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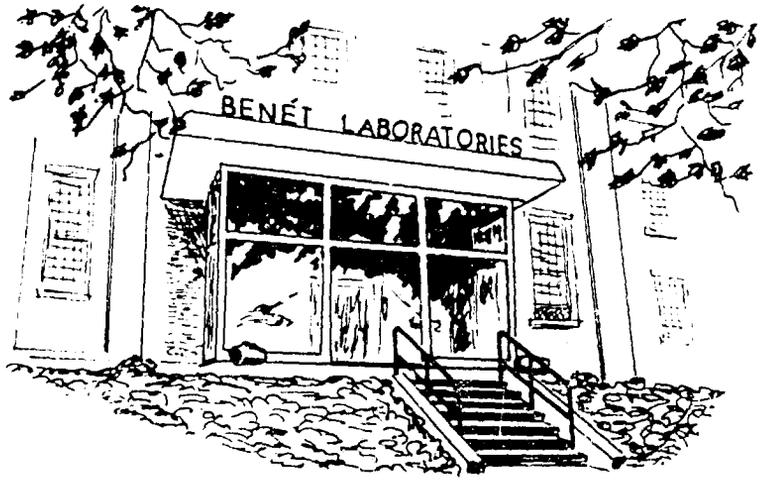
GUN TUBE EROSION AND CONTROL

February 25 & 26, 1970



EDITORS

I. Ahmad
J. P. Picard

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Watervliet, New York

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FOREWORD

The specification of performance characteristics for conventional weaponry is of considerable interest and concern to the organizations utilizing such equipment. As might be expected, one of the primary considerations is the stipulation of the safe operating-life limits. In the case of large caliber cannon, modifications in propellant charges through the addition of wear reducing agents have been largely responsible for extending weapon life limits to the point where fatigue considerations became extremely important. However, it has been shown recently that application of a prestressing fabrication process (autofrettage) and use of materials having improved fracture toughness, results in a large caliber cannon which will again be wear and erosion limited.

Invariably, for small caliber automatic cannon, life limits depend almost entirely upon the wear-erosion behavior of the tube. Thus it would seem likely that any significant advance with respect to useful cannon tube life will depend largely upon improved techniques for minimizing tube degradation resulting from thermal, mechanical and chemical processes taking place at the bore surface during the firing cycle.

Although erosion of cannon tubes has been recognized as a serious problem for a long time, no compendium or review of work accomplished in this field since the mid-1940's exists. The last comprehensive review of the subject was published by Division I of the National Defense Research Council in 1946. Therefore, to provide

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The findings in this publication are not to be construed as an official Department of the Army position.

a means by which an updating of information generated during the past 25 years, as well as providing a means for assessing on-going work, the Watervliet Arsenal organized an inter-service technical meeting on gun tube erosion and control, which was held at Watervliet, New York on 25-26 February 1970. The principal aspects of erosion which were considered during the course of this meeting were

1. Description of eroded bores
2. Influence of erosion on the accuracy and life of gun tubes
3. Erosion vs fatigue in various cannon tubes
4. Erosiveness of propellants
5. Physical chemistry of erosion
6. Metallurgical aspects of erosion
7. Thermal checking - its nature and effects
8. Techniques of studying gun erosion
9. Effect of rotating bands on the tube erosion
10. Erosion resistant coatings
11. New concepts in material applications to gun tubes
12. New concepts in propellants
13. New concepts in tube design

During the course of three technical sessions and one general session, 20 papers and three prepared discussions were presented. These papers, and the discussion which took place from the floor, are included as part of this volume. A bibliography prepared by the Technical Information Services Office, Benet Laboratories, Watervliet Arsenal is also included.

While it is recognized that the information contained in this volume is merely an updating of the state of the technology, it does represent a means of reassessment of effort and perhaps, most importantly, a common base of understanding. It is quite sincerely hoped that the information contained herein will assist scientists and engineers in devising better methods for control of gun tube erosion.

