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NATIONAL DEFENSE RESEARCH COMMITTEE

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THE EROSION OF GUNS

Part One: Fundamentals of Ordnance Relating to Gun Erosion

by

John S. Burlew

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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 and elsewhere under the auspices of Section A.

Through arrangements made in July, 1941 with Brigadier General R. H. Somers, then Ordnance Department Liaison Officer with the National Defense Research Committee, the writer was given access to the confidential reports of the Ordnance Department dealing with gun erosion, for the purpose of preparing this report. The information gained during several months of work in the Ordnance Department Technical Library was supplemented by discussions with both officers and civilian personnel of the War and Navy Departments.

This report has been issued in two volumes. The present volume comprises Part One, on the fundamentals of ordnance relating to gun erosion. The second volume will comprise Part Two, on the characteristics of gun erosion. A bibliography and an author index appears in each volume, but the subject index appears only at the end of the second volume.

Acknowledgements. -- The writer is grateful for the friendly cooperation of the many persons who assisted him in gathering information. He is especially indebted to Mr. S. Feltman, Principal Ordnance Engineer of the Ballistic Section of the Technical Division, Industrial Service, Ordnance Department, who was a friendly mentor in matters of ordnance, to Mrs. S. H. Pendleton and her assistants in the Ordnance Department Technical Library, and to Mrs. R. E. Gibson, who helped collect data and who prepared the manuscript.

Distribution of copies of the report. -- The editorial staff of Division A completed preparation of this report for duplication on September 15, 1942. The initial distribution of copies was as follows:

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FUNDAMENTALS OF ORDNANCE RELATING TO GUN EROSION

PART TWO*

THE CHARACTERISTICS OF GUN EROSION

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*Part Two appears in a second volume designated as NDRC Report A-91.

FOREWORD

By L. H. Adams

Shortly after Section A of Division A was constituted for the purpose of attacking the problem of gun erosion and other aspects of hyper-velocity, and the facilities of the Geophysical Laboratory of the Carnegie Institution of Washington were made available for this work, Dr. John S. Burlew of the scientific staff of that laboratory was requested to prepare a report on gun erosion. It was realized that there existed a vast amount of factual material in this field and a large number of conflicting interpretations and conclusions relating to the observations. The intention was to have an outline of the subject that would be comprehensive but not necessarily exhaustive, and to include merely a cross-section of existing data together with an explanation of the terms used and a summary of the conclusions that have been drawn. Collecting and assembling the necessary information was a task of considerable magnitude, which would have been even greater but for the hearty cooperation and encouragement of various individuals in the Army and Navy and in other organizations.

The purpose of the report has been to provide the necessary ground work for planning investigations on the mechanism of gun erosion. A considerable portion of it has been available for some time to me and to other persons working on this problem. The program was first presented and discussed at the Conference on Gun Erosion held at Watertown Arsenal on October 15, 1941, at which representatives of the National Defense Research Committee as well as of various establishments of the Army and Navy were present. Since then the investigation of the mechanism of gun erosion has been going forward actively at the Geophysical Laboratory and elsewhere under the auspices of Section A. The present report, which in its completed form provides a convenient background for these investigations, does not include any of the results already obtained in them. Those results are being presented in a series of Division A memorandums and reports, the first few of which have already been issued or are in preparation, as mentioned in footnotes to the appropriate parts of the text of the present report.

Washington, D. C.
August 11, 1942.

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THE EROSION OF GUNS

Part One: Fundamentals of Ordnance

Relating to Gun Erosion*

CHAPTER I. INTRODUCTION

1. The present survey of the erosion of guns aims to collate the principal factual data on the subject and, in addition, to summarize the different theories that have been proposed to explain or to correlate these facts. Special care has been exercised to separate the facts from the various interpretations that may be placed upon them, since the latter in many instances depend on unverified assumptions. The sources of all information have been indicated in order that the reader may consult them for further details; for, although this survey attempts to be comprehensive, the treatment of the various items mentioned is not intended to be exhaustive.

2. Definitions

A gun consists essentially of a hollow metal tube having one end -- the breech -- tightly closed and having within it a projectile that is expelled with a high velocity from the open muzzle by the rapid expansion of the gases which are formed by the burning of the propellent powder placed in the chamber behind the projectile before firing. Erosion of a gun is the gradual removal of metal from the surface of the bore of the tube as a result of firing. It has been suggested that it is desirable to distinguish between the "erosion" caused by the hot powder gases and the mechanical "wear" caused by

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the movement of the projectile; but there is not yet enough evidence to permit this distinction.1/ Hence in the present discussion the inclusive term erosion will be used to refer to enlargement of the bore without implication as to the cause.

This enlargement of the bore radically affects the flight of the projectile. Erosion at the breech end of the tube decreases the range of the gun, and erosion at both ends decreases its accuracy. The two effects combine to determine the useful life of the gun. Some of the methods of estimating the life of guns from the extent of erosion are treated in Chap. XIV.

3. High muzzle velocity

Because the rate of erosion increases very rapidly with an increase of muzzle velocity, as will be illustrated in detail later (Sec.105), a muzzle velocity of about 3000 ft/sec is the upper limit that may be employed at present without decreasing the life of a gun too much. Actually, even most high-powered guns are rated at somewhat lower muzzle velocities.

1/ Dr. P.R. Kosting, of Watertown Arsenal, in commenting on this statement pointed out (private communication, Aug. 22, 1942) that "the phenomena accompanying the change in bore diameter at the muzzle end are different from those at the breech end," and in particular, that "metallographic studies reveal that there is a difference in the effect of service on the bore metal between the muzzle and breech end. In discussions of erosion one hears frequently of references to the wear at the muzzle end and the erosion at the breech end." The distinction that Kosting makes with respect to the phenomena is probably valid; but until we are certain that this difference is anything more than that caused by modification of the same agent by two different sets of local conditions, it seems unnecessary to introduce an extra term in referring to it. Conversations with Navy personnel have shown that they still use the term "muzzle erosion."

The depth of penetration of armor plate by a projectile increases as a function of the striking velocity of the projectile. At relatively low velocities -- up to about 2500 ft/sec -- the depth of penetration of a projectile is proportional to approximately the three-halves power of its striking velocity as is indicated by such empirical formulas as that of de Marre [1886][2/] which is still in use today [Naval Ordnance, 1939]. Whether this same relation holds true at velocities exceeding 2500 ft/sec is not known with certainty. It has been claimed that the phenomenon of penetration is different at hypervelocities -- greater than, say, 3500 ft/sec -- and that at such velocities projectiles made of lead or other soft metal will penetrate armor as well as steel projectiles. This opinion, which has not been substantiated as yet, was extravagantly insisted upon by Gerlich [1930, 1931, 1933], and it has been repeated even by Hayes [1938, p. 670]. Be that as it may, a gun firing at a muzzle velocity of nearly 5000 ft/sec would be an especially effective weapon against the armor carried by tanks, because in this way it would be possible to deliver a projectile having a striking velocity of over 3000 ft/sec at battle ranges up to 1000 yd, and also because the decreased time of flight and flat trajectory would reduce the uncertainty in the estimation of range and position.

The probability of hitting an airplane is increased by decreasing the time of flight of the projectile, which may be accomplished

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2/ The name of an author followed by an underscored date refers to the appended bibliography.

by increase of muzzle velocity.[3/] The experience of the present war led the Director of Artillery of Great Britain, for instance, to suggest that there is need for an antiaircraft gun capable of sending a projectile to a height of 10,000 ft in only 3 sec, which would require a muzzle velocity of between 5000 and 6000 ft/sec [O.B.P., 1941].

The attainment of such high muzzle velocities is prevented, not by the impossibility of designing a gun to produce them, but simply by the realization that such a gun of conventional design would erode so rapidly that its use would not be economically feasible. Therefore, if a means of greatly retarding erosion could be discovered, it would not only increase the life of guns in general, but also it would permit the development of these special weapons having high muzzle velocities without bringing in the complication of novelty of design.

4. Outline of the present survey

A discussion of some of the elementary features of the construction and firing of guns has been included in this report, so that the main discussion may be understood by a reader who has had no previous acquaintance with ordnance. This is especially necessary

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3/ In a recent discussion of this subject, Weaver [1942] concluded that "in general the probability of hitting varies with at least the inverse second power of the time of flight; and with an inverse power of the time of flight which may be 3, 4, 5 or even 6 in cases progressively complicated by more severe dodging." Earlier Kent [1933] had calculated that the probability of hitting a maneuvering airplane varies inversely as the fourth power of the time of flight.

because this report is primarily intended for the use of civilian scientists. Although these scientists are technically well qualified to investigate the problem of erosion of guns, ordinarily they have had no more opportunity to become acquainted with the details of ordnance than most ordnance officers have had to learn as much as they would like to know about the pure sciences underlying the applied science that is a part of ordnance. Those readers who are familiar with ordnance, therefore, may well omit Chapters II, III and IV and a few sections in some of the later chapters.

The design of some parts of a gun affects the rate of erosion, and therefore a description is given in the present volume of certain features of gun tubes, projectiles, propellants and the conditions of firing, so that the necessary information will be at hand for later application in a discussion of the relation of these factors to erosion. Other parts of a gun -- the breech mechanism, the firing mechanism, the recoil system, the carriage or other mounting, the aiming and laying devices, and the fire control instruments -- do not affect the progress of erosion and therefore they are not discussed.

In the second volume -- Chaps. VIII to XV -- erosion is considered as a result of the interaction of the gun tube with its environment during the few thousandths of a second that elapse during firing. The eroded surface is described in detail and then the effect of varying the different factors of the environment are set forth to the extent that information concerning them is available. The experimental methods of study of gun erosion are described; formulas for the life of guns are summarized; and finally, some of the theories that have been suggested to explain the erosion of guns are discussed.

CHAPTER II.[4] GUNS

5. Classification

Guns are classified first, with respect to purpose, and second, with respect to size. To a certain extent the two systems are not mutually exclusive, for the use of the weapon often demands a certain size in order that it should be effective. The purpose of the gun is related to erosion only in so far as it may be reflected in the design or in the conditions of firing -- for instance, the large projectile and low muzzle velocity of a howitzer or the rapid fire of an antiaircraft gun.

The size of a gun is measured in terms of the diameter and the length of the bore. The diameter, which is called the caliber of the gun, is the principal dimension. The length of the gun from the muzzle to the face of the breech block is usually expressed in terms of calibers, that is, it is expressed as the ratio of the actual length to the diameter. Table I shows the dimensions of a representative series of guns.

Guns may be broadly classified on the basis of caliber into small arms and cannon (or artillery). A .50-caliber machine gun is the largest size, standard small arm, and a 20-mm gun is the smallest size cannon in the U.S. Army. The old classification of artillery into guns, howitzers and mortars has lost some of its

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4/ Most of the information contained in this chapter, for which no other source is indicated, has been taken from Hayes [1938] or from Naval Ordnance [1939].

Table I. Principal dimensions and other details of representative guns and their projectiles. (Taken by permission from offical drawings in the Ordnance Department, U. S. Army.)

Gun*	.30-MG M1917A1	.50-MG M2	20-mm M1,M2	37-mm M3	75-mm[a] M2-M3	3-in. AA M3	90-mm AA M1	105-mm AA M3	4.7-in. AA T2	155-mm M1	8-in. Mk VI	14-in. M1920M2	16-in. M1919M3
Construction [b]	Monobloc	Monobloc	Monobloc	Monobloc	Monobloc some CW	Built-up CW liner	Monobloc CW	Monobloc CW	Monobloc CW	Built-up 2 hoops	Built-up liner	Built-up liner	Wire-wound
Muzzle velocity(ft/sec)	2800	2800	2850	2600	1850-2050	2600	2700	2800	3150	2800	2750	2650	2700
Pressure, desired max. (lb/in.²)	48,000	48,000	42,000	36,000	36,000	34,000	38,000	36,000	38,000	36,000	38,000	38,000	38,000
Tube, length (calibers)	72	72	85.5	53.5	28.5-37.5	50	50	60	60	45	45	50	50
— diameter at breech: inside (in.)	0.47	0.80	0.98	1.98	3.21	3.90	4.71	5.81	7.06	7.40	11.00	16.5	22.0
outside (in.) [c]	1.10	1.68	2.05	4.75	6.60	6.12	10.60	15.50	15.0	14.6	12.2	19.5	26.2
Bore diameter,lands(in.)	0.300	0.500	0.787	1.457	2.950	3.000	3.543	4.134	4.700	6.100	8.000	14.000	16.000
— groves (in.)	0.308	0.510	0.817	1.497	2.990	3.080	3.623	4.224	4.790	6.200	8.140	14.240	16.240
Depth of rifling (in.)	0.004	0.005	0.015	0.020	0.020	0.040	0.040	0.045	0.045	0.050	0.070	0.120	0.120
Travel of projectile(in.)	21.75	33.25	63.68	69.95	72.5-99.2	127.73	156.4	221.3	248.4	238.3	298.9	604.7	679.5
Length of rifling (in.)	21.25	31.75	63.08	68.45	69.6-96.2	125.83	152.4	216.7	241.6	230.6	288.8	598.3	667.5
Twist of rifling	1/33.3	1/30	1/25.586	1/25	1/25.59	1/40	1/32	1/30	1/30	1/25	1/25	1/32	1/30
Number of grooves	4	8	9	12	24	28	32	36	42	48	64	136	144
Width of grooves(in.) [d]	0.167	0.13	0.205	0.231	0.248	0.187	0.198	0.211	0.202	0.249	0.236	0.173	0.209
Width of lands (in.)	0.06	0.06	0.068	0.15	0.139	0.15	0.15	0.15	0.15	0.15	0.157	0.15	0.14
Powder chamber, length (in.)	2.75	4.25	4.24	9.20	13.89	24.17	24.25	31.47	40.40	46.80	71.21	102.66	157.3
— net volume(in.³)[e]	0.25	0.98	2.22	19.92	80.59	200	300	600	1046	1596	5156	19,377	39,960
Charge (lb)	50 gr	250 gr	0.07	0.50	2.00	4.875	6.82	11	24	30	98.5	460	832
Density of loading	0.79	1.01	0.87	0.695	0.686	0.675	0.629	0.508	0.66	0.63	0.52	0.66	0.59
Projectile type [f]	Ball M2	Ball M1	H E MkI	AP M51B1	HE M48[g]	H E M42A1	H E M71	H E M38A1	H E M73	H E M101	AP Mk XXM3	AP Mk VI	AP Mk IX
Fuse	None	None	MkI/A/	None	Point det. M48	M43 A2	M43 A2	M43 A2	M61	Point det. M51	Base det. Mk X	Mk X	Mk X
Projectile, — weight (lb)	150 gr	708 gr	0.286	1.92	14.60	12.81	23.4	32.77	50	94.86	261.8	1560	2340
— length (in.)[h]	1.12	2.38	3.25	6.36	15.00	10.19	16.34	17.96	23.50	27.54	38.18	62[i]	72[i]
— body diameter (in.)	0.3095	0.5115	0.770	1.453	2.928	2.980	3.520	4.10	4.67	6.07	7.95	13.93	15.93
Rotating band, diam. (in.) [j]	—	—	0.828	1.507	3.011	3.098	3.643	4.244	4.82	6.180	8.16	14.17	16.24
— width, total (in.)	—	—	0.197	0.74	0.49	1.02	1.20	1.42	2.25	2.02	3.30	4.65	5.33
— width,cyl.(in.)[k]	—	—	0.170	0.37	0.35	0.87	1.00	1.17	1.65	0.95	2.13	3.66	3.53
— dist.from base (in.) [l]	—	—	0.40	0.58	2.22	1.20	2.60	3.02	3.53	3.45	2.00	not specified	
Bourrelet, diameter(in.)	—	—	0.784	[o]	2.945	2.995	3.537	4.128	4.693	6.092	7.977	13.984	15.982
— clearance - lands (in.) [n]	—	—	0.003	—	0.005	0.005	0.006	0.006	0.007	0.008	0.023	0.016	0.018
— width (in.)	—	—	0.25	—	1.480	0.5	0.75	0.85	0.78	1.1	1.62	2.33	2.67
— dist.from base(in.)[m]	—	—	1.92	—	6.27	5.30	7.23	7.98	8.80	7.48	10.78	not specified	

* See pp.10 ff for notes concerning the purposes for which these guns are designed.

