a criterion of the end of life. This was done in World War I by the French and subsequently by the A.E.F. when using French guns. For the 155-mm gun,

for instance, the criterion was an advance of the forcing cone of 150 mm. It had been found that beyond this point, which was reached after 3500 ± 500 rounds, a maximum of 400 more rounds could be fired [Ord. Dept., 1920]. This criterion was confirmed by a later study of the characteristics of a number of 155-mm guns at different stages of erosion (see Table XVI, Sec. 61).

(e) Stripping of the rotating band. -- Any arbitrary criterion of the life of a gun, such as the enlargement at the origin or the advance of the forcing cone, has the disadvantage that frequently during actual service a gun can still be fired after the measured erosion indicates that it has reached the end of life. The gun will not perform as satisfactorily as a less worn one, but it will be much better than no gun at all. This situation occurred during World War I, when the French twice found it expedient to relax the regulations concerning the replacement of 75-mm guns in the field.

Such continued use of an eroded gun cannot go on indefinitely, however, when the gun fires fixed ammunition. Eventually the forcing cone is advanced to such an extent that the projectile attains so high a velocity by the time its rotating band hits the forcing cone that the upper surface of the band is sheared off by the rifling and the projectile is not rotated. When this occurs the projectile tumbles in flight. This stage of erosion of the gun truly represents the end of its life, for accurate firing is no longer possible. It has frequently been used as the criterion of the end of accuracy life in erosion tests of small arms, the occurrence of keyholes in a close target giving the indication of when it happens (see Sec. 82).

(f) Economic life. -- An artificial criterion of the end of life of a gun has been considered in at least two recent erosion studies of army guns, namely, those of the 155-mm gun (Sec. 61) and of the 4.7-in. gun [Sec. 105(b)]. This criterion, which is called the economic life, is defined as the maximum number of rounds that can be fired at a minimum cost per round, taking into account the replacement cost of the gun and the increasing cost of ammunition per hit as the accuracy decreases because of erosion. This criterion is without real significance, because it presupposes an abundant supply of guns. In effect, the replacement cost of a gun is infinite during an engagement when the replacement gun is not available.

126. The R.D. system of rifling and banding^{106/}

The basic feature of the special design of rifling and of projectile banding which is known as the "Probert" or "R.D. System" is an attempt to prolong the accuracy life of a gun by minimizing the effects of erosion as well as by reducing the erosion itself. To this end the original contour of the bore is made to approximate that of a somewhat eroded barrel and then the projectile is designed to function well in such a bore, by reducing the extent to which its resistance to movement at the beginning of travel changes as erosion proceeds.

^{106/} See Sec. 136 for the decrease of muzzle erosion observed with the R.D. system.

This is accomplished by a combination of (i) making the initial resistance to movement as small as possible in a new gun and (ii) making the proportional decrease of resistance for a given increase of wear as small as possible. The former end is achieved by making the slope of the forcing cone as small as is consistent with the need for sealing the gas as quickly as possible and by reducing to the minimum the quantity of copper that has to be displaced when the shot starts to move. The latter end is achieved by making the diameter of the upstanding copper in the rotating band exceed that of the bore by the greatest practicable amount in order to dwarf the effect of the wear in the bore on the rate at which this copper is displaced after shot travel. An attempt is made to reduce the erosion itself both by improving the gas seal (Sec. 122) and by placing the origin of rifling farther from the mouth of the cartridge case.

The few trials that have been made of this system have shown very favorable results. Thus, in the two quick-firing 3.7-in. guns mentioned in Sec. 122, there was a marked difference in the effect of erosion on muzzle velocity. Whereas in the conventional gun the velocity had decreased 94 ft/sec after 81 rounds, in the modified gun it actually increased 63 ft/sec after 80 rounds, even though the bore of the latter gun had been increased two-thirds as much as that of the former.

127. Navy formula for the life of guns^{107/}

A general formula for erosion in U.S. Navy guns was proposed by Captain G. L. Schuyler [Bur. Ord., 1928]. As a preliminary step to developing tabulated numerical functions of the several variables on which the life of a gun depends, he expressed the average bore enlargement per round, \underline{E} , during the first 100 rounds by the equation

$$\log E = \log A - 1.54 \log l - 16.4 \log d + 12.0 \log V + 6.0 \log M, \text{ (XIV-3)}$$

where \underline{E} is measured in inches at a point 1 in. in front of the origin of rifling, \underline{l} is the length of the gun in calibers, \underline{d} is the diameter of the bore in inches, \underline{V} is the muzzle velocity in feet per second, \underline{M} is the projectile weight in pounds, and \underline{A} is an empirical constant. This constant and the other four in the equation were evaluated from data for 12 guns that ranged in caliber from 3 to 16 in., in length from 25 to 105 calibers, in muzzle velocity from 2200 to 4800 ft/sec, and in projectile weight from 10 to 3100 lb.