June 1970 Robert E. Weigle

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SUMMARY

In a two-day, three-session meeting on "Gun Tube Erosion and Control," held at Watervliet Arsenal, Watervliet, N. Y., (25-26 Feb 70), representatives from the Army, Navy, Air Force, industry, U.K., and Canada, reviewed various aspects of the subject including, in particular, interior ballistics and heat transfer, wear-reducing additives, erosion-resistant coatings, and use of new materials for gun barrels.

A casual look at the history of research on gun tube erosion will show that the most active periods have coincided with major international conflicts such as the two World Wars and the Korean War. Indeed, after the Korean War, except for the introduction of wear-reducing additives in 1960 by a Swedish firm, there has been very little advance made in erosion protection. This observation was fully confirmed at this meeting. The problems which existed during World War II still exist today, although they have been aggravated because of an increased demand for higher muzzle velocity and rate of fire. Also, as a result of some of the recent work, considerable improvement of fatigue life in some weapon systems has been achieved which cannot be fully exploited because the tubes wear out rapidly by erosion and are condemned. Therefore, for the increase in the service life of gun tubes, erosion protection is of paramount importance.

With the exception of the United States, R&D activities on erosion are nearly non-existent in all the countries of the free world. All the current work reported at this meeting was entirely by the U.S. Groups, which, as became obvious, was not extensive. Picatinny Arsenal,

Dover, N. J. and the Naval Ordnance Station, Indian Head, Md., are involved in the development and evaluation of wear-reducing additives. The Air Force Base in Eglin, Florida, is supporting half a dozen projects on the use of refractory coating and tube materials for small arms. For the protection of large bore cannons, evaluation of various coating materials and application techniques is being conducted on a very modest scale at the Watervliet Arsenal. This total United States R&D activity is estimated to represent less than a million dollars, which is quite small when compared with the cost of the annual condemnation of tubes on the basis of erosion.

Erosion is a complex phenomenon resulting from the interaction of powder gases and the projectile with the surface of the bore. The bore surface is exposed for a short time to temperatures approaching the melting point of steel, pressures as high as 50,000 psi and a reactive atmosphere composed of CO, CO_2, H_2O, H_2, N_2, and numerous other minor identified and unidentified constituents. Superimposed on these conditions are the high velocity of the gases and swaging action of the projectile rotating band. The process is further complicated by the variation of these conditions along the length of the tube. Complete comprehension of erosion, therefore, has not been achieved even after a century's work. Physical metallurgical and chemical transformations caused by heat, pressure, and chemistry of gases, have been partly understood. Two approaches are taken to explain this phenomena. Some explain erosion as entirely a heat transfer effect with insignificant influence of chemical interactions. The others consider the chemical interaction to be of considerable importance not only in the loss of

material from the surface, but also in the propagation of fatigue cracks. However, it appears that when low temperature propellants are used, chemistry does play an important role in the formation of various compounds with low melting point which are easily removed. At high temperatures, when the melting point of the steel is approached, it becomes less significant. What actual chemical or metallurgical transformations are involved at this temperature are not known. Most of the suggested mechanisms are based on observations of the products after the firing which, obviously, have undergone secondary reactions.

Two main approaches to control erosion have been taken: a) addition of wear-reducing additives to the propellants; b) application of erosion resistant coatings or liners. The first approach has proven to be very successful. It involves providing a cooler gaseous layer at the bore surface by using a sheath of an organic compound such as paraffin wax or polyurethane, with or without dispersant particles of inorganic compounds such as TiO_2. At Picatinny Arsenal, in search for better wear-reducing additives, talc, which is a complex hydrated magnesium silicate, has been found to be even better than TiO_2. The effectiveness of an additive has been shown to be, in general, related to its heat content. Most of the work at Naval Ordnance Station is related to the use of polyurethane. Improvements comparable to TiO_2-wax have been achieved. However, all this development of better additives involved ad hoc methods. Very little effort has been made to understand the mechanism of the wear reducing action.