Footnotes for Table I

[a] The M2 and M3 guns differ in length only, and hence in muzzle velocity.

[b] CW: "cold-worked."
The liner of the 3-in. gun is loose. Those of the 155-mm, 8-in. and 14-in. guns are shrunk in place.
The smaller guns, up to and including the 105-mm, use fixed ammunition; the 4.7-in. gun is separate loading with the powder packed in bags in a cartridge case; and the 155-mm and larger guns use separate-loading ammunition without a cartridge case.
The machine guns are automatic. The 75-mm, 3-in., 90-mm and 105-mm guns are semiautomatic; that is, the force of the explosion ejects the fired cartridge case and leaves the breech so that it closes automatically when another cartridge is inserted by hand.

[c] Outside diameter of the tube or liner. Over-all outside diameters of the built-up guns are: 3-in., 9.00 in.; 155-mm, 18.8 in.; 8-in., 33.5 in.; 14-in., 48 in.; 16-in., 65.8 in.

[d] The width of the cutter fixes the width of the grooves. The width of the lands is a nominal residual dimension.

[e] For small arms ammunition this volume is called the "powder space," but on drawings of cannon using bag ammunition the "powder space" is the linear dimension from the obturator pad to the base of the projectile. The "volume of powder chamber" of cannon is the net volume between the obturator pad and the projectile of a bag-loaded gun, and the net volume inside the cartridge case of a case-loaded gun, allowing for the volume of the primer, wads and base of projectile.

[f] AP: "armor-piercing"; H E: "high explosive."
The projectile listed for each gun is the standard one now being manufactured, although older models on hand are still issued for service. Frequently a different projectile may be fired from the same gun; or the same projectile may be fired at reduced charge and hence with lower velocity.

[g] An AP projectile (M61) is used with almost equal frequency. It differs from the H E type in the following dimensions: weight, 14.40 lb; length, 8.91 in.; rotating band, 0.76 in. from base; bourrelet, 0.51 in. wide and 5.08 in. from base. A semi-armor-piercing projectile (M74) that is also frequently fired differs from the AP type in not having a cap and windshield.

[h] Length includes fuze, if any, and windshields on AP projectiles.

[i] This dimension is not specified. The one given is an approximate one taken from a scale drawing.

[j] The rotating bands on the larger projectiles have a "hump" that projects beyond the main cylindrical portion. The diameters of these "humps" for the several projectiles are: 4.7-in., 4.98 in.; 155-mm, 6.320 in.; 8-in., 8.36 in.; 14-in., 14.40 in.; 16-in., 16.58 in. The top of the hump is only 0.05 to 0.1 in. wide.

[k] All rotating bands are beveled at the front end, and those on the larger projectiles also at the rear. The cylindrical portion is cut by from one to five circumferential grooves known as <u>cannelures</u>, which provide space for the copper to flow into during the engraving.

[l] The distance to the rear of the rotating band or bourrelet.

[m] This projectile, which is of the so-called <u>shot</u> type, has no bourrelet. The clearance between the body and the lands is only 0.004 in. on the diameter.

[n] This clearance is the minimum. The tolerance on the diameter of the lands is +0.002 in. and that on the diameter of the bourrelet is -0.005 in., so that the tolerance on the clearance is +0.007 in.

Notes on the Purposes of the Guns Listed in Table I

The .30-caliber M1917A1 Browning machine gun is the standard ground machine gun, and is also used as an auxiliary antiaircraft weapon. It is a recoil-operated and belt-fed automatic gun firing at the rate of 400 to 525 shots/min from a tripod mount. It is water-cooled.

The .50-caliber M2 Browning machine gun is made up in three types -- water-cooled, heavy barrel (air-cooled) and aircraft (air-cooled) -- by assembly of the proper barrel and jacket on a basic receiver. The water-cooled gun is the principal antiaircraft machine gun of antiaircraft regiments. It fires at the rate of 600 rounds/min from a tripod mount.

The 20-mm guns M1 and M2 are automatic aircraft weapons mounted either for firing through the hub of the propeller or as a fixed gun in the wing. The rate of fire is 600-700 rounds/min. The only difference between the M1 and M2 guns, the former of which is a substitute standard, is in the dimensions and shapes of some of the receiver parts.

The 37-mm gun M3 is the smallest field gun used by the infantry and cavalry in the U. S. Army. It is intended especially for antitank service. Its carriage M4, which is designed for great mobility over any kind of ground, can be controlled by one man. The gun is manually operated. Its tube can be easily unscrewed from the breech ring for replacement when it becomes overheated or worn out. This gun fires both armor-piercing (1.92-lb) and high-explosive (1.63-lb) projectiles. The 37-mm gun M1A2, which is the standard antiaircraft weapon of this caliber, is an automatic gun firing a lighter projectile (1.34 lb) than gun M3 at a rate of 120 rounds/min, with a muzzle velocity of 2600 ft/sec. This gun is slightly longer, and the twist of rifling is 1/30.

The 75-mm guns M2 and M3, which are the same except for length, have been designed for mounting on tanks. The former is a substitute standard, to be used as long as the stock on hand lasts. They are recent (1941) adaptations of the original 75-mm gun M1897 (French). Ballistically, the new guns differ from the M1897 only in length. They use the same ammunition. The longer of these guns is nearly 20 percent lighter than the M1897A2 gun because it is of monobloc construction.

The 75-mm gun M1897A2, which is still the standard light field gun, is 34.5 calibers long and has a muzzle velocity of 1950 ft/sec. The 75-mm guns M1916 (U. S.) and M1917 (British), which are limited standards for this same service, are only 28.4 calibers long and have a muzzle velocity of 1900 ft/sec. Their most distinctive feature is that they employ rifling of increasing twist. These light field guns are to be superseded by the 105-mm howitzer M2A1.

The 3-in. AA gun M3 is now a limited standard, to be superseded eventually by the 90-mm gun M1, of which production was started in 1940. The loose liners for the 3-in. gun continue to be made. These two guns are mobile antiaircraft weapons. Although the 90-mm gun has about one-third greater maximum range and fires a much heavier projectile at approximately the same rate of fire (25 rounds/min), the total weight of the gun and mount is less than 20 percent greater than that of the 3-in. gun, because improvements in metallurgy, especially in cold-working, have made possible monobloc construction.

The 105-mm AA gun M3 is now (1942) the standard fixed heavy antiaircraft weapon. The 4.7-in. AA gun T2 is an experimental heavy mobile model under development. Just as the substitution of the 90-mm for the 3-in. gun gives increased effectiveness in light antiaircraft guns, so the 4.7-in. is designed for use against targets at higher altitudes (50,000 ft) than can be reached with the 105-mm gun. This greater range is obtained by the use of greater muzzle velocity and a heavier projectile of radically improved ballistic form.

The 155-mm gun M1A1 is the most powerful of the standard heavy mobile artillery weapons. (The others are the 155-mm, 8-in. and 240-mm howitzers, all of which have lower velocities and shorter ranges.) It differs from the 155-mm gun M1 only in the breech ring, but it differs from the old 155-mm gun M1918 G. P. F. ("Grand Puissance Filloux"), which it superseded in 1941, by having greater power. The M1918 gun, which was only 32 calibers long, fired a high-explosive projectile of the same weight at a muzzle velocity of only 2410 ft/sec, using a charge of 26 lb.

The 8-in. gun Mk. VI, M3A2 and the 14-in. gun M1920M3 are the principal standard railway artillery. The former gun has been constructed by rechambering one designed by the U. S. Navy.

The 16-in. gun M1919M3 is a limited standard for the primary armament of harbor defense installations. It is not expected, however, that any more wire-wound guns will be produced. The present standard for new installations is the 16-in. gun Mk. IIM1, which is a built-up gun obtained from the Navy.

precision; but these names still denote differences of length that are implicit in the different purposes of the three types. A gun, in this special sense of the word, is the longest, heaviest type of weapon of a given caliber and has the highest velocity and the longest range. A howitzer is shorter and lighter and has a lower velocity and a shorter range. A mortar is a very short weapon that is fired at a high angle of elevation with a relatively short range for indirect fire. The term gun is also used in a special sense to refer to the tube (or tubes and jackets in a built-up gun) and breech mechanism as a complete unit as distinguished from the mount, which includes the recoil mechanism.

6. The tube

A gun must have walls strong enough to withstand the internal pressure of the powder gases. Because this pressure diminishes toward the muzzle, the wall thickness of the tube can be tapered in that direction. Right at the muzzle, however, the wall thickness of a large gun is usually increased somewhat to form the so-called bell muzzle, in order to make up for the loss of strength occasioned by the ending of the tube. The necessary strength of tube throughout its length is obtained by using a proper thickness of high-grade alloy steel having a high tensile strength. In addition, large guns are made stronger -- or rather equally strong with thinner walls -- by putting the inner layers of the tube under compression. This is accomplished by wrapping the tube with several layers of wire under tension, by shrinking on the tube a jacket and one or more steel hoops, or by expanding the bore beyond the elastic limit of the steel by hydraulic pressure before it has been machined to final dimensions. Wire-wound guns, although still in service, are no longer constructed in this country. Built-up guns are frequently made with two slightly tapered coaxial tubes, the inner one of which constitutes a liner that can be replaced after it has worn out. The replacement requires that the tube be sent to an arsenal, for it has to be expanded by heating in order to disengage the liner, which is made with a taper of about 0.003 times the diameter per inch. The use of a loose liner that can be screwed into a small-caliber tube by the gun crew was tried by the U.S. Army in its 3-in. antiaircraft gun, but it was discontinued because of the difficulty of replacement under field conditions. The British Army has used a loose liner with some success in their 3.7- and 4.5-in. antiaircraft guns.

The process of radial expansion[5/] -- called also autofrettage and cold-working -- has been applied to guns up to 8 in. in diameter. A hydraulic pressure of 110,000 to 150,000 lb/in.^{2} is used to produce a permanent enlargement of the diameter of the bore amounting to about 6 percent; then, after the pressure is removed, the outer layers contract and place the inner layers of the tube in a state

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5/ This process, which was originated by the French "autofrettage" is French for "self-hooping"), has been developed by the Navy at the Naval Gun Factory, Washington Navy Yard, and by the Army at Watertown Arsenal. A number of reports from Watertown Arsenal dealing with the development of the process are on file in the Ordnance Library, cataloged under "Cold-working." In 1941, equipment for cold-working on a production basis was put in operation at Watervliet Arsenal.

of permanent compression. A radially expanded monobloc tube instead of a tube with a replaceable liner is now preferred by the Army for small guns, because the former weighs less and hence can be used on a lighter mount. Also it has been found that the cost of an entire monobloc tube is not much more than that of a liner alone, and much less than that of a liner and tube [Ord. Dept., 1940a; II, p. 67].

7. Tapered bore

Although the bore of an ordinary gun is cylindrical, some guns having a tapered bore have been developed in order to obtain a higher muzzle velocity without a corresponding increase of erosion. They have been reviewed separately [Burlew, 1942].

8. The rifling

An elongated projectile requires a high rate of rotation for stability in flight and for the operation of fuzes of certain types. This rotation is obtained by the rifling cutting into a layer of soft metal on the circumference of the projectile as the latter is propelled down the tube. The rifling consists of a series of helical grooves in the surface of the bore, the depth of which is of the order of magnitude of 1 percent of the diameter. The raised portions of the bore between the grooves are called lands. The twist of the rifling, which is expressed as the number of calibers of length in one turn, in combination with the muzzle velocity of the projectile, determines the rotational velocity of the projectile.

The design of the rifling, in terms of the number, width, depth and form of the lands and grooves and the degree and uniformity of the twist, is a complex subject. Although many designs of rifling have been tried, there is not complete agreement today as to the most suitable one. The currently produced guns of the U.S. Army have rifling of uniform twist that varies from 1 turn in 25 calibers to 1 turn in 40 calibers. The number of grooves increases with the caliber, so that the widths of lands and grooves are approximately the same for guns of all sizes. The lands are about 0.15 in. wide and the grooves slightly wider; and the width of each is uniform throughout the length of a given gun (see Table I).

9. Effect of design of rifling on erosion

The effect of the rifling on erosion is not very well understood. The presence of stress concentrations at the sharp corners where the lands and grooves join has been mentioned as an important contributory factor by various writers [Howe, 1918; Justrow, 1923], but a quantitative evaluation does not seem to have been attempted. The strength of the lands in shear was calculated by Justrow [1923], who considered that the reduction of bearing surface as erosion proceeds tends to increase subsequent erosion.

The twist of rifling may affect erosion resistance. An erosion test was made at Aberdeen Proving Ground [Lane, 1933] of a 3-in. antiaircraft gun liner rifled with straight grooves for the first 23½ in. from the origin of rifling (see Sec. 11) and then with a twist that gradually increased to 1 turn in 40 calibers during the next 113½ in. For the last 7 in. to the muzzle the twist was uniform -- 1 in 40. This liner was fired 2950 rounds, for comparison with another having a uniform twist of 1 in 40 over its whole length.

Both liners had been made of carbon steel of the same chemical composition and practically the same heat treatment. Both had been radially expanded, the one with increasing twist slightly more than the other.

The gun with increasing twist of rifling eroded less than the other, except at the muzzle, throughout the course of the comparison. After 2950 rounds, for instance, at the origin of rifling, the increase of diameter of the lands was only 0.182 in. compared with 0.232 in., and of the grooves 0.112 in. compared with 0.166 in. At the same time, at 10 in. from the origin, the corresponding increases were 0.088 and 0.113 in. on the lands and 0.046 and 0.059 in. on the grooves. The decrease of muzzle velocity after 2000 rounds was only 50 ft/sec for the liner with increasing twist, but it was 145 ft/sec for the other one. The deviations in range were the same.

10. The forcing cone[6]

The rifling is terminated at the end of the bore toward the breech by a tapered section along which the diameter across the lands increases. This so-called forcing cone (called also band slope and compression slope) continues toward the breech a short distance behind the point at which the diameter of the lands equals that of the grooves. Its rear portion forms the seat for the rotating band on the projectile (see Sec. 18), which is machined to a matching cone; and the forward portion, along which the tops of the lands are

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6/ For a drawing showing the various parts of a gun tube, see Naval Ordnance (1939), plate 1, Chap IV.

tapered, facilitates the engraving of the rotating band when the projectile begins to move. The forcing cone is usually about $\frac{1}{2}$ in. long. At the rear of it, in a gun firing fixed ammunition (see Sec. 21) is the <u>centering cylinder</u>, into which the neck of the cartridge case fits. The diameter of this cylinder is 0.2 to 0.3 in. greater than the diameter across the lands. Behind it another enlargement of the diameter, called the <u>chamber slope</u>, joins the centering cylinder with the chamber proper. In guns firing separate-loading ammunition (Sec. 21), the forcing cone is frequently elongated, and sometimes -- for example, in the 155-mm gun M1 -- it is combined with the chamber slope, which eliminates the centering cylinder.

11. Origin of rifling

The <u>origin of rifling</u> is the point along the axis of the bore that corresponds to the place on the forcing cone where the lands and grooves have the same diameter; the <u>length of rifling</u> is measured from this point to the muzzle. In U. S. Army reports on the extent of erosion, however, "origin of rifling" refers to the forward end of the forcing cone, where the grooves have attained their full depth. In U. S. Navy and also in British reports, the erosion is commonly measured 1 in. in front of the true origin of rifling.