The observed bore enlargement of naval guns at the end of life was combined [Bur. Ord., 1935] with Eq. (XIV-3) to yield the following formula for the accuracy life of a gun in E.S.R.:

$$N = 0.1080 d^{2/3} E^{-1} \quad \text{(XIV-4)}$$

This formula was subsequently modified [Bur. Ord., 1939b], in order to take into account recently acquired experimental evidence of the

^{107/} See Sec. 130 for a comparison of this formula with others.

lack of effect of the weight of the projectile on erosion when the muzzle velocity is constant and to permit the calculations to be performed by means of equations instead of tabulations. The modified formula is

$$\log N = 6.35 + 0.03 l - 0.82 \log d - 0.001611 V_s, \quad (\text{XIV-5})$$

where

$$V_s = V\sqrt{M/M_s}, \quad M_s = \frac{1}{2}d^3,$$

and the other symbols have the same meaning as in Eq. (XIV-3). Values of the accuracy lives of U.S. Navy guns of various calibers computed according to this formula agreed within about 15 percent on the average with estimates made by the Naval Proving Ground, based on firing experience. Values of N calculated from Eq. (XIV-5) were arranged in the form of an alinement chart [Bur. Ord., 1939b] by means of which the calculation can be carried out quickly with an accuracy of about 2 percent.

128. Kent's formula for the life of guns^{108/}

The following formula for the life of guns, which is distinguished from the Navy formula in that it involves the maximum pressure, was developed by Kent [1939]:

$$N = Ad^a k^b P^c, \quad (\text{XIV-6})$$

^{108/} See Sec. 130 for a comparison of this formula with others.

where \underline{N} is the accuracy life in rounds, \underline{d} is the caliber in inches, $K [= \frac{1}{2}MV^2]$ is the muzzle energy in foot pounds, \underline{P} is the maximum pressure in pounds per square inch, and \underline{A} , \underline{a} , \underline{b} and \underline{c} are empirical constants. These constants were determined by the method of least squares from data for a number of Navy guns. When the values thus computed are used, the formula becomes

$$N = 10.26 \times 10^{19} d^{3.575} K^{-1.705} P^{-1.761}. \quad (\text{XIV-7})$$

Kent used this formula to calculate the accuracy lives of a number of Army guns and then compared the values so determined with those given in the Ordnance Proof Manual [Ord. Dept., 1936]. The calculated values were consistently lower than the latter estimates. Kent [1939] suggested that "this discrepancy arises mainly from failure to allow for the rounds fired with reduced charges in the estimated lives of the guns given in the Proof Manual."

129. Other formulas for the life of guns

(a) Jones' formula^{108a/} -- One of the earliest attempts to develop a formula for the life of guns was made by Jones [1911] on the basis of an analysis of the heat transferred from the powder to the bore surface in the region of the position of maximum pressure. He proposed the relation,

$$N = \frac{A}{V^2 d(d-2)P^{1.7}} \quad (\text{XIV-8})$$

^{108a/} See Sec. 130 for a comparison of this formula with others.

where the symbols have the same meaning as in Eq. (XIV-6). Jones proposed the value $A = 1.24 \times 10^{18}$ for guns firing cordite M.D.; Kent [1939] has remarked that the French have used a value of A that is 50 percent greater for guns firing nitrocellulose powder. These values of the constant are for the purpose of giving an estimate of the probable life before relining in peacetime, Jones having suggested that the actual life of serviceability would be 30 to 40 percent greater. Even the lower value of A , however, gives high estimates of life, as is shown in Table XXVIII, Sec. 130.

(b) Justrow's formula. -- As a result of a detailed consideration of the many factors that affect the life of guns, Justrow [1923, Eq. 20] proposed the following formula for the number of shots that can be fired from a gun before the initial muzzle velocity is decreased by 10 percent:

$$N = (xy/d^2)(AV^2/l)(G\epsilon/\mu k), \quad (\text{XIV-9})$$

where x is an empirical function of the maximum pressure, y is an empirical function of the caliber, d is the diameter of the bore, A is a factor of proportionality for expressing the weight of the projectile in terms of the cube of the caliber, V is the muzzle velocity, and l is the length of the tube in calibers; $G\epsilon$ is proportional to the tensile strength of the tube material and μk to that of the driving band, but the exact physical significance of these symbols was not stated.