The second approach to erosion control has not yet proven fruitful. Exhaustive work on materials evaluation was conducted in 1941-6 under the auspices of the National Defense Research Committee. A number of materials were found promising: Stellite 21 was found to be an excellent liner material, but it failed when a double-base propellant was used. Mo (1%Co) was another excellent material for coatings and liner but the technology at the time was not advanced enough for its successful application. Chromium was found to be the best under the circumstances. It can be easily applied by electroplating and has excellent erosion-resistant properties. However, it is very brittle and electroplated chromium has very high built-in stresses that easily induce crack formation. It has been adopted on a limited scale in various gun systems; however, not without skepticism. So far, no solution to the problem of brittleness of chromium has been achieved. During the last twenty years, some new technologies such as plasma spray, sputtering, Chemical Vapor Deposition, and metalliding have been developed and need evaluation. Watervliet Arsenal and Philco Ford are presently engaged in developing suitable coatings. To date, no successful coating has been developed.

Rapid fire rate, use of high temperature propellants and thin walled tubes have brought into focus the fact that gun steel, because of its low melting point, is not a suitable material for some advanced gun systems. Therefore, it is necessary to look into the possibility of using refractory metal alloys with high melting points. Considerable progress has been made in the development of excellent refractory metal alloys. Very little data exists on the dynamic response of these

materials. Consequently, all attempts to design gun barrels from them are based on their static mechanical properties. Similarly, suitable fabrication techniques are yet to be developed. Some of the techniques presently being used or developed include co-extrusion, swaging, shrink fitting, and explosive lining. Significant improvements in burst length capability and erosion life, compared to conventional gun steels, were reported at this meeting. However, these were not completed studies. As for the actual design of the tube, there appears to be little possibility of reducing erosion by this means. With respect to the projectile, it was believed that some benefits might be derived by modifying the material and design of the rotating band to improve obturation. However, considerably more work must be done to develop satisfactory materials, and techniques to meet the objectives of high performance weapons.

One of the most beneficial aspects of this meeting was the identification of the critical areas in the field which require attention and further investigation. These are outlined as follows:

1. Studies of the mechanism of erosion, preferably using one gun system, with a view to understanding:

   a. Metallurgical transformations.

   b. Chemical interactions, including identifications of the solid and gaseous species involved.

   c. Effect of heat and pressure on the two above.

   d. Measurement of bore surface temperatures.

   e. Stress profiles in the tube walls.

   f. Influence of chemical environment on the formation and propagation of cracks in the tube.

2. Development of erosion resistant coatings and liners.

a. Development of a standard erosion gauge for the quantitative determination of the erodibility of materials and correlating it with the number of EFC rounds for standard weapons.

b. Evaluation of the "erodibility" of various metals, alloys, and intermetallic compounds other than those previously investigated for gun tube applications.

c. Development and evaluation of techniques of application of the coatings of promising materials. New techniques such as plasma spraying, metalliding, sputtering, arc discharge coating, etc., can be included in this category.

d. Development of standard techniques for the evaluation of the coatings for adhesion, porosity, and hot hardness, erosion gauge and actual test firing.

e. Design and development of removable liners, and apply coating on these liners for erosion protection.

3. Development of wear reducing additives.

a. Studies of the mechanisms involved in the wear reducing action of the additives, such as TiO_2-was, talc-wax, and TiO_2-polyurethane.

b. Based on the above studies, develop improved additives, with better mechanical strengths and wear reducing action. Preferably develop additives that can be incorporated in the propellant to eliminate additional handling.

c. Study the influence of various additives on the CO/CO_2 ratio and select those that will increase this ratio without reducing the propellant power.

d. Develop new propellant compositions with high CO/CO_2 ratio and volume to charge ratio.

e. Study the eroding power of such propellants on standard materials such as gun steel and other promising materials for gun tubes.

4. New Materials.

a. Develop physical and mechanical property data under dynamic conditions on those materials found promising as a result of the determination of the erodibility of materials.

b. Develop the design criteria from the data developed in a.

c. Develop techniques to fabricate various barrels from these materials.