12. The chamber

The <u>chamber</u> is properly that portion of the gun between the centering cylinder and the face of the breech block; frequently, however, the term is used to embrace the whole space up to the origin of rifling,[7/] in which case the total length of the tube is the sum of the length of the rifling and the length of the chamber. The ratio of the diameter of the chamber to that of the bore, which is called the chambrage, varies from 1.05 in some German guns to 1.50 in the new 4.7-in. AA gun M1 of the U. S. Army. Gun designers of the U. S. Navy consider 1.20 a desirable ratio [Naval Ordnance, 1939, p. 86]. The walls of the chamber in a gun using a cartridge case are tapered, the diameter at the breech end being a few hundredths of an inch greater than at the forward end, in order to facilitate removal of the case. In large guns using bag ammunition, the rear of the chamber is necked down along a conical section, called the chamber rear slope, in order to decrease the size of the breech block.

13. Effect of chamber design on erosion

The greater the chambrage, the greater is supposed to be the erosion. According to Hugoniot and Sebert [1882], Charbonnier [1908, 1922] and Tulloch [1921], a bottle-necked chamber causes eddying of the powder gases at the origin of rifling, with the result that local washing action on the wall is set up. The effect of such turbulence was demonstrated by de Bruin and de Pauw [1931] in the case of an erosion vent plug (see Sec. 86) by means of a plug made in three parts. The first and third parts had holes 1 mm in diameter and 10 mm long, whereas the

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7/ The term is used in this way in Table I.

intermediate section had a hole 7 mm in diameter and 5 mm long. When such a vent plug was fired, using 40-percent NG powder, at a maximum pressure of 1400 atmos, the third part of the plug eroded more than the first, even though the gas had lost some of its energy.

The recommendation made by Hugoniot, Charbonnier and Tulloch that the chamber should not be much greater in diameter than the bore seems plausible, but no quantitative data to support it are known to exist. The reason for this is that ordinarily when two guns of the same caliber are made with chambers of different diameters, all other features of the design are not kept constant. The chamber of larger diameter, for instance, will have a larger volume and hence the correspondingly larger charge used in it may be the sole cause of the increased erosion (see Sec. 105).

14. Examination of the bore

The surface of the bore of a gun is examined by means of a boresearcher, which consists of an illuminated mirror and a telescope. For bores of diameter 6 in. or less, the two parts are combined in one instrument, called a boroscope, which may be quickly focused on any part of the bore surface. For measurement of the diameter of the bore, an instrument called a star gage is used. It consists of either two or three measuring points that may be extended radially in a plane by the movement of the handle at the opposite end of a long staff until the points make contact with the wall of the bore. Then the diameter may be read from a scale -- either vernier or micrometer -- on the handle.

All guns are examined with a boresearcher and measured with a star gage at the time of manufacture.

15. Steels used for gun tubes and liners 8/

The U. S. Navy has used for many years a plain carbon steel for its gun liners and a 3-percent nickel steel for tubes, hoops and jackets. Typical compositions of these two steels are given in Table II. The nickel steel differs from the carbon steel only in its nickel content and in having a slightly smaller amount of carbon. The yield strength of the gun steel must be at least 53,000 lb/in.² and that of the nickel steel at least 65,000 lb/in.² [Naval Ordnance, 1936].

Table II. Chemical composition, in percentages, of steels used in U. S. Navy guns*

	C	Mn	Si	P	S	Ni	SAE No.
Gun steel	0.42-0.50	0.70	0.27	0.03	0.03	0	1040
Nickel steel	0.35-0.42	0.70	0.27	0.03	0.03	3.00	2340

*After Naval Ordnance [1939], pp. 118-119.

The U. S. Army uses a variety of different compositions of low-alloy steels for gun tubes and liners, procured on the basis of a macro-etch test and tensile properties. The following quotation from Notes on the selection and use of metals in ordnance design [Ord. Dept., 1940b, p. 86], prepared at Watertown Arsenal, explains the present policy.

8/ The relation between the properties of the gun metal and erosion is discussed in Chap. XI.

"Chemical compositions are normally not prescribed because other factors such as proper melting and finishing of the metal and its final cleanliness play an important part. The method of pouring, size, relative dimensions and shape of molds, proper method of reduction in hot working, and heat treatment in various stages of the process are also important in securing the quality of product desired in gun steels.

"Every manufacturer, depending on his equipment, staff, conditions of work, etc., as well as his previous experience and traditions, will have a preference for certain definite compositions. It is advisable to let the manufacturer choose his own composition and assume the responsibility for his work so long as the physical and metallographic properties are satisfactory for gun material.

"In normal gun steels, the designer is primarily interested in the physical characteristics obtainable. Specification 57-103 provides for the following physical properties:

Yield strength	65,000 lb/in.^{2}
Tensile strength	95,000 lb/in.^{2}
Elongation	18.0 percent
Reduction of area	30.0 percent

The trend, however, is toward the following requirements which have been found more practical for Ordnance purposes:

For tubes and liners (medium strength) --	
Yield strength (set, 0.05 percent)	65-80,000 lb/in.^{2}
Reduction of area	45.0 percent minimum;
For 37-mm, 1.1-in., etc. (high strength) --	
Yield strength (set, 0.05 percent)	95-110,000 lb/in.^{2}
Reduction of area	45.0 percent minimum.

The above values are readily obtainable in centrifugal castings, and the manufacturer of forgings can meet such requirements with reasonably clean steel.

"The procurement of gun tubes and liners produced by the centrifugal casting process is covered by specification 57-66. The high ductility from transverse specimens in the case of centrifugal castings is due to the method of manufacture, which definitely eliminates the directional properties always present in forgings."

The compositions of a number of forgings and centrifugal castings used in guns recently completed by the Army are listed in Table III. The tensile properties of these steels exceeded

Table III. Chemical composition, in percentages, of steels currently used in Army guns*

Element	A	B	C	D
C	0.20-0.24	0.31-0.34	0.34-0.35	0.43-0.44
Mn	0.60-0.90	0.61-0.77	0.71-0.73	0.59-0.67
Si	0.15-0.23	0.20-0.30	~ 0.2	0.18-0.26
P	0.006-0.011	0.027-0.035	0.014-0.024	0.012-0.02
S	0.016-0.018	0.029-0.038	0.019-0.023	0.015-0.018
Mo	0.44-0.53	0.32-0.38	0.30-0.35	0.47-0.49
V	0.06-0.16	0.19-0.23	0.00-0.06	0.19-0.21
Cr	0.91-1.08	---	0.53-0.97	0.19-0.30
Ni	---	---	2.26-2.46	0.18-0.36

*From Record of measurements and report of inspection, in the files of the Artillery Division, Ordnance Department, U. S. Army.

A. Range of compositions of 14 centrifugal castings made in 1940-41 for 37-mm and 90-mm gun tubes and 3-in. AA gun liners to be either heat treated to strength or cold-worked.

B. Range of compositions of 8 forgings made in 1940-41 for 155-mm gun tubes, to be cold-worked.

C. Range of compositions of 3 forgings made in 1940-41 for 75-mm gun tubes, to be heat treated to strength.

D. Range of compositions of 3 forgings made in 1940-41 for 8-in. gun liners, to be heat treated to strength.

the requirements just quoted. The composition of the centrifugal castings in column A represents a development at Watertown Arsenal. Donald [1937] recommended essentially this same composition except for carbon content (0.35-0.40 percent) for making a centrifugal casting to be heat treated to a yield strength of 125,000 lb/in.^{2}, as a result of a test of 32 experimental castings of various compositions. Bender and Pappas [1941], after a study of five slightly different compositions, confirmed the choice.

Their work showed that the variations in chromium and manganese had only minor effects on physical properties, but "that substantial changes in physical properties may be brought about by changes in carbon content." The higher the carbon content, the higher the yield strength. Bender and Pappas recommended 0.30-0.35 percent carbon for a yield strength of 121,000 to 125,000 lb/in.^{2}

For rifles and machine guns the formerly used manganese steel, W. D. (S.A.E.) 1350, has been superseded by a chrome molybdenum steel, W. D. (S.A.E.) 4140 modified, which has been found to increase the service life. The compositions of these two steels are given in Table IV. For bars up to 2 in. in diameter the minimum yield strength specified is 110,000 lb/in.^{2}, the minimum elongation is 18 percent and the minimum reduction of area is 50 percent.[9/] These tensile properties represent a considerable improvement over those of the 23 alloy steels that had been tested (see Sec. 92) in the form of machine-gun barrels at Springfield Armory in the early nineteen-twenties, only one of which had contained any molybdenum.

Table IV. Chemical composition, in percentages, of steels used in small arms barrels.

Element	W.D. 1350	W.D. 4150 Mod.
C	0.45-0.55	0.45-0.55
Mn	0.60-0.90	0.60-0.90
Si	---	0.15 max.
P	0.045	0.025 max.
S	0.055	0.025 max.
Cr	---	0.80-1.10
Mo	---	0.15-0.25

9/ U.S. Army Specification No. 57-107-25, Oct. 11, 1939.

16. Yield strength

The yield strength referred to in the foregoing section is determined by the "offset method" as described in "Federal specifications for metals."[10] In this method the extensometer reading is plotted as a function of load -- by an autographic extensometer in many cases -- until the curve is no longer linear. Then a straight line is drawn parallel to the initial straight portion of the extensometer curve and offset from that curve by an amount equal to a prescribed set -- for example, 0.05 or 0.1 percent of the gage length. The load corresponding to the point of intersection of this line and the extensometer curve, divided by the original cross-sectional area of the specimen, is the yield strength. The value of the set now prescribed -- usually 0.05 percent -- was chosen so that the resulting yield strength corresponds closely to that determined by the proportional method,[11] which formerly was used for inspection.

For a given sample, the yield strength is numerically larger than the proportional limit,[11] the elastic limit or the proof stress. As defined in the same specification,[12] these three

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10/ Federal Specification [QQ-M-151a, Nov. 27, 1936, par. 22g(2)]; published in the Federal standard stock catalog, Sec. IV (part 5).

11/ The yield strength determined by the proportional method, which should not be confused with the proportional limit, is defined in Federal Specification QQ-M-151, par. 22g(1) as follows: "Proportional method. -- The yield strength shall be calculated at the reading last preceding the first increment of load which produces an increment of strain which clearly exceeds twice the increment of strain taken from the modulus line."

12/ Footnote 11, pars. 37a, b and c.

limiting stresses correspond, respectively, to 0, 0.003 and 0.01 percent permanent elongation. The yield point, on the other hand, corresponds to an extension under load of 0.5 percent or greater;[13/] and the tensile strength is the greatest load per square inch of original cross-sectional area carried by the material during a tension test.

13/ Footnote 11, pars. 22h and 37e.

CHAPTER III. PROJECTILES

17. General description of projectiles

Modern projectiles are elongated to secure a large ratio of mass to cross-sectional area, and thereby long range. The head of the projectile is provided with a curved surface in order to decrease the wind resistance; and, similarly, the rear end is frequently tapered slightly to give a boat-tailed shape, which reduces air resistance at velocities in the region of the velocity of sound. The longitudinal cross section of the head is bounded by an ogive, which is an arch-shaped curve, the two branches of which are arcs of two large circles of the same radius intersecting at the nose of the projectile. The longitudinal axis of the projectile is the perpendicular bisector of the line joining the centers of these two circles. The radius of the ogive, which is the radius of the two circular arcs, is expressed in calibers. Small arms projectiles, which are called bullets, have a soft outside jacket of copper alloy of diameter large enough to be cut by the grooves of the rifling. At the rear of a bullet is a circumferential groove, called a cannelure, into which the mouth of the cartridge case is crimped.

An artillery projectile is so long that, in order to keep it centered in the bore, it is provided with a bourrelet at the rear of the head. This is a cylindrical surface that has been machined to have a slight clearance in the bore (see Table I). Behind the bourrelet, which is about one-sixth caliber wide, the remainder of the body has a diameter slightly less than that of the bourrelet, so that it does not touch the lands. Near the rear of the projectile a rotating band (Sec. 18) is shrunk and forced into an undercut groove machined in the body of the projectile. The dimensions of the cavity of the projectile and the location of the center of gravity are features of design that are important in general but which do not relate to erosion.

The general proportions of artillery projectiles are expressed in approximate terms in Table V.

Table V. Approximate proportions, in calibers, of artillery projectiles*

Length	4 to 6
Length of head	2-1/3 to 3
Radius of ogive	7 to 9
Width of bourrelet	1/6
Width of rotating band	1/3
Length of cylindrical part of base	1/4
Angle of boat-tail	5° to 9°
Weight (lb)	$\frac{1}{2}$ (caliber in inches)^3

*After Hayes [1938], p. 560.

18. Rotating band

The rotating band -- called the driving band by the British -- performs two functions in addition to furnishing a convenient surface for the rifling to engage and thus to spin the projectile. It centers the rear of the projectile and it seals the forward end of the powder chamber. Erosion of the gun adversely affects the performance of all three of these functions of the rotating band. The lack of centering of the rear of the projectile in the bore of a worn gun has been suggested [Miller, 1920] as a major cause of the increase of dispersion. The increased opportunity for leakage of gas past the rotating band (see Chap. XIII) in a worn case gun (defined in Sec. 21) may account for the increased rate of erosion generally ascribed to such guns as compared to bag guns (Sec. 21), in which the projectile is rammed home regardless of how much the forcing cone has been advanced (see Sec. 63).

The band must be both soft and strong to serve its several purposes. Copper, which was formerly used exclusively, is still the standard material for the rotating bands of most projectiles used in Navy guns and of those of larger calibers of seacoast artillery. Gilding metal -- 90 percent Cu, 10 percent Zn -- is widely used for rotating bands by the Army in order to reduce coppering (see Sec. 60); but although it was tried by the Navy, it is now used by that service only for projectiles for the 1.1-in. and 6-in. guns.[14/]

The diameter of the rotating band, as may be seen from Table I, is about 0.02 in. greater than that of the grooves in a new gun, so that the grooves are completely filled when the rotating band is engraved as the projectile moves down the bore. The starting pressure -- or shot start pressure, in British usage -- which is required to engrave the rotating band, is considered as part of the friction of the projectile in the bore (Sec. 44). A

14/ Dr. L. T. E. Thompson, Naval Proving Ground, personal communication, Sept. 13, 1941.

recent British investigation [A. C. 1942c] has shown that engraving of the rotating band of a 3-in. proof shot occurred partly by plastic flow and partly by shear. The amount of shear increased with the age of the gun after it had been two-fifths worn. It also increased with the degree of filling of the grooves and with the hardness of the copper.

Many experiments have been made with rotating bands for the purpose of reducing "fringing." Depending upon the design of the band, excess copper may be dragged back during engraving by the rifling to form a fringe at the rear edge of the band, and then, as the projectile leaves the muzzle, this fringe is flared out by the powder gases and by centrifugal force into a shape like a hoop skirt, which seriously affects the flight of the projectile. A résumé of the modifications of rotating bands tried during World War I to overcome fringing was given by Veblen and Alger [1919]. Fringing is eliminated by providing some place for the displaced copper to flow into, as, for instance, by cutting a cannelure at the rear of the band.

19. Effects of the rotating band on erosion

The rotating band may affect erosion in three different ways. The frictional wear between it and the surface of the bore (Sec. 44) is generally considered important, although there is no means of evaluating its contribution to the total erosion. Some investigators -- for instance, Justrow [1923] -- consider that the frictional wear *per se* is insignificant, whereas others -- for instance, Kosting [1939b] -- conceive of it simply as the means of removal of portions of the bore surface that had already been loosened by previous chemical or physical action. Tulloch [1921] suggested that the frictional wear is increased at the muzzle by the abrasive action of particles of steel carried forward from the rear of the bore. At any rate, some evidence that wide rotating bands caused more erosion than narrow bands was obtained [Lane, 1933] in the firing of 3-in. antiaircraft liners (see Sec. 9). In the second place, the design of the rotating band helps to determine the extent to which gas can leak past the projectile, which is an effect that is considered in detail in Chap. XIII. In the third place, the material of which the rotating band is made may add another factor to these two mechanical ones by reason of metal fouling, which is considered briefly in Sec. 68.