Justrow published graphs for x -- which varied from 0 to 1.25 -- and for y -- which varied from 0 to 1.0 -- but did not tell how they

were derived. He gave a table [Justrow, 1923, Table VI] showing calculated values for the lives of guns of different calibers and lengths, having different maximum pressures, velocities and weights of projectiles; but he gave no indication of how closely these values agreed with experience.

(c) The formula of Lintès. -- Another attempt to include the physical properties of the metal of the tube as factors in the life of a gun was made by Lintès [1935, Eq. (28)]. Adopting the criterion that the end of life is characterized by a 10-percent loss of muzzle velocity, he deduced that

$$N = A(\tilde{\omega}/\omega_0)(d^2/K)(R^2/e), \quad (\text{XIV-10})$$

where A is a factor of proportionality, $\tilde{\omega}/\omega_0$ is the ratio of the weight of charge to the initial surface of the charge, d is the diameter of the bore, $K[= \frac{1}{2}MV^2]$ is the kinetic energy of the projectile, $R(\text{kg/mm}^2)$ is the elastic limit of the metal of the tube, and e is its modulus of elasticity. Lintès found empirically that A is 700 for bag guns and 350 for case guns; and since $\tilde{\omega}/\omega_0$ usually is 0.5, the formula is simplified to $N = 175 d^2 R^2 / Ke$ for case guns. He stated that in rapid fire, N is reduced in the ratio n_0/n , where n_0 is the normal rate of fire and n is the increased rate. The examples of the application of this formula which Lintès cited showed reasonably good agreement between the calculated and the observed values for the length of life.

130. Comparison of estimates of lives of guns

The lives of a few typical unplated guns firing nitrocellulose powder have been computed for the present report by Eqs. (XIV-5), (XIV-7) and (XIV-8), with the results listed in Table XXVIII. The Navy formula [Eq. (XIV-5)] was not intended to be used for calibers smaller than 3-in.; and Jones formula [Eq. (XIV-8)] obviously cannot be used for small calibers because of the term $(d-2)$. Similar calculations using Eqs. (XIV-9) and (XIV-10) were not made because of lack of data concerning the physical properties of the gun steels.

The remarkably close agreement between experience and the estimates for the life of the 4.7-in. gun T2 given by Eq. (XIV-5) and (XIV-7) is probably a coincidence, inasmuch as the two equations show systematic deviations from actual values for different calibers. Both of them tend to give somewhat low estimates, those computed by Kent's formula [Eq. (XIV-7)] being in general lower than those computed by the Navy formula [Eq. (XIV-5)]. Except for the 155-mm, 14-in. and 16-in. guns, the estimates by the Jones' formula [Eq. (XIV-8)] are much too high.

All three formulas indicate the general inverse dependence of the life of a gun on the muzzle energy. However, the exact functional relation between them and the extent to which it is modified by other factors are not adequately expressed by any of these formulas.

Table XXVIII. Calculated accuracy lives of guns.

Gun	Velocity V (ft/sec)	Pressure P (lb/in. ²)	Caliber d (in.)	Length L (calibers)	Proj. Wt. M (lb)	Muzzle Energy, E (ft lb)	Accuracy Life, N (rds)		
							Equation Number XIV-5 XIV-7 XIV-8	Exp. *	
Caliber .50	2800	48 000	0.5	72	0.101	1.24 × 10 ⁴	--	5174	--
37-mm M1A2	2600	36 000	1.457	53.5	1.34	1.38 × 10 ⁵	--	6161	--
75-mm M1897	1950	36 000	2.95	34.5	14.6	8.67 × 10 ⁵	4365	3490	20850
4.7-in. T2	3150	38 000	4.7	60	50.0	7.76 × 10 ⁶	398	400	1613
5-in./25 Mk X	2175	38 000	5.0	25	51.7	3.96 × 10 ⁶	2203	1669	2862
155-mm G.P.F.	2400	28 000	6.1	38	95.8	8.62 × 10 ⁶	1995	1452	2370
8-in. Mk VI	2750	38 000	8.0	45	261.8	3.09 × 10 ⁷	518	226	507
8-in. Mk IX	2800	38 000	8.0	55	260.0	3.18 × 10 ⁷	269	253	560
14-in./50 Mk IV	2800	38 000	14.0	50	1400.0	1.71 × 10 ⁸	230	91	140
16-in. M191M3	2700	38 000	16.0	50	2340.0	2.67 × 10 ⁸	166	77	124

* This column lists the life based on experience, according to the following sources of information:
 caliber .50, Capt. C. E. Balleisen, personal communication; 37-mm, Ord. Dept. [1941]; 75-mm, Ord. Dept. [1936]; 4.7-in., S. Feltman, personal communication; 5-in./25 Mk X, Bur. Ord. [1942]; 155-mm, Weyher [1939]; 8-in. Mk IX and 14-in., Bur. Ord. [1942]; 16-in., Ord. Dept. [1936].