5. Improve the design of the gun system including the barrel, rotating bands, and devices for quick heat transfer from the bore surface.

Consideration should also be given to conducting a tri-service erosion control meeting every two to three years so that a periodic updating of the state-of-the-technology is guaranteed.

The foregoing observations are made with the hope that they may contribute to not only the establishment or better communications between workers in this field but also to the development of a systematic approach to the effective control of erosion.

IQBAL AHMAD

JEAN-PAUL PICARD

Session I

Chairman: R. E. Weigle
Watervliet Arsenal
Watervliet, N. Y.

A GENERAL VIEW OF GUN EROSION AND CONTROL

Iqbal Ahmad
Benet R&E Laboratories
Physical Chemistry Laboratory
Watervliet Arsenal
Watervliet, New York

ABSTRACT

Various processes involved in the gun erosion are briefly reviewed. The progress made during the last two decades in the control of erosion is also discussed and some areas have been indicated in which further R&D efforts should be directed.

INTRODUCTION

Since the invention of the gun, the artillerymen have been haunted by a dream - an everlasting gun tube with an infinitely safe and effective life. To realize this, a continuous improvement of the material of construction of the tube and the propellants has been sought. For example, guns are now made from specially thermomechanically treated steels instead of bronze or cast iron. Smokeless propellants of various description have replaced the old black powder. Side by side there has been an increasing demand on the enhancement of the capability of a gun. The gun has been, and is being, required to throw a heavier projectile at a longer distance at an increased rate of fire and with greater accuracy.

"Oh, the sacred hunger of ambitious minds!"

Today's meeting is part of the quest to fulfil the dream of, if not an everlasting tube, at least one with an increased service life.

There are two basic factors which limit the safe and effective life of a gun tube:

1. Fatigue: The mechanical properties of the tube material deteriorate as a result of thermal and stress cycling set by firing. After a certain number of cycles, a crack initiates and then propagates at a certain slow rate followed by an accelerated rate until the tube, depending upon the properties of the material, fails either by perforation or catastrophically.

2. Erosion: Defined as the enlargement or damage of the bore surface as a result of firing, erosion, after a certain point, will result in loss of accuracy and, therefore, effectiveness of the weapon.

The two factors, to a great deal, are interdependent. However, in view of the limitations of the scope of this meeting, and space, only a brief review of the causes and cures of erosion will be made. Also, as erosion characteristics vary from weapon to weapon and in each tube from region to region, to cover all the aspects of erosion will require a compendium. Therefore, the subject will be discussed in very generalized terms and, mostly, erosion at the origin of the rifling will be discussed.

HISTORICAL BACKGROUND

Systematic studies of erosion date as far back as the end of the nineteenth century. These have been covered in excellent reviews such as in References 1, 2, 3, 4, 5, and 6. The most exhaustive and authentic work was done during World War II (1941-1945) under the sponsorship of Division I of the National Defence Research Committee of the Office of