20. Cartridge case

Ammunition is of two general types, depending on whether the powder and primer are, or are not, contained in a cartridge case. The cartridge case, which is usually made of drawn brass, also serves as an obturator to prevent the escape of powder gases through the breech mechanism. The thin body of the case at the forward end is expanded by the gas pressure until it makes a gas-tight seal with the wall of the chamber. (Obturation of the breech of a gun that does not use a cartridge case is obtained by means of an asbestos mushroom pad or other gas check device which is part of the breech mechanism.) The case and the chamber into which it fits are tapered slightly, in order to facilitate removal of the empty case after firing. The primer is held in a recess in the bottom of the case, so that it is struck by the firing pin that operates through the breech mechanism. A cartridge case is only slightly affected by firing, and therefore can be used a number of times, if it is resized to the proper dimensions.

21. Fixed and separate-loading ammunition

A complete round of fixed ammunition consists of the projectile and fuze (if any) firmly crimped in the end of a cartridge case that contains the powder and primer. Such ammunition is used for small arms and for most guns up to and including the 105-mm gun in the Army and the 5-in. 25-caliber AA gun in the Navy. It is essential for all automatic and semiautomatic guns.

Semifixed ammunition, in the nomenclature of the U. S. Army, differs from fixed ammunition only in that the projectile is loose in the end of the cartridge case and the powder is in bags. This type of ammunition is employed for guns, such as the 105-mm howitzer, that use charges of different sizes in order to vary the range. The cartridge case is loaded originally for the maximum range, and then, if a shorter range is desired, one or more bags of powder are removed. The projectile and cartridge case are loaded into the gun as one unit. In the U. S. Navy the term semifixed ammunition has a slightly different connotation. It is a form of separate-loading ammunition in which the powder charge is packed in a cartridge case for convenience in handling, but in which the projectile and the cartridge case are loaded separately into the gun. This manner of loading gives opportunity to ram home the projectile against the forcing cone. The 5-in. 38-caliber AA gun and the latest 6-in. guns of the Navy use this form of semifixed ammunition. It is also used in the new Army 4.7-in. gun M1 without being designated by any special name.

Bag ammunition, which is the general form of separate-loading ammunition, consists of a projectile, one or more bags of powder and a primer. The powder bags are made of silk cloth, and an ignition charge is contained in the base of each. The primer is attached to the end of the mushroom stem. Bag ammunition is used for all large guns, which sometimes are called bag guns as distinguished from case guns.

CHAPTER IV. PROPELLANTS

22. Classification of explosives

Propellent powders are always low, or progressive, explosives, characterized by propagation of the explosion -- really a very rapid burning -- only on exposed surfaces, by the heating of successive layers to the ignition temperature (see Chap. V). In high explosives, on the contrary, a detonating wave is transmitted practically instantaneously throughout the mass after initiation of the explosion by heat or shock.[15/] Both nitroglycerin and trinitrotoluene (TNT) are high explosives, but when either is incorporated into a colloid with nitrocellulose, as is done in the manufacture of some propellent powders (see Table VI), it loses its tendency to detonate and merely increases the rate of burning of the mixture. A low explosive, on the other hand, may acquire the power to detonate under special circumstances, such as extreme shock.

23. Granulation

After General Rodman of the U. S. Army discovered the principle of the progressive burning of gunpowder in 1860 and applied this principle by compressing gunpowder into perforated grains of different sizes, the term powder as applied to explosives lost its etymological connotation of a pulverized material. Powders today are produced in the form of cylinders, cords, tubes, flakes and strips. Most propellent powders in the United States are made in the form of cylindrical grains, the diameters of

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15/ A recent discussion of the theory of detonation has been given by Carl [1940].

which vary from 0.03 in. for a .30-caliber rifle to 0.9 in. for a 16-in. gun. The lengths vary correspondingly from 0.06 to 2.1 in. For a weapon of a given caliber several different sizes of powder may be used, depending on the type of projectile.

The smaller cylindrical grains have single axial perforations, and the larger ones have seven perforations parallel to the axis. Six of these latter perforations are at the vertices of a regular hexagon and the seventh is at the center, the distances between centers of all adjacent pairs being nearly equal. Such multiperforated powders are said to be progressively granulated, because the burning surface increases as burning proceeds, and hence the rate of burning increases.

The <u>web thickness</u>, which is the minimum thickness of the grain between any two boundary surfaces, either internal or external, determines the time required to consume a powder of given composition. The web thickness of a singly-perforated grain is $\frac{1}{2}(D-d)$ and that of a multiperforated grain is taken as $\frac{1}{4}(D-3d)$, where D is the diameter of the grain and d is the diameter of the perforation [Naval Ordnance, 1939, p. 37]. Hence, the grain diameter is about three times the web thickness of a singly-perforated grain, and from five to ten times the web thickness of a multiperforated grain.

24. Chemical composition[16/]

Gunpowder -- frequently called <u>black powder</u> -- was used as a propellant until 1884, when Vieille introduced colloidal <u>smokeless</u>

16/ The effect of the chemical composition of propellants on erosion is discussed in Sec. 106.

powder made of nitrocellulose. Today the two general types of propellant used by all nations are single-base and double-base powders. A single-base powder is one in which the principal ingredient is nitrocellulose. A double-base powder contains a considerable quantity of nitroglycerin in addition to nitrocellulose. In both types the nitrocellulose is gelatinized by suitable solvents. For a single-base powder ether and alcohol are usually used. The nitroglycerin in double-base powder assists considerably in the gelatinization, so that if enough nitroglycerin is present, no solvent is needed; otherwise acetone is used. Double-base powders, which give better ballistic results than single-base powders, have been standard propellants in Great Britain and some other countries for many years. Because their erosive effect is greater, however, double-base powders have not been used extensively in the United States.

25. American propellants

For many years the standard smokeless propellent powder used in this country was pyro powder. This is made from "pyrocellulose" (a nitrocellulose containing 12.6 percent nitrogen) to which is added 0.5 to 1.0 percent diphenylamine as a stabilizer. This is still the standard powder in the Navy. Much of it is still on hand in the Army, especially for the larger caliber guns; but NH powder ("nonhygroscopic") and FNH powder ("flashless and nonhygroscopic") are the ones being produced today. The first lot of FNH powder was made in 1924, but the total amount produced before 1930 was very small.[17/] Therefore, much of the data on the erosion of guns in the U. S. services apply to guns fired with pyro powder.

The composition of the various smokeless powders, other than pyro powder, currently used by the U. S. Army are listed in Table VI, which is based on the confidential specifications of the Ordnance Department. The NH and FNH powders keep better than pyro powder because they are less hygroscopic. This property is obtained by the inclusion of dinitrotoluene (DNT) and dibutylphthalate. Double-base powders in general are less hygroscopic than single-base ones, and hence much less DNT is needed in M2- than in M1-type powder. These same two compounds serve also as coolants in the M1-type FNH powder, causing the powder gases to emerge from the muzzle at a temperature below their flash point when mixed with the oxygen of the air. The flash from FNH, M2 powder is repressed by the inclusion of barium and potassium nitrates. In some of the small arms powders it is repressed by potassium sulfate, and this compound can be used also as an aid in the M1-type cannon powder.[18/] Flashlessness, which depends on granulation and ignition as well as on composition, has been achieved only to a partial degree in large-caliber weapons. The potassium nitrate used in some of the powders improves the ignition. The tin and tin oxide were used as decoppering agents

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17/ Mr. Bruce E. Anderson, Ammunition Division, Industrial Service, Ordnance Department, personal communication, Aug. 29, 1941.

18/ FHN/P powder also contains potassium sulfate; see last footnote (*) under Table VIB.

(see Sec. 69). The graphite glazing on the M2 cannon powder, which is also used sometimes on other powders of small granulations, is simply a lubricant to make the powder flow more readily and therefore pack better.

Attempts have been made from time to time to develop a powder that would have a high propellent power without causing a high temperature in the gun, and that would therefore be flashless and presumably less erosive. The most successful of such cool powders are those based on nitroguanidine, also called picrite.19/ The Du Pont Company experimented with nitroguanidine powders for several years after World War I, but abandoned them after the development of the present FNH powder. They were found excellent as regards flashlessness, but were objectionable because of smoke and ammonia fumes. Also the weight of charge was larger than for pyro powder -- 15 percent larger for a 75-mm gun [Storm, 1925]. These objections are considered by the British to be outweighed by the advantages of flashlessness and reduced erosion (Sec. 108); and so they are using two picrite powders (see Table VIB).

26. British powders

In 1888 a special committee adopted as standard for the British services a smokeless powder made by gelatinizing a mixture of highly nitrated nitrocellulose and nitroglycerin with acetone. It was called cordite because it was formed in cords of various

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19/ Chemical formula, $NH_2C(:NH)NHNO_2$. Attempts to make the dinitro derivative, which would presumably have a higher potential, have failed. (Dr. G. B. Kistiakowsky, private communication, Apr. 24, 1942.)

Table VI. Nominal composition in parts by weight of smokeless powders.

A. American Powders

Ingredient	Cannon Powders			Small Arms Powders					
	NH,M1	FNH,M1	FNH,M2	No.5	IMR 1185	IMR 4676	IMR 4166	IMR 4814	EC[a]
Nitrocellulose[b]	87.0	85.0	76.45[c]	99.0	91.0	100.0	97.5	100.0	80.0[d]
Nitroglycerin			19.5						
Dinitrotoluene	10.0	10.0	1.0	1.0	6.5	7.5	10.0	8.5	
Diphenylamine	1.0	1.0	0.60	1.0	0.5	0.70	0.6	0.70	0.75
Dibutylphthalate	3.0	5.0							
Potassium sulfate						1.0	1.0	1.0	
Barium nitrate			1.4						8.0
Potassium nitrate			0.75						8.0
Tin					1.93				
Tin dioxide							1.5		
Graphite glazing			0.30						

[a]Also contains 3.0 parts of starch and 0.25 parts of aurine, a red coloring agent.

[b]Containing 13.15 percent nitrogen.

[c]Containing 13.25 percent nitrogen.

[d]Containing 13.20 percent nitrogen.

B. British Powders (Cordites)*

Ingredient	Mk. I	M.D.	W.	W.M.	S.C.	N.	N.Q.
Nitrocellulose[e]	37	65	65	65	49.5[f]	19	21.5
Nitroglycerin	58	30	29	29.5	41.5	18.5	20
Picrite						54.7	54.7
Mineral jelly	5	5	6	3.5			
Carbamite				2	9	7.5	3.5
Chalk				0.4		0.2	0.15
Cryolite						0.3	0.3

[e]Containing 13.1 percent nitrogen,

[f]Containing 12.2 percent nitrogen.

*After Littler (1942). To save space we have omitted from this table NH, FNH and FNH/P, which are American-made single-base powders used by the British services. The first two have essentially the compositions given in Table VIA. The FNH/P contains 1 percent of potassium sulfate in addition to the ingredients listed for FNH,M1.

Notes for Table VI A

(1) Abbreviations. -- NH, nonhygroscopic; FNH, flashless and nonhygroscopic; IMR, improved military rifle; EC, Explosive Company, the name of the English manufacturers who first made this powder after its invention in 1882 [Marshall, 1917, p. 48.]; AP, armor-piercing.

(2) Use of small arms ammunition. --

Caliber .22, no standard composition.

Caliber .45, Du Pont Pistol No. 5.

Caliber .30 (ball and AP), 1925-40, IMR1185 principally, but also several lots of pyro and FNH powders; since the summer of 1941, IMR4676.

Caliber .30 (blank), EC.

Caliber .50 (ball and AP), before 1928, various smokeless powders to which different metallic compounds had been added; 1928-41, IMR4166; since the spring of 1941, IMR4814.

Caliber .50 (blank), EC.

Notes for Table VI B

(1) General notes on British cordites. --

Mark I, the original British cordite (1889); still made for pistol and "blank" ammunition.

M.D., manufactured on a large scale for small arms ammunition.

W., Land Service propellant of improved stability; largely replaced M.D. after 1932 for major caliber guns.

W.M., "Emergency" Land Service propellant; introduced April 1940; replaces W.

S.C., the principal Naval propellant; developed by Research Department, Woolwich Arsenal and introduced about 1923; made by solventless process.

N., mainly used for antiaircraft guns (3.7 and 4.5-in.), but flashless charges have been determined for most guns and howitzers.

N.Q., mainly used for smaller guns (for example, Q.F. 6-pdr) and howitzers (for example, Q.F. 25-pdr, B.L. 5.5-in., etc.).

(2) Special notes on nomenclature of flashless propellants. -- The shape of the grain (other than cords) or the source of the nitrocellulose is denoted by the following additions after the solidus: tube =/T; slotted tube =/S; multitube =/M; nitrocellulose from cotton waste =/A; nitrocellulose from wood =/F.

The web thickness in thousandths of an inch is denoted by a figure following the letter; thus, "cordite N/M. 048."

diameters. The original cordite Mk. I caused so much erosion that the amount of nitroglycerin was greatly reduced to give cordite M.D. (= "modified"). The mineral jelly (vaseline) in it serves the double purpose of coolant and preservative [Marhsall, 1917, I: 304-5]. The compositions of these and other more recently developed British powders are listed in Table VI B.

Ballistite was invented by Alfred Nobel in 1888 by gelatinizing a nitrocellulose of low nitration with nitroglycerin. The ratio of nitrocellulose to nitroglycerin has varied from 40/60 to 50/50, and various stabilizers have been added. Ballistite or powders of nearly equivalent composition were used by the German and Italian governments at one time [Marshall, 1917, I: 301-2].

27. Stability

All smokeless powders deteriorate during storage. Among the products of decomposition are oxides of nitrogen, which progressively accelerate further decomposition. Stabilizers act by combining with these oxides and preventing the acceleration, without actually stopping the decomposition. The common stabilizers are diphenylamine, vaseline and "centralite."[20/] Powder that is deteriorating produces objectionable fumes even before its ballistic properties are impaired. Air-dried pyro powder has been found to last 30 to 40 years, but water-dried pyro powder lasts a somewhat shorter time, depending upon the

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20/ Also called "carbamite." The chemical name is s-diethyldiphenyl urea [Pike, 1942].

size of granulation and various conditions of manufacture. On the basis of accelerated tests, NH and FNH powders are expected to last considerably longer than even air-dried pyro powder. Because both moisture and high temperatures accelerate to some extent the deterioration of smokeless powder, considerable care is taken to protect it during storage.

28. Primers

The initial impulse required for the ignition of a charge of powder is obtained from a small amount of highly sensitive explosive that can be readily set off by percussion, friction or heat. Smokeless powder in all but the finest granulations is so difficult to ignite that in addition to the detonating element most primers contain an igniter charge of black powder which burns very rapidly with a hot flame and ignites the main powder charge. The best ballistic results might be obtained if the ignition were simultaneous throughout the charge. This condition is approached in practice by the method of distribution of the igniter charge, a perforated tube along the axis of the chamber being frequently used to contain the black powder. The proportion of black powder to smokeless powder varies, because the same primer is often used with cartridge cases of several different calibers.