CHAPTER XV. THEORIES OF THE MECHANISM OF EROSION

131. The foregoing account of the erosion of guns reveals that it is a complex phenomenon. The various theories of the mechanism of erosion^{109/} are attempts to explain in specific terms the following generalized description of that phenomenon: during the firing of a gun a physical or chemical agent, or a combination of such agents, loosens some of the steel on the surface of the bore and then either the same or some other agent removes it from the bore. Whereas each theory has emphasized the alleged effectiveness of some particular agent or agents, the convincing evidence adduced in partial confirmation of each of them lends weight to the opinion, already expressed by earlier writers [for instance, de Bruin and de Pauw, 1929; Kosting, 1939a] that the true explanation of erosion must take account of more than one causative factor.

In the present chapter^{110/} the several theories are classified with respect to the agents proposed, in an attempt to summarize some of the facts presented in the earlier chapters and to point out deficiencies in our knowledge that need to be supplied before the mechanism of erosion will be understood. This classification is most conveniently made with respect to the agents responsible for

^{109/} A convenient review of the principal theories was given by de Bruin [1930].

^{110/} At some time in the future it is intended to prepare a more complete analysis of these theories, with consideration being given to the additional information acquired in recent investigations of erosion.

loosening the material from the surface of the bore. After the material has been loosened, it is considered to be either blown out of the bore by the powder gases or else rubbed off the surface of the bore by the rotating band.

132. Melting of the bore surface

The quantity of heat liberated inside a gun is a major factor in determining the amount of erosion, as is demonstrated by the fact that in a given gun the amount of erosion is greatly increased either by an increase in the weight of the powder charge or by the use of the same weight of a powder having a higher heat of explosion. It has not yet been possible to express quantitatively either how much of the heat liberated inside a gun is absorbed by each portion of the surface of the bore or to what temperature that surface is raised by the heat absorbed. Hence there is yet no proof that the surface is melted -- which is the simplest hypothesis to account for the loosening of metal from the surface of the bore -- for raising the temperature of the bore surface may simply accelerate some other change.

The hypothesis that the surface of the bore is melted has usually been combined with the idea that the loosened material is swept out of the bore by the powder gases. Considerable difference of opinion, however, has arisen as to whether this supposed melting of the surface and removal of the melted layer is performed by small jets of gas escaping past the rotating band or by the main stream of gas moving down the bore behind the projectile. As

mentioned previously (Sec. 114), the gas leakage theory has had a long history, beginning with Lanfroy [1885] and continuing with Vieille [1901], Yarnell [1910], Bourgoin [1913] and Justrow [1923]. Charbonnier [1908, 1922], Alger [1910] and Jones [1911], among others, opposed this point of view very strenuously.

Greaves, Abram and Rees [1929], who also considered that during erosion a layer of molten metal is blown off the bore surface, implied that this was done by the main stream of gas. They did not, however, go as far as Charbonnier [1908, 1922] had gone in attributing erosion to a vena contracta effect of the stream of gas following the projectile. Létang [1922] and also Justrow [1923] calculated that a major part of the heating of the bore surface to its melting point was caused by the heat resulting from the work of engraving the rotating band.

Johnson [1942] combined the action of both gas leakage and the main stream of gas in his theory of erosion, according to which the escape of gas past the band heats the skin surface of the bore almost to the melting point before the projectile moves, so that after it has moved, the main stream of gas is able to erode a short section of the bore by fusion. Farther up the bore the surface is not eroded by the main gas stream because it has not been subjected to preheating by gas leaking past the band. This theory has the appeal of a compromise, but it has no more basis in terms of observational evidence than either of the separate theories relating to fusion of the bore surface; as yet there is not even proof that the bore surface reaches the melting point.

133. Abrasion by unburned powder

As part of his theory of the vena contracta, Charbonnier [1908, 1922] suggested that some of the erosion is caused by the scouring effect of unburned grains of powder which are swirled about by the gases. It is admitted that the powder grains are hard enough to act like a sand blast, but there is no experimental evidence that they do so. Kent [1941] pointed out that the escape of gas from the burning grains might form a cushion which would prevent violent contact between the grains and the bore surface. He suggested that a test of this idea might be obtained by comparing the rate of erosion of a gun fired with strip powder with that of one fired with grain powder of the same composition.