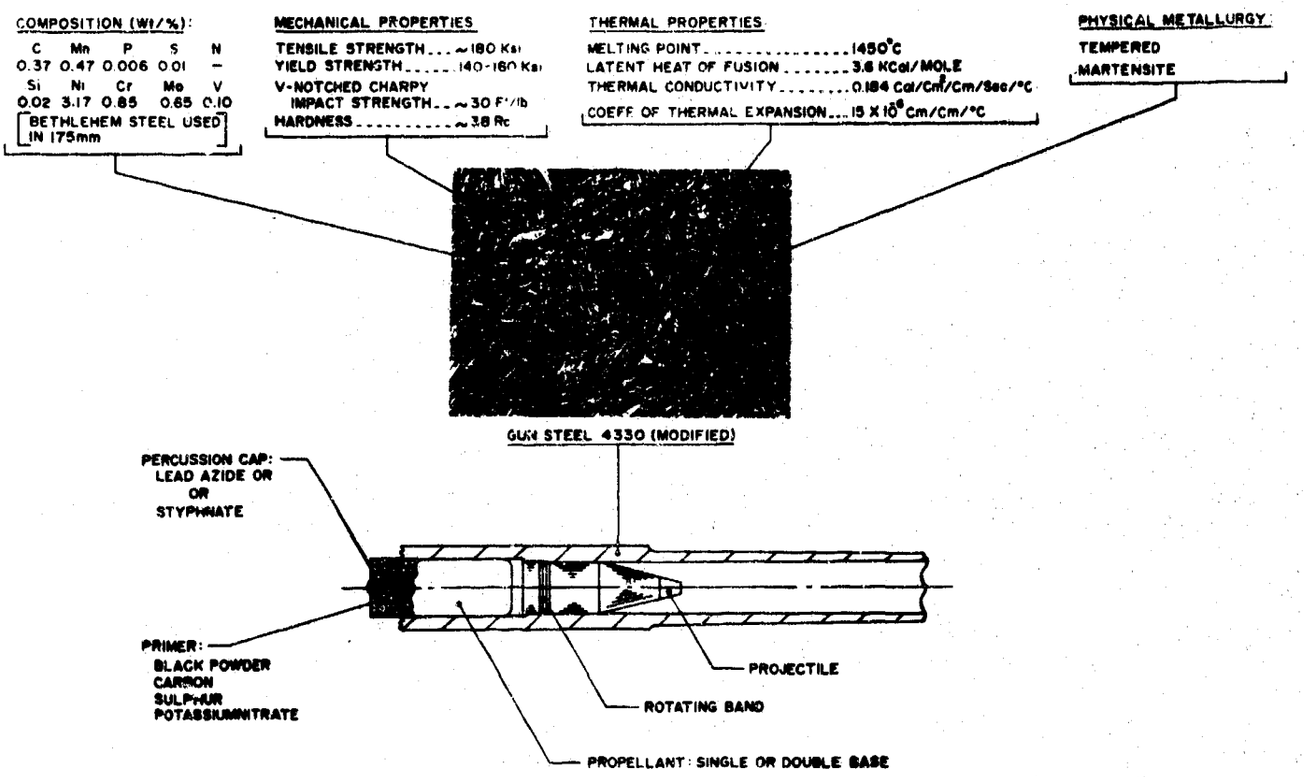
Scientific Research and Development, Washington, DC. The results were reported as a summary technical report entitled, "Hypervelocity Guns and the Control of Gun Erosion." After the war, interest in the subject slowly waned as is evident from the Proceedings of 1950 [7] and 1952 [8], symposia on gun barrel erosion organized by the Office, Chief of Ordnance. In fact, during the last twenty years, only a few publications of import have been made. The major contribution has been the introduction of wear-reducing additives by a Swedish firm [9] which will be discussed later in this paper. Since 1952 no major meeting on the subject of erosion was held. So, today, we are getting together after a long interval of seventeen years.

WHAT IS INVOLVED IN EROSION

Figure 1 illustrates the three major elements involved in the process of erosion, namely: 1. Gun steel at the bore. 2. Propellant (also the primer and the igniting powder) which could be a single base or a double base. 3. Projectile with its rotating band (usually copper). The representative composition and properties of the presently used gun steel and composition of representative propellants are also shown. Some of the standard propellants used in various types of guns, their composition, and some thermochemical properties are [10] summarized in Table I.

When the gun is fired, the propellant burns and develops a high temperature (2500-3700°K), and a high pressure (20-60,000 psi) due to the formation of a large volume of gases which propel the projectile and give it the required muzzle velocity.