CHAPTER V. BURNING OF THE POWDER

29. Effect of pressure on rate of burning

A colloidal propellant burns by parallel layers. This law, first enunciated by Piobert [1839] in the case of gunpowder, has been verified for colloidal propellants by the observation that unburned pieces of powder recovered after having been fired in a gun retain their original chemical and physical properties below the surface [Crow and Grimshaw, 1931b, p. 392; Muraour and Aunis, 1938.] Recent observations, however, show that under certain conditions the burning takes place below the surface as well.[21/] The rate of burning increases very rapidly with increase of pressure of the liberated gases. Thus the rate is increased about a thousand-fold by increase of pressure from 1 to 2500 atmos.

The highest pressure to which smokeless powder can be subjected without having it detonate or burn erratically does not seem to have been determined. During the test of a certain 37-mm gun having an extra strong barrel, a series of five rounds were fired at pressures ranging from 63,400 to 67,900 lb/in.^{2}, as measured by a piezoelectric gage. The velocities, which varied from 3355 to 3375 ft/sec, were acceptably uniform. Hence, as far as the burning of the powder is concerned, a pressure as high as this might perhaps be used in a hypervelocity gun.

21/ R. E. Gibson, personal communication, July 1942.

30. The mechanism of the burning process

The surface of a burning solid propellant remains relatively cold while a gaseous reaction at a very high temperature (Sec. 36) takes place at a distance of approximately 10^{-5} cm from the surface. The slow step in the complex process is the transfer of heat to the surface by the molecules of the burning gas that impinge upon it, for a surface layer of the solid must be kept at the temperature of spontaneous decomposition in order that burning may continue. Because an increase of pressure means that more hot gas molecules are available to transfer energy, the rate of burning is increased by pressure. This view of the burning process has been elaborated recently by Boys and Corner [1941] and by Lennard-Jones and Corner [1941]. Crow and Grimshaw [1931b] and Muraour [1931] had suggested essentially the same theory, except that they had postulated a cruder method of heat transfer.

Earlier investigators[22/] had derived empirical equations of the form,

$$r = a + bp^{c},$$

where *r* is the rate of regression of the burning surface, *p* is the pressure, and *a*, *b* and *c* are empirical constants. Frequently *c* was considered unity and *a* was very small or zero. In such equations, however, the apparent rate-of-burning constant, *b*, had been found to increase under conditions giving rise to increased

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22/ See Crow and Grimshaw [1931b, pp. 387-8, 397] for bibliography. Bennett [1921, p. vii], in the preparation of his Tables for interior ballistics, assumed that the rate of burning of pyro powder is proportional to the two-third powder of the pressure.

cooling. This tendency was explained by Crow and Grimshaw by showing that b is in reality a function of the temperature of the powder gases.

Instead of assuming that the heating of the surface of the powder to the ignition temperature results from molecular impact, Kent [1935] suggested that radiation from the powder gases is the cause. He argued that the escape of volatiles from smokeless powder while it is being warmed up prevents contact of hot powder gas with the surface, whereas radiation could penetrate to the surface. He explained various experimental phenomena by this hypothesis.

Ignition of powder at temperatures below the normal ignition point by photochemical decomposition caused by the absorption of radiation of selected frequencies was suggested as a possibility by Crawford [1937], in his proposal for experiments involving the application of spectroscopy and photography to interior ballistics. He also suggested the possibility of the photosensitization of the ignition of powder by radiation from cool mercury vapor emitting resonance radiation of wave-length 2537A. Later Crawford[23/] remarked that the efficacy of potassium in promoting ignition might be explained as the result of emission of radiation of just the proper frequency by excited potassium ions. He suggested that this hypothesis could be tested by exposing some powder to irradiated potassium vapor in an evacuated tube.

23/ Maj. D. J. Crawford, Jr., Ordnance Department, personal communication, Aug. 30, 1941.

31. Quickness of powder

The rate of burning of a powder — often referred to as its quickness -- is one of the most important factors in determining the effectiveness of the powder for a particular purpose. The criterion which is applied to the burning of a powder in a gun is that a maximum proportion of the energy of the powder shall be transferred to the projectile without allowing the powder pressure to exceed the limit imposed by the strength of the walls of the tube. If the powder burns too fast, a dangerously high pressure will be set up; whereas if the powder burns too slowly, some of it will remain unburned when the projectile leaves the muzzle, and hence its energy will be wasted. The rate of burning is controlled by variation of the form and the dimensions of the grains, particularly the web thickness. The smaller the web, the faster will a powder burn, because for a given total weight, powder grains with small web have a larger surface area.

Direct measurement of the quickness of a powder is now possible by a method developed at the Burnside Laboratory of the Du Pont Company. While a sample of the powder is being burned in a closed chamber, an automatic oscillograph record is made of dp/dt, the time-rate of change of the pressure, as a function of the pressure. By comparison of this result with that obtained with a standard powder, the ballistic properties of which had been determined by firings in a particular gun, it is possible to calculate the charge of powder required to achieve a desired velocity in a similar gun.

The uniformity of the rate of burning is also important; for if the rate is irregular, pressure waves may be set up in the bore of the gun. Such waves are potentially dangerous, for by reinforcement of two of them, a pressure large enough to burst the gun may be attained. Uniformity of burning is aided by proper design of the ignition system, striving toward the ideal situation of enveloping the charge of smokeless powder in a hot flame from the igniter charge so that all the grains are ignited simultaneously.

32. Heat of explosion and heat of combustion 24/

The heat of explosion of a propellent powder is the quantity of heat evolved when the powder burns at constant volume in a closed chamber without added oxygen. It is less than the true heat of combustion, which is the heat liberated when the same powder is burned at constant volume in an excess of oxygen. (Some writers, as for instance de Bruin and de Pauw [1928], designate the heat of explosion as the heat of combustion.) The heat of explosion is of more practical interest, because it measures the potential 25/ of the powder -- that is, its capacity for doing work.

24/ A summary of the heats of formation of the constituents of propellants has been given by Schmidt [1934] and by Pike [1942].

25/ This definition of powder potential follows Hayes [1938, p. 50]. J. O. Hirschfelder [personal communication, Aug. 29, 1942] supports an earlier suggestion by R. H. Kent in recommending that the powder potential be taken as the product of T_e, the adiabatic flame temperature (Sec. 36), and C_V, the high-temperature molal heat capacity of the gas at constant volume. This change of definition is equivalent to considering C_V in the product T_eC_V as the average value between, say, 2000°K and the adiabatic flame temperature instead of as the average value between 0°C and the adiabatic flame temperature [compare Eq. (V-1) in Sec. 36]. The potential calculated in this way is some 20 percent larger than the heat of explosion.

In the calorimetric determination of the heat of explosion [26] the calorimeter is usually at or near room temperature, and therefore the water formed during the reaction is condensed and its heat of vaporization appears as part of the apparent heat of explosion. To obtain the true heat of explosion (water gaseous) the amount of water must be determined. The correction for the heat of vaporization amounts to slightly less than 10 percent of the apparent heat of explosion (water liquid) [Noble 1906, pp. 476-80; de Bruin and de Pauw 1928, Tables III and IV].

Values for the heats of explosion and of combustion of a number of powders appear in Table VII. The results of Dunkle [1935] showed that the ratio of the heat of explosion Q to the heat of combustion H of a smokeless powder is a linear function of the ratio of the number of moles of atomic oxygen per gram of powder to the sum of the corresponding numbers for carbon and hydrogen $[O/(C + H_2)]$ in the powder; and also that it is a linear function of the corresponding ratio $[CO_2]\cdot[H_2O]/[CO]\cdot[H_2]$ of the products of explosion of the powder. The slight variation of the heat of explosion with the density of loading [27] [Noble 1906, Plate 14], which is related to the question of change of composition of the products of explosion during cooling, is discussed in Sec. 39.

26/ Noble [1905, pp. 216-20]; de Bruin and de Pauw [1928, 1929]; Crow and Grimshaw [1931a].

27/ The density of loading is the ratio of the weight of charge to the weight of water that would fill the chamber at 4°C; hence in the metric system it is numerically equal to the weight of charge in grams divided by the volume of the chamber in milliliters.

Table VII. Heat of explosion, heat of combustion and temperature of explosion of propellent powders.*

Composition[a] (percent by wt.)	Nitrocellulose Powders		Double-base Powders		FNH Powder
	N3	X-927**	C2	1511**	1358**
Nitrocellulose					
(12.6% N)	94.80	95.23			
(13.2% N)			70.16	78.20	83.97
Nitroglycerin	---	---	28.67	19.80	---
Dinitrotoluene	---	---	---	---	9.88
Dibutylphthalate	---	---	---	---	4.94
Diphenylamine	0.45	0.49	---	0.99	1.00
Volatile matter	4.75	4.28	1.17	1.01	0.22
Total	100.00	100.00	100.00	100.00	100.01
H(kilocal/gm)[b]	831	861	1220	1153	754
Q(kilocal/gm)[c]	---	2614	---	2377	2980
Temp. (°C)[d]	2485	---	3433	---	---
Temp. calc. (°C)[e]	2400	2425	3300	3075	---

[a] See Table IX for composition of products of combustion of these same powders.

[b] Heat of explosion, water liquid.

[c] Heat of combustion.

[d] Calculated by Crow and Grimshaw from heat of explosion and heat capacity of powder gases.

[e] Calculated for this report from composition by method of de Bruin and de Pauw [1929]. (J.S.B.)

*Crow and Grimshaw [1931b].

**Dunkle [1935].

Table VIII. Products of combustion of gunpowder.*[a]

Loading[b] / Pressure[c]	0.10 / 1.6		0.50 / 10.7		0.90 / 35.6	
Gases	Composition (percentage)					
	Wt.	Vol.	Wt.	Vol.	Wt.	Vol.
CO_2	25.97	48.99	25.22	47.21	27.50	52.65
CO	3.03	8.98	5.63	17.04	3.56	10.73
N_2	12.01	35.60	10.22	30.29	10.85	32.64
H_2	0.05	2.07	0.07	3.01	0.03	1.27
CH_4	0.06	0.29	0.16	0.84	0.15	0.81
H_2S	0.41	4.06	0.66	1.61	0.77	1.90
Total	41.53[d]	99.99	41.96	100.00	42.86	100.00
Solids	Composition (percentage)					
K_2CO_3	30.07		35.20		37.55	
$K_2S_2O_3$	11.66		14.70		4.91	
K_2SO_4	11.71		2.69		4.87	
K_2S	2.30		2.06		4.13	
KCNS	0.00		0.17		0.21	
KNO_3	0.32		0.29		0.11	
$(NH_4)_2CO_3$	0.03		0.06		0.09	
C	0.72		0.00		0.00	
Free S	0.41		2.87		5.27	
Total	57.22		58.04		57.14	

*After Noble and Abel [1875], Tables 2, 3, 4.

[a]Large-grain rifle powder, Waltham - Abbey. Composition: KNO_3, 74.95%; K_2SO_4, 0.15%; S, 10.27%; charcoal, 13.52%; water, 1.11%.

[b]Proportion of space occupied by the charge; not "density of loading."

[c]Long tons per square inch.

[d]Should be 42.78% - error in original for one of the individual percentages.

33. Products of combustion of gun powder

The composition of the products of combustion of propellent powders after explosion in a closed chamber have been determined by various investigators. Noble and Abel [1875], for instance, as a part of their classic research on Fired gunpowder analyzed the products of combustion of several kinds of gunpowder at different densities of loading. Their results for a representative gunpowder at three densities of loading are given in Table VIII.

Over half the weight of the material is solid, which is responsible for the smoke from burning gunpowder. Among gaseous products the volume percentages of nitrogen and of carbon dioxide are much greater than from colloidal powder, whereas the percentages of carbon monoxide and of hydrogen are much less (compare Tables VIII and IX). These differences reflect the higher nitrogen and oxygen contents of gunpowder as compared with smokeless powders.

Table IX. Products of combustion of smokeless powders, in moles per kilogram of powder. Table VII, in which these powders are listed in the same order, gives their composition.

Product	Nitrocellulose Powders		Double-Base Powders		FNH Powder
	N3*	X-927*	C2*	1511**	1358**
CO_2	3.200	5.242	6.607	8.322	3.292
CO	20.244	16.484	12.771	11.704	20.543
H_2O	8.827	5.922	11.272	7.923	5.001
N_2	4.269	5.242	5.195	5.604	5.894
H_2	6.979	8.219	1.676	5.120	9.139

*Crow and Grimshaw [1931b].

**Dunkle [1935]. Density of loading, 0.12.

34. Products of combustion of smokeless powder

Because smokeless powder burns without leaving any appreciable solid residue, the determination of its products of combustion is just a specialized application of the standard technic of gas analysis. The water formed during combustion, after it has condensed in the explosion chamber, is either wiped out and weighed as liquid water [Noble, 1905, p. 203], or else it is distilled out of the bomb and absorbed [de Bruin and de Pauw, 1928, p. 9], which is preferable. Analyses of the products of combustion obtained from different kinds of smokeless powder have been published by Sarrau and Vieille [1884], by Noble [1894], by Macnab and Ristori [1894], by Noble [1906] and by de Bruin and de Pauw [1928]. A number of unpublished reports from Picatinny Arsenal [Valente, 1929; Dunkle and Volsk, 1932; Volsk and Dunkle, 1932; and Dunkle, 1935] contain analyses for the new FNH powders, and also for some experimental powders of special compositions. A selection of results from Dunkle [1935] at a density of loading of 0.12 is given in Table IX in the columns headed X-927, 1511 and 1358.

The variation in composition of powder gases with change of density of loading is illustrated by the results of Noble, some of which are reproduced in Table X. Whereas the amounts of nitrogen and of water show only slight variation with density of loading for all three powders, the amount of carbon monoxide decreases while that of carbon dioxide increases as the density of loading, and hence the pressure, is increased. Similarly the ratio of methane to hydrogen increases very greatly with increase of density of

Table X. Variation in composition of powder gases with change of density of loading.*

A. Composition of powders, in percentages by weight.

Component**	NC	C-I	C-M.D.
Nitrocellulose (sol.)	85.5	37.0	65.0
Nitrocellulose (insol.)	14.5		
Nitroglycerin		58.0	30.0
Mineral jelly (vaseline)		5.0	5.0

B. Pressure and volume of gas.

Density of Loading	Pressure (atmos)			Total Gas (ml/gm)			Permanent Gas (ml/gm)		
	NC	C-I	C-M.D.	NC	C-I	C-M.D.	NC	C-I	C-M.D.
0.05	457	495	457	993.1	870.0	955.4	814.7	670.0	781.8
.10	975	1066	990	980.0	878.5	948.0	810.5	692.5	790.0
.15	1516	1783	1600	958.5	880.0	931.0	795.0	699.0	786.5
.20	2103	2591	2354	934.0	875.5	913.5	776.0	697.0	773.0
.25	2789	3467	3193	906.5	865.0	893.5	751.5	688.0	754.0
.30	3498	4404	4069	883.0	848.0	873.0	730.0	671.5	733.5
.40	5228	6302	5830	841.0	820.0	832.0	695.0	644.9	693.5
.50	7133	8124	7544	802.0	798.8	789.5	659.5	623.6	653.5

*After Noble [1901, pp. 454, 476-7, 480].

**NC, nitrocellulose; C-I, cordite Mark I; C-M.D., cordite M.D.

[Table X continued on next page.]

TABLE X. (Continued.)