134. Cracking of the bore surface

The severe thermal stresses developed on the surface of the bore during the sudden heating followed by sudden cooling that occurs during firing have been analyzed by Tschernoff [1913], by Howe [1918], by de Sveshnikoff [1922] and by Justrow [1923] (see Sec. 70). Tschernoff in particular considered these stresses as the main cause of loosening material from the bore surface, whereas Howe and Justrow attributed to them merely secondary influence. Similarly, Vieille [1901] had ascribed to the cracks on the bore surface only a contributory effect that made leakage possible.

135. Chemical reaction between the bore surface and the powder gases

Intimately related to the cracking of the surface of the bore is the question of chemical reaction between the powder gases and the surface. Vieille [1901], on the basis of a microscopic examination by Osmond [1901] of an eroded gun, had concluded that the surface layer of steel was hardened by carburization, and that it cracked more readily because of this condition. The various investigations by Fay [1916, 1925], Howe [1918], Wheeler [1922], de Sveshnikoff [1925], Greaves, Abram and Rees [1929], Lester [1929a], Snair and Wood [1938] and Kosting [1939a, 1940] on the possibilities of the formation of a hardened layer on the surface of the bore by reaction with the powder gases have been summarized in Secs. 75 to 79. In spite of those extensive investigations, we are still ignorant of the nature of the altered layer on the surface of the bore, and therefore we cannot say definitely how great an influence chemical reaction between the bore surface and the powder gases may have on erosion.

An entirely different type of chemical reaction was suggested by Cole [1941]. He assumed "that gases under extreme pressure and high temperature approach the characteristics of dilute solutions" and that they are highly ionized, both because of thermal agitation and because of collisions. The alloying elements in the steel complete a galvanic couple, whereby iron is converted into an oxide film when the highly ionized gas comes into contact with the surface of the bore. An earlier suggestion of the possibility of oxidation had been made by Crawford [1937], who supposed that the

surface of the bore is covered by an adsorbed "film of one or more molecular layers of oxygen, which, when the surface reaches a critical temperature, is released and forms an oxide with the surface layer of the metal." The layer of oxide, according to both hypotheses, is swept away by the gases moving with high velocity.

136. Muzzle erosion

The foregoing discussion of causes of erosion has been limited to erosion in the region of the forcing cone. The cause of erosion at the muzzle is equally unknown. Three principal theories have been advanced to account for it. According to the first, which has already been mentioned (Sec. 47), muzzle erosion is simply the result of frictional wear between the projectile and the bore, although why the erosion decreases progressively away from the muzzle is not explained. This point of view seems to be current among students of the subject in the U.S. Army today.

The other two theories explain muzzle erosion as caused by the powder gases. Charbonnier [1922] pointed out that his vena contracta theory of erosion at the forcing cone applied equally well to erosion at the muzzle, where another discontinuity in the gas stream occurs. Thompson [1941], on the other hand, advanced the theory that muzzle erosion is caused by the jet of high-velocity gas that rushes through the annular orifice formed at the moment the rotating band breaks contact with the bore.

The remarkable reduction of muzzle erosion in guns using the R. D. system of rifling (Secs. 122 and 126) seems to discredit both the theories of frictional wear and of the vena contracta effect.

In the R. D. system [Naval Intell., 1942] the grooves decrease gradually in depth toward the muzzle, and for the last three calibers of its length the bore is smooth. The original purpose of this change was to erase the rifling marks from the rotating band in order to decrease the air resistance of the projectile in flight. Limited tests of guns rifled in this way, however, have given the unexpected result of almost complete absence of muzzle erosion. Thus the modified 3.7-in. quick-firing gun mentioned in Secs. 122 and 126 showed no erosion at the muzzle after 80 rounds, whereas the conventional gun fired under similar conditions showed an increase of diameter beginning about 27 calibers from the muzzle and increasing almost linearly to a maximum of 0.018 in. at the muzzle.

137. Summary

The one single feature of the mechanism of erosion to which all investigators have subscribed is that it is a dynamic phenomenon. Erosion occurs only when the bore surface is attacked by hot powder gases in motion, as was pointed out by Sir Andrew Noble [1906], one of the earliest students of the subject. Therefore, in order to achieve a true explanation of erosion, it will be necessary to understand in detail the physico-chemical changes that the material of the bore undergoes as it reacts with a rapidly changing environment during firing.

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