CO, CO_2, H_2O, H_2, and N_2 are the major constituents of the powder gas. Also present are small amounts of NH_3, CH_4, NO, and H_2S (from the primer),



	SINGLE BASE	DOUBLE BASE	
	FNH-M1	FNH-M2	M2
NC	83.74	77.60	77.46
NG	–	19.40	19.50
DNT	9.84	–	–
DBTh	4.92	–	–
DPhA	0.49	0.97	–
C_2H_5OH	0.30	0.48	2.3
CH_3COCH_3	–	0.48	–
H_2O	0.69	0.97	0.70
$Ba(NO_3)_2 + KNO_3$	–	–	2.15
ETHYLCENTRALITE	–	–	0.60
ISOCHORIC TEMPERATURE	2400°K	3300°K	3319°K

Figure 1. Showing Major Elements Involved in the Process of Erosion.

Table 1.

Calculated thermochemical values for standard propellants (including residual volatiles)

Use	Artillery								Recoilless				Mortar			Small arms		
Propellant	M1	M2	M	M5	M14	M15	M17	T20	M10	T18	T25	T28	M7	M8	M9	IMR	M12	5018
Specification	JAN-P-303	JAN-P-323	JAN-P-12	JAN-P-309	JAN-P-309	PA-PD-26	PA-PD-26		PA-PD-123	PA-PD-323	PA-PD-329	PA-PD-[illegible]	JAN-P-639	JAN-P-351	MIL-P-20306	JAN-P-733	JAN-P-528	PA-PD-26A
Nitrocellulose	95.0	77.45	[illegible]	87.0	90.0	20.0	[illegible]	20.0	98.0	72.0	73.25	[illegible]	54.6	52.25	57.75	100.0	87.7	[illegible]
% Nitrogen	13.15	13.25	13.2	13.15	13.15	13.15	13.15	[illegible]	13.15	13.15	13.15	[illegible]	13.15	13.25	13.25	13.15	13.15	13.15
Nitroglycerin	...	19.50	[illegible]	...	...	14.0	[illegible]	[illegible]	...	19.75	20.00	[illegible]	35.5	43.00	40.00	...	...	10.0
Barium nitrate	...	1.40	1.40	...	...	...	...		...	0.5	[illegible]	[illegible]	...	...	...	...	...	...
Potassium nitrate	...	0.75	0.75	...	...	...	...	...	...	0.70	0.[illegible]	0.70	...	1.25	[illegible].0	...	...	...
Potassium perchlorate	...	[illegible].6	...	...	...	...	...	...	...	...	...	...	[illegible].1	...	...	...	...	...
Nitroguanidine	...	...	...	...	...	54.7	54.7	60.0	...	...	...	...	...	...	...	...	...	...
Dinitrotoluene	10.0	...	...	10.0	9.9	...	...	...	...	...	...	...	...	...	...	8.0‡	...	...
Dibutyl phthalate	5.0	...	...	3.0	2.0	...	...	5.0	...	...	...	...	...	...	...	...	...	9.0
Diethyl phthalate	...	...	...	...	...	...	...	...	...	...	...	...	...	3.00	...	...	...	...
Potassium sulfate	...	...	...	...	...	...	...	...	1.0	...	...	...	...	...	...	1.0*	0.75	...