C. Total composition in percentage by volume.

Density of Loading (gm/ml)	0.05	0.10	0.15	0.20	0.25	0.30	0.40	0.50
				I. Nitrocellulose				
CO_2	14.95	16.19	17.50	19.40	21.50	23.50	27.60	31.60
CO	35.36	34.60	33.35	31.90	29.95	28.25	24.65	20.96
H	20.01	20.67	19.90	18.00	15.80	14.05	11.60	10.00
CH_4	0.49	0.71	1.58	2.89	4.80	6.20	8.44	9.80
N	11.19	10.75	10.62	10.83	11.04	11.16	11.00	11.00
H_2O	18.00	17.08	17.05	16.98	16.91	16.84	16.71	16.64
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
				II. Cordite Mark I				
CO_2	21.07	21.98	23.13	24.37	25.87	27.64	30.56	32.48
CO	26.46	26.13	25.20	23.91	22.31	20.44	17.46	15.43
H	13.53	15.12	15.60	15.53	14.96	13.93	11.73	9.47
CH_4	0.23	0.32	0.54	1.00	1.65	2.45	3.98	5.54
N	15.97	15.08	14.93	14.86	14.90	14.95	15.11	15.60
H_2O	22.74	21.37	20.60	20.33	20.31	20.59	21.16	21.48
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00
				III. Cordite M.D.				
CO_2	14.85	16.45	18.35	20.30	22.25	24.15	28.15	32.35
CO	34.87	33.95	32.40	30.50	28.45	26.45	22.60	19.00
H	18.95	19.20	19.00	18.00	16.65	15.00	11.80	8.45
CH_4	0.29	0.83	1.60	2.70	3.95	5.40	7.80	9.95
N	12.89	12.57	12.45	12.50	12.65	12.85	13.05	13.45
H_2O	18.15	17.00	16.20	16.00	16.05	16.15	16.60	16.80
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

loading. The cause of these variations is considered in Sec. 39 in connection with a discussion of the gaseous equilibria existing at the temperature of explosion.

35. Composition of powder gases from a gun

The experiments that have been referred to so far were performed with closed chambers. A few analyses have been made, however, of the gases formed in an actual gun. Thus Noble [1906, pp. 455-6] obtained the results shown in the second column of Table XI by analysis of a sample of gas withdrawn from the breech end of a 9.2-in. gun just after it had fired a charge of 103 lb of cordite, giving a pressure of 16.1 tons/in^2 and a muzzle velocity of 2600 ft/sec. For comparison, the last two columns of this table give Noble's analyses of the gases obtained from firing charges of cordite at a density of loading of 0.05 in a closed chamber, which in one case had been exhausted and in the other had been initially filled with air at atmospheric pressure. The composition of the gases in the gun agrees closely with those in the closed chamber. Poppenberg and Stephan [1909b] found from an analysis of gaseous mixtures taken at various parts of the barrel that there is more carbon monoxide at the moment of explosion than there is after the gases have cooled down.

The presence of considerable quantities of iron in the powder gases was claimed by Siwy [1908], but he published no supporting evidence. He did not even describe the method of detection.

Table XI. Products of combustion of cordite in a gun compared with those obtained in a closed chamber, in percentages.

Product	Gun (Mean of Two Rounds)	Closed Chamber	
		With Air	Evacuated
CO_2	25.6	27.15	26.35
CO	35.8	34.35	35.05
H	19.0	17.50	19.50
CH_4	0.5	0.30	0.60
N	19.1	20.70	18.50
Total	100.0	100.00	100.00

36. Explosion temperature

The theoretical explosion temperature[28/] refers to the temperature to which the products of an explosion would be raised if the reaction took place adiabatically. This temperature on the centigrade scale is

$$T_e = Q/C_v, \qquad \text{(V-1)}$$

where Q is the molal heat of explosion at constant volume (referred to products cooled to 0°C), summed over all the components of the original explosive, and C_v is the mean molal heat capacity from 0 to T°C, summed over all the products of the explosion. Calculations of the explosion temperature based on this equation are discussed in the next section.

Various attempts have been made to measure the temperature of explosion directly. Noble and Abel [1875; p. 171 in 1906 reprint]

28/ Also called adiabatic flame temperature.

showed that the temperature of explosion of gunpowder is higher than the melting point of platinum, by firing a very thin sheet of platinum and a coil of fine platinum wire with large charges of gunpowder in a closed chamber. Portions of the wire were welded to the sheet, and the sheet itself showed the beginning of fusion when examined under a microscope.

Measurement of the explosion temperature of smokeless powders by means of thermocouples was attempted by Macnab and Ristori [1900]. Because the heat loss is so great, the maximum temperature recorded by a platinum-platinrhodium thermocouple in a closed chamber depends on the diameter of the wire. Each couple of a series of ten made of wires ranging in diameter from 0.010 to 0.040 in. was used to measure the temperature of explosion of the same charge of powder under the same conditions. The emf of the galvanometer was recorded as a function of time on a fixed photographic plate fitted with a moving slit. The maximum deflection was given by the couple made of the thinnest wires; the deflections of the others were progressively less. It was hoped to extrapolate the deflections to a thermocouple of zero thickness, and to calibrate them in terms of temperature; but the attempt was not entirely successful. It was demonstrated that the explosion temperatures of the three explosives, guncotton, cordite, ballistite, increased in the order named, which is the same order as that obtained from calculated temperatures.

It has been suggested that explosion temperatures might be measured by means of the spectra of the burning gas,[29/] a method that has been discussed recently by Brinkman [1940]. The line-reversal method has been used successfully in measuring the flame temperatures in the internal combustion engine. It was suggested by Lewis and von Elbe [1938, p. 337] that this method might be adapted to the measurement of the explosion temperature in a closed chamber "by suspending highly dispersed sodium salts in explosion mixtures and recording the reversal point photographically by progressive adjustment of the comparison radiator."

37. Explosion pressure

The explosion pressure is the maximum pressure that would be developed by the powder gases if the reaction took place adiabatically in a closed chamber. It is related to the temperature of explosion T_e by the equation of state of the powder gases. At the high temperatures of explosion, the intermolecular attraction term in the equation of state can be neglected, and the following simple form of equation suffices:

$$P_e \ (v - \alpha) = RT_e, \qquad \text{(V-2)}$$

where v is the specific volume of the powder gases at the pressure P_e, α is their average covolume and R is the gas constant per gram.

29/ The temperature of the powder gases burning inside a closed chamber has been determined recently at the Geophysical Laboratory by measuring with photoelectric cells the intensity of radiation in different parts of the spectrum that is transmitted by a quartz window in the side of the chamber. This technic will be described by F. C. Kracek, W. Benedict and L. G. Bonner in a forthcoming NDRC report.

Since the density of loading Δ is the reciprocal[30] of $\underline{v}$, this equation may be written in the form

$$P_e = \Delta RT_e/(1-\alpha\Delta). \qquad (V-3)$$

Since α is approximately 0.001 for the six gases commonly found as products of combustion of powder [Sarrau, 1893; Burlot, 1924], the explosion pressure increases almost linearly with an increase in density of loading. Because the number of moles of gas per gram of powder depends on the gas composition, the constant $\underline{R}$ for a given charge also depends on the composition.

Because of the rapidity with which the powder gases lose their heat to the walls of the chamber, the pressure measured[31] in a closed chamber never quite attains the theoretical maximum. For the same reason it is doubtful whether the adiabatic explosion temperature is actually reached. Some of Noble's experiments [1905, p. 227] demonstrated the extreme rapidity of cooling. Thus the pressure of the powder gases from cordite fired in a closed chamber decreased from 39,000 lb/in.^{2} to 60 percent of that value in 1 sec. The loss of pressure is greater at a low density of loading. Noble, nevertheless, did not correct the observed pressures, and hence his measurements — some of which are reproduced in Table X,B — show considerable departure from linearity at low densities of loading

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30/ This relation assumes that the weight $\underline{W}$ of the powder gases is the same as the weight of the original charge. Then $v = V/W$, and in the metric system, Δ is numerically equal to W/V, where $\underline{V}$ is the volume of the chamber (see footnote 27). The expansion of the chamber by the pressure is neglected.

31/ See Chap. X for methods of measurement.

and approach linearity at high densities. He had previously come to the conclusion [Noble and Abel, 1875] that the pressure loss due to the cooling would not exceed 1 percent. However, the special experiments of Muraour [1923, 1925a, and 1925b] and of Crow and Grimshaw [1931b] have shown that this loss may easily exceed 10 percent, especially at low densities of loading or in a small chamber.

In a gun the conditions are much more complex than in a closed chamber, because of the expansion of the gases as the projectile moves forward. They will be considered in Sec. 50 in conjunction with a discussion of the movement of the projectile.

38. Approximate calculation of temperature of powder gases

The temperature of the powder gases at the time of explosion may be calculated by either of two independent methods, which are based on Eqs. (V-1) and (V-3), respectively. The former is related to the thermochemical properties of the powder and of the evolved gases. Equation (V-1) seems to have been used first for this purpose by Mallard and Le Chatelier [1883]. Equation (V-3) was developed by Abel as an empirical relation in the form

$$P = \lambda \Delta/(1 - \alpha \Delta), \qquad \text{(V-4)}$$

where λ and α were empirical constants, and it is often referred to as the Abel, or the Noble and Abel, equation.

The calculation of the temperature of explosion from the maximum pressure developed in a closed chamber, in accordance with Eq. (V-3), involves two difficulties. The equation itself is only an approximation, and there is not at present sufficient knowledge of the kinetic properties of gases under the conditions of temperature and pressure concerned for it to be improved. The covolume, in particular, is imperfectly known. An equally important difficulty is that of measuring the true pressure of the explosion. As already mentioned, the gas is cooled so quickly by the walls of the chamber that the maximum pressure measured is somewhat less than the true pressure. The correction to be added to the observed pressure was evaluated by Muraour [1923, p. 323; 1925a, p. 460] from experiments in a closed chamber in which the area of the surface exposed to the gases could be varied. It was calculated by Crow and Grimshaw [1931a, p. 50] as an example of heat conduction, from pressures measured in two chambers of widely different surface areas.

In the early applications of Eq. (V-1) to the calculation of the temperature of explosion, C_V was evaluated on the basis of the composition of the cooled powder gases. It was expressed as a linear function of the temperature; whereupon Eq. (V-1) could be solved[32/] for T. It was soon realized, however, that the products of combustion found in a closed chamber after it has cooled to room temperature are not necessarily the same as those present under the conditions of high temperature and high pressure existing at the time of the explosion, and also that the heat capacities of gases at high temperatures are not linear functions of the temperature.

32/ See Hayes [1938, p. 55] for an exposition of this solution.

39. Secondary reactions during cooling

Experiments intended to elucidate the changes that take place during cooling of the products of the explosion were conducted by Poppenberg and Stephan. They confirmed Noble's observations (see Table X) that the ratio

$$k = [H_2O]\cdot[CO]/[CO_2]\cdot[H_2]$$

decreased with increase of density of loading. They explained this variation by the assumption that the mixture cooled more slowly at high densities of loading, and hence that the "water gas" reaction [Eq. (V-6)] had more time to proceed. This view was substantiated by firings [Poppenberg and Stephan, 1909a] made at the same density of loading with the explosion chamber cooled to -120°C in one case and heated to 90°C in the other. More carbon dioxide was produced at the high than at the low temperature.

The formation of methane was shown to be a secondary reaction by later experiments made by Poppenberg and Stephan [1910a] and by Poppenberg [1923]. In some of them the explosion took place inside a small porcelain bomb contained in an evacuated chamber. The sudden expansion of the gases when the porcelain bomb burst so cooled them that the equilibrium was frozen. Criticism by Kast [1910] of the interpretation of these results was met by a further discussion by Poppenberg and Stephan [1910b]. Their conclusion with respect to the secondary formation of methane was confirmed by Muraour [1919a], who quenched the equilibrium mixture by having it expand through a 1-mm canal into an evacuated vessel. It also is in agreement with the latest calculations [Kent, 1938a].

40. Calculation of corrections for composition of powder gases

After it was realized that the composition of the cooled gases reflected secondary reactions during cooling, methods of calculation were developed to correct for them. These corrections, combined with improved data for heat capacities of gases at high temperatures and with increasingly precise measurements of explosion pressures, gradually decreased the discrepancy between the values of explosion temperatures calculated from the maximum pressure and those calculated from heat capacities. At first [Noble, 1906, pp. 463-5; Poppenberg, 1909; Muraour, 1919b] the temperatures calculated from the maximum pressure were much too low, except at high densities of loading. In a later comparison [Muraour, 1924a, 1924b, 1924c, 1926] the disagreement was much less. Finally the very thorough investigation of Crow and Grimshaw [1931b] resulted in agreement within 2 percent for the value of λ -- the ballistic force of the propellant -- derived from the heat capacity and heat of explosion and that derived from direct measurements of the explosion pressures at different densities of loading. This function is the leading coefficient in the equation of state adopted by Crow and Grimshaw,

$$p_o = \lambda(\Delta + \alpha\Delta^2 + a\alpha^2\Delta^3 + \dots), \qquad (V\text{-}5)$$

which is merely a more elaborate form of the Noble and Abel equation, Eq. (V-4).

The method of calculation used by de Bruin and de Pauw [1928] and by Schmidt [1929] to correct for the change in gas composition by the secondary reactions in cooling consisted in calculating the corrections to the composition of the cooled gases, by application of the equilibrium constant for the secondary water-gas reaction,33/

$$CO + H_2O \rightleftharpoons CO_2 + H_2. \qquad (V-6)$$

41. Calculation of temperature and composition of powder gases34/

The method of Henderson and Hassé [1922], which was later used by Poppenberg [1923] and by Crow and Grimshaw [1931b], is superior in that it does not require a knowledge of the composition of the cooled gases. By a series of successive approximations the equilibrium composition of the hot gases is derived from the following experimental data: (i) the molal heat of explosion at constant volume; (ii) the chemical composition of the powder in terms of the chemical elements present; (iii) the equilibrium constant as a function of the temperature for each of the reactions in which the products of combustion may be assumed to participate; and (iv) the mean molal heat capacity from 0°C to the explosion temperature for each of the substances that it is assumed might be present in the explosion.

The molal proportions of the chemical species assumed to participate in the equilibria at the temperature of the explosion

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33/ For a discussion of this reaction, particularly in flames, see Bone and Townsend [1927, p. 322].

34/ Hirschfelder, McClure and Curtiss [1942] have systematized the calculation of the adiabatic flame temperature and the composition of the powder gas. Their method is based on the same data as is the one described in Sec. 41; but instead of carrying out the approximation by assuming successive values for the flame temperature, they calculate the energy loss at two different assumed flame temperatures, and then, by linear interpolation between these values for that flame temperature which would correspond to zero energy loss, they obtain the true flame temperature.

form the unknowns of a series of simultaneous algebraic equations. One group of these equations of condition is based on the known chemical composition of the powder. The other is derived from the equilibrium constants for the assumed equilibria, evaluated at a provisionally assumed temperature. The solution of these simultaneous equations gives the first approximation to the molal composition at the time of explosion. (Henderson and Hassé considered only the water-gas reaction in the main calculation, and then used the equilibrium constants for various other possible reactions to obtain second-order corrections.) From this result and the assumed temperature, the mean molal heat capacity C_v of the whole mixture is calculated, and then the experimental value for the heat of explosion is divided by C_v to compute the temperature [Eq. (V-1)]. This value of the temperature, which will differ somewhat from that originally assumed, is used as a basis for a repetition of the calculation. Finally, after one or more repetitions, the computed temperature will agree with the assumed temperature. This value and the corresponding molal composition are considered as those of the burning gases.

This method of calculation, which involves the simultaneous consideration of a number of equilibria, was used by Kent [1938a] in a recalculation of the composition of the gases from two of the powders previously considered by Crow and Grimshaw [1931b]. The equilibria involving the formation of methane and nitric oxide and those for the dissociation of water and nitrogen were included in addition to the water-gas reaction, which had been the only one considered by Crow and Grimshaw. This recalculation[35/] made use of the latest values for heat capacities of gases at high temperatures, obtained largely from measurements of band spectra [David and Leah, 1934; Lewis and von Elbe, 1938, Chap. XVI]. The results, which are reproduced in Table XII, show that the early assumption of the dominance of the water-gas reaction was correct. Later unpublished computations [Kent and Lane, 1941] involving a total of twelve different equilibria have not changed the results materially.

The water-gas reaction does not involve a volume change if the gases are ideal, and hence the equilibrium is not affected by change of pressure. On this basis it has been argued that the apparent change of explosion temperature and of heat of explosion with variation in density of loading are spurious effects. The existence of reactions involving volume changes in the powder gases, however, brings in a slight variation of the explosion temperature with change of pressure, as shown in Table XII.

42. Equilibrium conditions during burning

Although the calculations just discussed furnish us with our best knowledge of the composition and temperature of powder gases at the time of explosion, there remain two possible sources of uncertainty, in addition to the uncertainties of the experimental data involved in the calculation. The variation of the heat capacity of the gases with pressure [Muraour, 1924a, p. 330] has

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35/ Hirschfelder, McClure and Curtiss (reference 34) have repeated the calculation, using a variation of this method with the additional refinement of correcting for the fact that the gas is nonideal.

Table XII. Partial pressures, in atmospheres, of the constituents of powder gases, and temperature of explosion.*

Powder	Nitrocellulose		Ballistite	
Pressure (atmos)	340	3400	340	3400
CO	138.48	1386.5	81.04	756.8
CO_2	40.92	411.0	73.86	827.5
H_2O	82.00	827.9	88.89	964.8
N_2	36.17	326.6	50.84	522.5
H_2	40.69	407.4	12.60	111.2
O_2	—	—	5.08	26.0
N	0.01	—	0.17	1.3
H	.84	2.9	3.11	16.1
O	.01	—	1.76	7.2
OH	1.02	3.5	18.99	133.9
NO	0.06	0.2	3.86	34.7
Temp. (°C)	2663	2689	3398	3684

*After Kent [1938].

not been taken into account. Moesveld [1928, p. 34] concluded, however, on the basis of the van der Waals equation, that the variation is negligible at high temperatures.

The other source of uncertainty, namely, the assumption of a state of equilibrium among the atoms of a gas, is more important, because this assumption underlies all the calculations. Muraour [1924a, p. 335] suggested that during combustion equilibrium may not be maintained; oxygen, for instance, may react more rapidly with hydrogen than with carbon. He considered, nevertheless, that equilibrium would be established as soon as burning was completed.

Lewis and von Elbe [1938, p. 306] pointed out that in the absorption of the energy of explosion by the gas molecules there may be a lag in the excitation of the translational degrees of freedom of carbon dioxide, carbon monoxide and nitrogen. The resulting momentary excess of translational energy causes "a higher pressure which lasts for a period comparable with explosion times. Ultimately, energy equilibrium among all the degrees of freedom is established. Thus, the heat capacity of these gases is a time function." A somewhat similar possibility of nonequilibrium conditions is that suggested by Crawford [1937], who considered that because of the very rapid rate of burning in a gun, the gas kinetic energy of the products of combustion lags behind the radiant energy field of the explosion system. This would cause a considerable deviation from the van der Waals equation.

An investigation of equilibrium has been made recently at Aberdeen Proving Ground in collaboration with Professor H. C. Urey [Kent and Lane, 1941]. A small amount of barium carbonate containing a heavy isotope of carbon was fired with a charge of powder, and then the distribution of the heavy isotope between carbon monoxide and carbon dioxide was determined in the products of the combustion after they had been quenched by rapid expansion. According to a preliminary report of these experiments,[36] the heavy isotope was found uniformly distributed

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36/ R. H. Kent, personal communication to R. E. Gibson, Jan. 28, 1942.

between the two gases. This is considered as evidence that chemical equilibrium had been reached during the combustion of the powder.

CHAPTER VI. MOVEMENT OF THE PROJECTILE IN THE BORE

43. The detailed mathematical description of the movement of the projectile in the bore of a gun, which is one of the principal problems of interior ballistics,37/ is too involved to be presented in this report. Instead, a few outstanding details of that description will be mentioned in their relation to erosion.

44. Rate of increase of pressure

The rate at which the pressure increases behind a projectile in a gun depends on the interaction of several factors. It is controlled principally, of course, by the rate of burning of the powder, but this reciprocally depends on the pressure. In a closed chamber the pressure rises at an ever-increasing rate until the powder is nearly all burned. In a gun, however, the rate of increase of pressure is partly checked by the increase of volume caused by the movement of the projectile. At first the expansion is slow, because the pressure is low and also because the resistance to movement of the projectile is high until the rotating band has been engraved by the rifling (see Sec. 46). Later the expansion is fast enough to offset partially the increased rate of burning of the powder. Next the amount of burning powder becomes so small that the evolution of gas begins to

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37/ The Le Duc equation for the velocity of the projectile in the bore, which is used in designing new guns, is described in Hayes [1938, pp. 74-81] and in Naval ordnance [1939, pp. 50-85]. A more refined form of semiempirical calculation is afforded by the use of the Tables for interior ballistics prepared by Bennett [1921].

decrease. This effect combines with the ever-increasing expansion to cause the rate of increase of pressure to become zero. After the attainment of a maximum pressure, the remainder of the powder is burned within a short interval of time during which the pressure decreases slowly. Finally the pressure continues to decrease approximately as in an adiabatic expansion. The curves of pressure versus time for several guns (Fig. 1) clearly show these variations of the pressure. They are photographic records made by means of a cathode-ray oscillograph attached to a piezo-electric gage during the firing of actual guns.

45. Position of projectile at maximum pressure

Although the time required for the pressure to build up to a maximum is a considerable fraction of the total time the projectile is in the bore, up to the moment of maximum pressure the projectile has moved only a few caliber lengths from its initial position. At the time of maximum pressure that part of the bore of the gun between the breech and the base of the projectile is subject to the maximum pressure. After that the pressure decreases slowly as the projectile continues to move toward the muzzle. The muzzle pressure, the exact value of which depends on the speed of burning of the powder and on the length of the tube, is of the order of one-fourth the maximum pressure.

46. Friction of the projectile in the bore[38/]

Both static and dynamic measurements[39/] have been made of

38/ See Sec. 53 for heat of friction.

39/ Some of the earliest static measurements were made at Watertown Arsenal with the "United States Testing Machine" and were reported in Tests of metals published annually by that Arsenal.

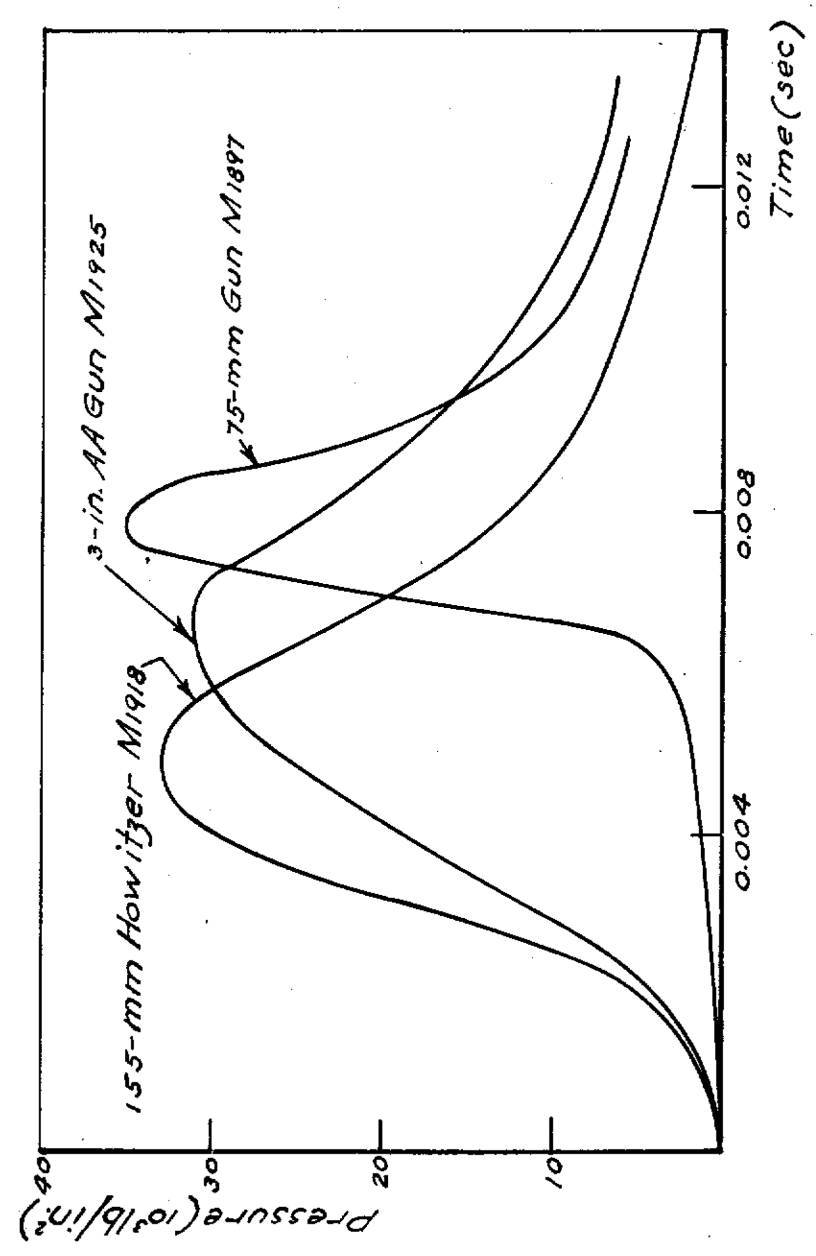

Fig. 1. Typical pressure-time curves.

the initial resistance of the projectile to movement, caused by the work required to engrave the rotating band -- or the soft metal jacket, in the case of a bullet -- and the subsequent friction between the bore and the two parts of the projectile that touch it, namely, the rotating band (Sec. 18) and the bourrelet (Sec. 17). In one case, for instance, the resistance in a worn 75-mm gun, M1897 (fired 7755 rounds) was found to be 40,000 lb at the origin of rifling and about 15,000 lb at the muzzle [Ord. Dept., 1922b]. The actual resistance to a moving projectile, however, is probably much less than the result of such a static measurement. This was indicated by the fact that when projectiles having rotating bands of reduced diameter were fired from a 240-mm howitzer, practically no effect on pressure or velocity was found [Ord. Dept., 1922a]. This conclusion is in agreement with the suggestion of Justrow [1923] that the friction between the band and the bore corresponds approximately to that of a piston adjusted for suction.

A summary of several dynamic methods of measuring bore friction has been given by Kutterer [1942]. In Cranz' method a shot is fired from a shortened tube from which it initially protrudes about one-third its length. The engraving resistance is taken equal to the mean pressure corresponding to a series of equal charges which are just sufficient to eject the projectile about half the time. In several other methods the frictional force is evaluated as the difference between the force tending to push the projectile forward and the force of recoil. In Sébert's method the frictional force is evaluated as the difference between the force acting on the projectile and that acting on a frictionless piston inserted in an axial hole through the shot. These two forces are measured by differentiation of two space-time curves obtained by means of recording tuning forks on frictionless slides attached to the shot and the piston. Liebessart improved Sébert's method by measuring the displacement optically.

The method of Cranz and Schardin [1932] utilizes a breech block consisting of a heavy frictionless piston, having the same area as the projectile, so that the forces on them are the same. Hence, when the gun is fired from a free recoil carriage, the tube is pulled forward by the frictional drag. The frictional force is the product of the mass of the tube and its acceleration. The latter is obtained by the double differentiation of the space-time curve for the tube. Kutterer [1942] modified this method by measuring the acceleration of the tube directly by attaching to it a frictionless piston which registered against a piezoelectric quartz gage.

The methods mentioned have required a modification of the operation of the gun or projectile. The friction of a standard projectile in the bore of a 14-in. Navy gun was determined indirectly during an investigation of the ballistics of this gun [Bur. Stand., 1924a]. The pressure on the base of the projectile computed from the acceleration of recoil was less than the gas pressure in the chamber measured with a spring pressure gage. This difference was considered a measure of the friction.40/

40/ Preparations are being made for application of this method to measurement of the friction and also other ballistic properties of several guns of moderate caliber, under the supervision of H. L. Curtis of the National Bureau of Standards, for Section A, Division A, NDRC.

A direct-reading gage[41/] has been suggested recently by Smith [1942]. It consists of a quartz piezoelectric gage mounted in the base of the projectile and connected to an oscillograph by means of a wire that comes out the muzzle of the gun.

47. Relation of friction to erosion

The divergent views concerning the influence of the rotating band on erosion have already been mentioned (Sec. 19). The magnitude of neither that influence nor that of friction between the bourrelet and the bore has been evaluated. Nonsymmetrical muzzle erosion has been ascribed[42/] to the wear between the bourrelet and a particular land with which it remains in contact during most of its path down the bore.

It is generally agreed, however, that the amount of erosion caused by friction between the projectile and the bore is greater in small arms than in guns firing projectiles with rotating bands. The difference between the erosion in the two kinds of weapons, however, seems to be merely one of degree rather than of kind. This point of view was emphasized by Greaves, Abram and Rees [1929, p. 158], who suggested that although the total amount of metal eroded per round increases with caliber (see Table XVIII), a smaller proportion is removed by friction in the larger guns. This

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41/ This gage is now being used in a series of measurements with a 3-in. gun at Aberdeen Proving Ground under the auspices of Section A, Division A, NDRC. See Crocker and Smith [1942].

42/ Arthur E. Jewell, Gage Section, Aberdeen Proving Ground, personal communication.

conclusion is based on the fact that the force applied to unit area of the surface of contact between the rotating band and the bore is about the same for all guns fired at the same pressure, whereas the heat input to unit area of the bore surface increases very rapidly — because the ratio of the weight of charge to bore surface increases linearly -- with an increase of caliber.

48. Velocity of the projectile in the tube

The velocity of the projectile continues to increase as the gases expand after the time of maximum pressure. Noble invented the chronoscope for the determination of the velocity at different points down the tube by recording the times when the projectile passed these points. In the original arrangement described by Noble and Abel [1875], the tube of the gun was drilled at a series of points along its length. Each hole was fitted with a plug which carried a wire arranged in such a way that it was cut when the projectile passed that point. Cutting the wire interrupted the primary current of an induction coil, whereupon a spark recorded itself on a piece of paper attached to a disk, 36 in. in circumference, that was rotating with a constant speed of about 1250 rev/min. The instrument was capable of recording the millionth part of a second, and when it was in good working order, the probable error of a single observation did not exceed 4 or 5×10^{-6} sec. After the distance of travel of the projectile had been expressed as a function of the time, the velocity and the pressure were computed by two differentiations. A somewhat similar contacting arrangement was used at Aberdeen Proving

Ground [Kent and Hitchcock, 1923] in a study of the internal ballistics of a 240-mm howitzer. A series of 13 contacting plugs were connected to an oscillograph to obtain a direct time-travel record.

49. Muzzle velocity and energy

The muzzle velocity of the projectile, which is an important characteristic of the gun, is determined by measuring with a chronograph 43/ the time required for the projectile to pass between two velocity frames set up at measured distances in front of the gun, and then applying a correction to take care of the small change of velocity between the muzzle and the point of measurement. For the first 10 yd or so the velocity is increased by a few feet per second by the rush of the escaping gases, and then it decreases. The muzzle velocities of the guns in use today generally range from 1500 to 3000 ft/sec at full charge. If the full range is not needed, some of them, howitzers especially, are fired at reduced charge, which yields a lower muzzle velocity.

The muzzle energy, which is a measure of the power of the projectile, is determined by the muzzle velocity, the velocity of rotation and the mass of the projectile. The proportion of the powder energy represented by the muzzle velocity is the thermodynamic efficiency of the gun. This efficiency is about 30 percent, as is shown in Table XV (Sec. 52). The mechanical efficiency of a gun, considered as the ratio of the muzzle energy to

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43/ See Ordnance Dept. [1936, No. 40-17] for a description of the procedure of this measurement.

the work represented by the area of the ideal indicator diagram, was calculated by Henderson and Hassé [1922, p. 473] as 84 to 90 percent for a number of British guns fired with cordite M.D. at muzzle velocities of about 2700 ft/sec.