Talc	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	...	0.75	...
Diphenylamine	1.0*	...	...	1.0*	1.0*	...	...	...	1.0	...	...	...	...	...	0.75	0.7	0.40	1.0
Ethyl centralite	...	0.60	0.50	...	...	6.0	1.5	2.0	...	6.50	5.00	6.00	0.50	0.50	...	...	...	...
Graphite	...	0.30	0.30	...	...	...	0.[illegible]†		0.10†	0.30	0.30	0.30	...	...	...	...	...	...
Carbon black	...	...	...	...	...	...	...	...	...	...	...	...	1.20	...	...	...	...	...
Cryolite	...	...	...	...	...	0.3	0.3	...	...	...	...	...	...	...	...	...	...	...
Ethyl alcohol (Residual)	0.75	2.30	2.30	0.30	1.90	0.30	0.30	0.30	1.50	1.20	1.[illegible]0	[illegible].0	[illegible].0	1.50	0.50	0.60	1.50	0.50
Water (residual)	0.50	0.70	0.70	0.50	0.25	0.00	0.00	0.00	0.50	0.30	[illegible].0	0.30	0.00	0.00	0.00	1.00	1.00	0.00
Lead carbonate	...	...	...	...	...	...	...	1.0*	...	...	...	...	...	...	...	...	...	...
Isothermic flame temp., °K	2817	3319	3245	2570	2[illegible]	2534	3017	2383	3000	2938	3071	3081	2734	2685	2709	2827	2996	2577
Force (ft-lbs/lb, x 10)^3	305	360	355	317	327	336	364	311	333	346	353	356	368	362	382	325	336	319
Unoxidized carbon %	8.6	0	0	6.8	5	9.5	3.9	11.6	4	3.4	1.8	2.2	0	0	0	1.9	6	6.8
Combustibles, %	65.3	87.2	87.4	82.4	58.9	51.0	38.7	53.1	54.5	59.1	...	...	50.4	37.2	32.8	59.2	53.66	66.6
Heat of explosion, cal/gm	700	1080	[illegible]947	758	809	796	962	[illegible]12	936	910	963	966	1255	1244	1295	866	933	772
Gas volume, moles/gm	0.04533	0.03900	0.03935	0.04432	0.04358	0.04645	0.04536	0.04[illegible]	0.04[illegible]	0.04219	0.04135	0.04157	0.03543	0.03711	0.03619	0.04137	0.04037	0.04457
Ratio of specific heats	1.2593	1.2238	1.2258	1.2543	1.2696	1.2557	1.2402	1.2591	[illegible]	1.2421	1.2373	[illegible].2 83	1.2100	1.2148	1.2103	1.2400	1.2326	1.2523
Isothermic flame temp., °K	1919	2712	2547	2050	[illegible]168	2066	2433	1897	2431	2365	2482	[illegible]4	1985	[illegible]3.2	3139	2280	2431	2058
Density, lbs/in^3	0.0567	0.0594	0.0[illegible]96	0.0571	0.0582	0.0600	0.0633	...	0.0602	0.0583	[illegible].0585	0.0[illegible]		...	...	...	...	...
Covolume, in.^{3}/lb	30.57	27.91	[illegible].62	29.92	29.54	31.17	29.50	30.41	27.70	29.13	28.66	28.77	...	26.83	25.97	28.87	27.91	30.24