50. Effect of expansion of powder gases

Although the pressure in a gun firing a service round is about the same as in a closed chamber at a density of loading of 0.20 to 0.25 (see Tables I and X), the gases in the two enclosures are not subject to the same conditions up to the moment of maximum pressure. In the closed chamber this pressure is attained without the performance of any work by the gas, whereas in the gun the gas expands at the same time that the pressure increases. Because the secondary water-gas reaction [Eq. (V-6)] involves no volume change if the gases are ideal, this expansion has less effect on the gross composition of the powder gases than it otherwise might. On the other hand, a possibility which may be of special significance in connection with erosion is that the expansion may promote some reaction that is affected by the change of pressure, and thereby cause the formation in the gas mixture of a chemical combination that might readily react with the steel bore.

Another possible cause of a local disturbance of the gaseous equilibrium is the cooling of the gas. In a 3-in. antiaircraft gun, for instance, the cooling has been found by calculation to be about 1000°C by the time the gases reach the muzzle, which corresponds to a gradient of about 3° per centimeter travel of the projectile.[44/] Most of this cooling is caused by the work performed in pushing the projectile down the bore. Because it affects the mass of gas as a whole, any change of composition resulting from this part of the cooling is distributed uniformly. Part of the cooling, however, is caused by contact of some of the gas molecules with the cold surface of the bore; and this change is not uniform. Not only is the cooling confined to the layer of molecules adjacent to the wall of the bore, but the return of these molecules to the main mass of gas is hindered because they are drawn forward by the movement of the projectile. This unidirectional gas stream may have a different composition from that of the rest of the gas, since an exothermic reaction would be promoted by cooling. This possibility may be important with respect to erosion, because this stream of gas adjacent to the surface of the bore might react with it.

44/ The adiabatic explosion temperature (see Sec. 36) is independent of the amount of the propellant. The temperature of the gases at the muzzle, however, is lower the smaller the amount of charge. For a 3-in. AA gun M3, the muzzle gas temperature was calculated to be 1640°C for a charge of 4.84 lb of pyro powder, for which the explosion temperature was 2700°C. With a charge of 5.00 lb of NH powder, which had an explosion temperature of 2400°C, the muzzle gas temperature was calculated to be 1430°C [Tolch, 1936b, p. 4].

CHAPTER VII. REACTION OF THE TUBE TO FIRING

51. Temperature of the tube

Direct measurements of the temperature of a gun tube have been made by means of thermocouples welded to its outer surface. The average results obtained for a number of different guns at Aberdeen Proving Ground are summarized in Table XIII, which has been copied from a survey by Lane [1938]. In arriving at this average rise of temperature per round, allowance was made for cooling effects when the fire was slow enough to warrant such a correction. In the case of the 3-in. AA gun M3, for instance, the cooling was found to be unimportant at rates of fire of 10 rounds/min and more [Tolch, 1936b]. The larger temperature rise per round shown in Table XIII for the measurements near the muzzle compared with those near the breech end of the tube resulted from the heating of a smaller amount of metal rather than from the presence of a larger quantity of heat. This situation is demonstrated by the figures in the last column, which show that the most heat was absorbed by the part of the tube farthest from the muzzle.

Translation of these results into terms of the heating of a gun under service conditions is difficult except in the cases of very rapid fire or of sustained fire at a steady rate. The expected temperature rise for a single burst fired very rapidly is practically the product of the number of rounds fired in one burst and the average rise in temperature per round. Thus Lane [1935] calculated that the bore surface of an aircraft machine gun reached

Table XIII. Heating of gun tubes firing single-base powder*.

Gun	Projectile and Velocity	Firings	Tube Diam. (in.)	Dist. from Muzzle (in.)	Max. Temp. Measured (°C)	Average Temp. Rise (°C/rnd)	Average Heat Absorbed (cal/cm² rnd)
Cal. .30 tank machine gun	172-gm ball 2600 ft/sec	Mean of thousands of rounds	1.21 1.21	3.7 11.2	200-400 Maintained	1.05[a] 1.44[a]	2.81[a] 3.92[a]
Cal. .50 M.G., heavy barrel air-cooled	750-gm ball 2600 ft/sec	100 rnd and 2(199) rnd with 15 min cooling between groups	1.5 1.87 2.31 1.94	5.25 17.1 23.5 27.25	384 370 314 322	1.36 1.26 .89 1.13	5.34 4.95 5.45 4.76
Cal. .50 M.G., water-cooled	750-gm ball 2600 ft/sec	2(100) rnd and 1(198) rnd	—	—	100[b]	—	...
75-mm M1897E3	15.96-lb slug 1755 ft/sec	Group of 300 rnd	4.80 5.28 5.67	12 36 55.5	320 328 328	1.51 1.40 1.33	4.55 5.65 6.54
3-in. AA T8	15-lb slug 2600 ft/sec	Four groups 100 rnd each	5.03 5.86	12 48	352 295	3.30 2.39	11.15 12.54
3-in. AA M3	15-lb slug 2600 ft/sec	Group of 247 rnd	5.95 7.28	13 63	430 360	2.18 1.59	12.0 14.2
105-mm AA M1	33-lb slug mod. 2800 ft/sec	Group of 169 rnd	6.95 8.33 9.69	12 88 164	285 303 282	2.01 2.06 1.89	9.5 16.2 21.8

*After Lane [1938, Table I].

[a] Corresponding values for double-base powder were 1.14 and 155°C/rnd and 3.04 and 4.25 cal/cm²rnd.

[b] Temperature of outside barrel practically constant at temperature of boiling water.

1370°C after having fired 600 rounds in $\frac{1}{2}$ min. In this calculation the cooling effect was allowed for to the extent of 4 percent of the heat input. In calculating the temperature of the tube after sustained fire at a steady rate it is necessary to make allowance for the cooling, which depends materially on the wind velocity. Cooling rates for the same guns listed in Table XIII have been compiled separately by Lane [1939a].

One important way of expressing the heating of the tube is in terms of the rate of fire necessary to maintain a particular temperature. For the caliber .30 machine gun these rates, measured directly for temperatures of 200°, 300° and 400°C above ambient temperature, are given in Table XIV in comparison with similar rates that had been calculated from the results of temperature measurements with other guns. Such data are of practical importance in deciding on allowable maximum rates of fire; for if the temperature at the breech end of the tube increases too much, the steel will be weakened to such an extent that the gun may burst. Tolch [1936a] calculated for the 105-mm AA gun M1 that at 164 in. from the muzzle the maximum allowable temperature was 405°C; that is, at this temperature the tensile strength of the steel had decreased to such an extent that the factor of safety was reduced to unity.

The effect of artificial cooling of the barrel, as by the use of a self-circulating water cooler, is illustrated by the data in Tables XIII and XV for the air-cooled and water-cooled caliber .50 machine guns. After similar firing of the same ammunition, the

Table XIV. Temperature of the breech end of the gun tube as a function of the rate of fire; single-base powder.

Temperature Above Ambient (°C)	Rate of Fire Necessary to Maintain Temperature (rounds/min)				
	Cal. .30 M.G.[a]	Cal. .50 M.G. air-cooled[c]	75-mm M1897E3[c]	3-in. AA Gun M3[d]	105-mm AA Gun M1[e]
200	11.4	8.7	3.3	1.1	0.9
300	17.8	14.3	5.5	1.8	1.4
400	22.1	20.8	7.7	2.6	2.0

[a]Corresponding rates of fire obtained with double-base powder were: 200°C, 9.1; 300°C, 15.4; 400°C, 18.8 rnd/min [Tolch, 1935].

[b]Tolch [1936c].

[c]This gun had been modified by the removal of the bronze jacket from the regular gun of this model. It was concluded as a result of the temperature measurements during firing tests that "the increase in heating effect due to the modification is partially, if not wholly, compensated for by the increase in cooling rate" [Dickinson, 1936].

[d]Tolch [1936b].

[e]Tolch [1936a].

barrel of the former had reached an average temperature of nearly 350°C, whereas that of the latter was not much above 100°C. The quantity of heat absorbed by the water-cooled barrel was nearly 40 percent greater than that absorbed by the air-cooled one; and yet its projectile derived 1 percent more energy from the same amount of powder. Thus the lowered temperature of the barrel, which tends to increase the life of the barrel, was secured without any loss of efficiency.

52. Distribution of energy in gun

The proportion of the total energy of the powder that is absorbed by the gun tube is shown in Table XV in comparison with the distribution of the remainder of the energy of the powder. The amount shown as absorbed by the tube includes that absorbed by the brass cartridge cases. For the caliber .50 machine guns this part was found by a calorimetric measurement to amount to about 300 cal, which raised the temperature of the case to about 81°C. The percentages of energy absorbed by the tube, shown in Table XV, agree reasonably well with the figure of 22 percent calculated by Cranz and Rothe [1908] and with that of 15 percent deduced by Muraour [1925, p. 477] from closed-chamber measurements.

Table XV. Percentage distribution of energy of powder.

Distribution	Cal. .50 M2 Machine Gun		3-in. AA Gun M3[c]	
	Air-cooled, Pyro Powder[a]	Water-cooled, Pyro Powder[b]	Pyro Powder	NH Powder
Velocity and spin of projectile	28	29	29	32
Heat of gun	16	22	11	9
Velocity of gases	27 } 56	27 } 59	60	59
Heat of gases	29	22		
	100	100	100	100
Energy (cal/rnd)	11,340	11,340	1,035,000	1,540,000

[a]Muzzle velocity, 2600 ft/sec. Fired 500 rounds in three groups at different rates [Tolch, 1936c].

[b]Muzzle velocity, 2600 ft/sec. Fired 400 rounds in three groups at different rates [Tolch, 1937].

[c]Muzzle velocity, 2800 ft/sec. Pyro powder: 15 rounds in 45 min; NH powder: 25 rounds in 80 min [Tolch, 1936b].

53. Heat of friction

Transfer of some of the energy of the powder to the tube takes place indirectly by means of the heat of friction of the projectile as it passes down the bore (see Sec. 46) as well as directly by contact of the hot gases. A measurement of the extent of this indirect transfer was attempted [Ord. Dept. 1924] by comparison of the heat absorbed by two 37-mm guns that had been fired 100 rounds each under the same conditions, except that the projectiles for the one gun had standard bands, whereas those for the other gun had very narrow bands, the cylindrical portion having been 0.03 in. wide instead of 0.5 in. Each gun was immersed in the same quantity of water at the end of firing. The rise in temperature of the water was 5°C in both cases. Hence, as far as this somewhat rough measurement was concerned, the heat of friction was probably less than 10 percent of the heat absorbed from the powder gases.

54. Temperature of the surface of the bore

No direct measurement of the temperature of the surface of the bore of a gun has been attempted during firing. Some measurements have been made directly after firing by pushing a thermocouple junction into the muzzle of the gun and holding it against the bore surface with an asbestos pad. Such a procedure yields a result of very questionable validity, because of cooling before the measurement can be made.

The closest approach to a direct measurement of the temperature of the bore surface was made by Kosting [1935] on a Garand caliber .30 automatic rifle. A thermocouple junction was placed at the bottom of a hole drilled into the barrel 7 in. from the breech end (0.06 in. in front of origin of rifling) so that the junction was only 0.077 in. from the bore surface.[45] The maximum temperature after firing 51 rounds in 1.3 min, with the tube already hot from previous firing, amounted to 485°C. At the same time the temperature at the surface on the same radius was 428°C. Hence the temperature of the bore surface was estimated to be somewhat in excess of 500°C. Measurements at several other points along the barrel were made simultaneously by means of recording potentiometers. They indicated that longitudinal heat flow was much greater than radial heat flow.

The temperature of the bore surface was computed from that of the outside surface of the tube of a 105-mm AA gun M1 by Tolch [1936a, p. 10], using the Fourier equation for heat flow. The greatest difference between inside and outside temperatures was at the measuring point nearest to the breech. There the maximum outside temperature was 279°C, and the corresponding bore temperature was calculated to be 349°C; but this result depends on several somewhat doubtful assumptions.

The calculation of the temperature to which the bore surface is raised by a single round is even more uncertain. Lane [1939b] developed a method suggested by R. H. Kent that is based on a known rate of heat input. For a 75-mm gun an increase of 179°C

45/ In a private communication, dated Aug. 22, 1942, Kosting pointed out "that because of the use of the recording potentiometer the time lag would be such as to measure average temperatures and not peak temperatures, and also that the thermocouples placed within the hole drilled into the barrel were held in place by friction and were not spot-welded to the steel. I now look with disfavor on any experimental work for evaluating temperatures in which the thermocouple is not spot-welded at the point where the temperature is to be measured."

was indicated at the interface, whereas it was only 2° at a depth of 0.045 in. below the surface. Kent [1941] himself criticized this method, on the grounds that it assumes that the heat capacity and conductivity of the surface layer of the bore are those of the steel throughout the tube, whereas he pointed out that possibly these properties are considerably different in the altered surface layer. He recommended that an attempt be made to measure them.

55. Dilation of the bore

Part of the pressure of the powder gases during firing neutralizes the residual compressional stress that is present in a modern gun as a result of the method of manufacture (see Sec. 6), and then the remainder of the pressure places the tube in a state of tension. There is no quantitative information as to how much compressive stress is retained by a built-up gun or by a radially expanded (cold-worked) one. The final machining operations, especially the rifling, must relieve some of the compressive stress, and later, when the gun is in service, probably more of it is gradually dissipated. The calculation of the increase of diameter of the bore from the pressure is further complicated by the nonhomogeneity of the stress distribution that is occasioned by the rifling.[46] Justrow [1923] rather naively disregarded these

46/ Dr. P. R. Kosting (private communication, Aug. 22, 1942) remarks that recent British firings have shown that the engraved portions of the rotating bands of some recovered projectiles were larger than the diameter of the bore of the gun. Hence the tube must have expanded ahead of the rotating band; and therefore the stress distribution in the tube is more complicated than if the gun is considered merely as a cylinder subject to a uniform internal pressure.

factors in his elaborate calculations of the dilation of the bore.

The bore diameter is also changed by the rise of temperature. If the whole tube heats up gradually, the inside diameter increases. Thus for a 105-mm gun the increase would amount to about 0.004 in. for each 100°C rise of temperature above ambient [Tolch, 1936a, p. 6].

56. Contraction of the bore

Contraction of the bore may occur whenever the bore layers are stressed beyond their yield point, which varies inversely as some function of the temperature. A sudden increase of 100°C in the temperature of the bore would correspond to an increase of 30,000 lb/in.^{2} in the compressional stress.[47/] Fleming [1918] ascribed to this cause the complete elimination of the rifling in a Lewis antiaircraft machine gun that had been fired 2500 rounds automatically (cyclic rate not known), during which time the barrel had been observed to have become red hot. He suggested that the projectile acted as a mandrel in the contracted bore.

57. Elongation of the tube

Compressive stress in the inner layers of the tube may be relieved by elongation of the tube. This action is assisted by the longitudinal stress caused by friction between the projectile and the bore. Liners have been known to be caused to protrude in this manner, and even 15-in. gun tubes have been reported [Miller, 1920, p. 53] to have been permanently elongated as much as ½-in.

47/ R. W. Goranson, private communication.

58. Tangential stress

The rotary motion of the projectile during firing imposes a considerable tangential stress on the tube. For a 240-mm howitzer this stress was calculated under various assumptions to be as high as 9000 lb/in^2. It was therefore considered to have been a factor that contributed to the failure of a number of such guns by bursting or swelling [Ord. Dept., 1931]. Justrow [1923] attributed to the tangential stress on the sides of the lands considerable influence as a cause of erosion.

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