*Added †Glazed ‡Coating Added

and perhaps a number of unidentified free radicals, ions, and metastable molecular species. The amount of CO, CO_2, H_2O, and H_2 is controlled essentially by a water gas reaction

$$CO_2 + H_2 \rightleftharpoons CO + H_2O \qquad (1)$$

the CO/CO_2 ratio, in general, for the single base powders is higher (2-3) than that for the double base (approximately 1). In other words, the single base powders are less oxidizing than the double base powders. Figure 2 shows the variation [11] of temperature, pressure, muzzle velocity, and the fraction of the propellant burnt as a function of time, prior to the ejection of the projectile which is indicated as zero time. It demonstrates that the bore surface for a few milliseconds is subjected to:

1. Temperatures as high as 2500-3500°K.
2. Pressures 20-50,000 psi.
3. Severe chemical reactions of powder gas.
4. Severe mechanical stresses because of 1 and 2, and swaging action by the accelerating projectile.
5. Sweeping action of gases on the softened or chemically interacted bore surface.
6. Improper obturation resulting in high velocity and high temperature gases streaming past the projectile.
7. Abrasive action of the unburnt powder or loosened gas-metal reaction products.
8. Combined action of any or all of the above severe conditions which make erosion to be a highly complex phenomenon.

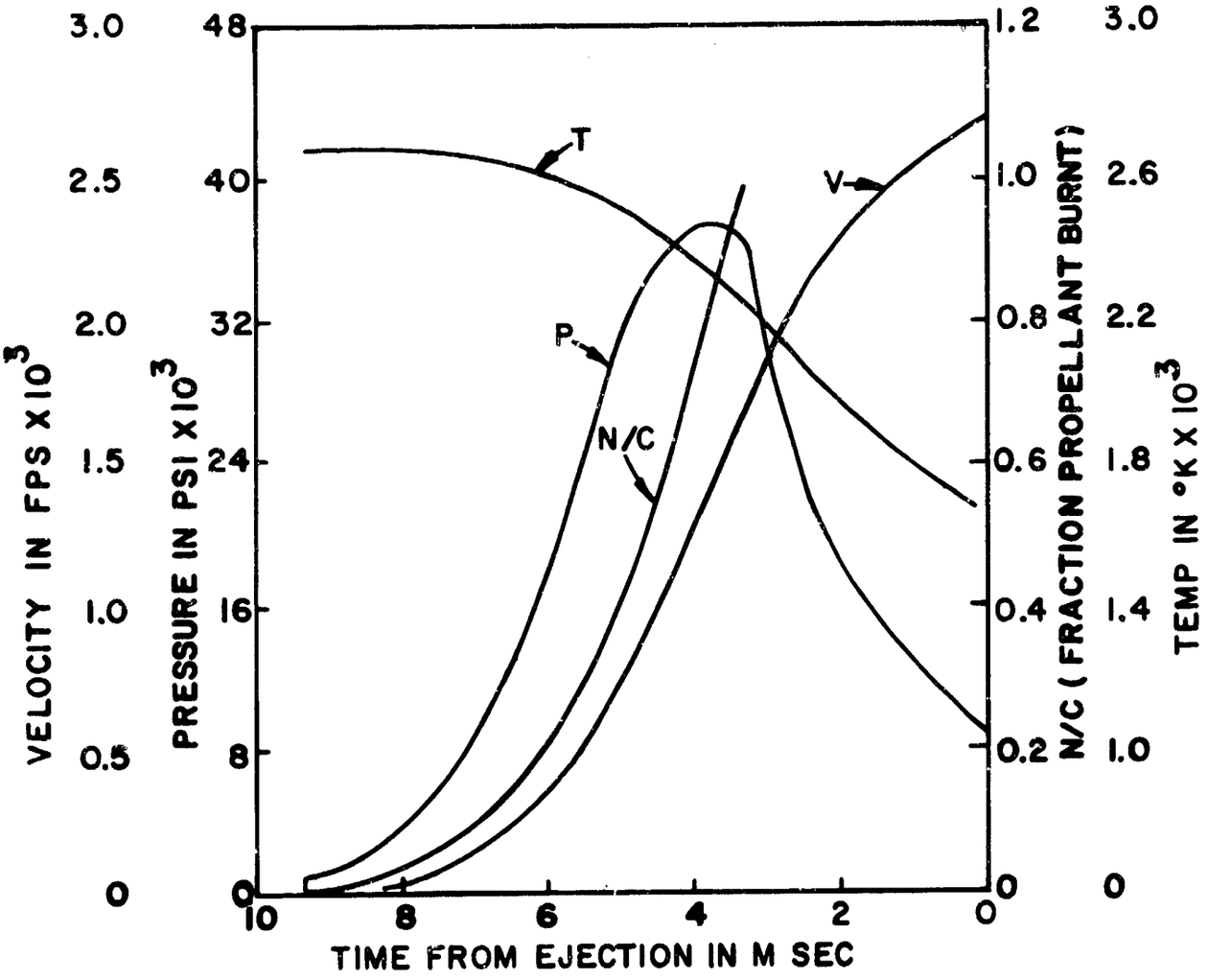


Figure 2. Variation of Temperature (T), Pressure (P), Muzzle Velocity (V), and Fraction of the Propellant Burnt (N/C), as a Function of Time Prior to the Ejection of the Projectile. (3" Gun Cardrock Range).

Further complexity is added by the fact that these conditions vary along the length of the tube. The severest conditions occur near the origin of the rifling (O.R.) and, therefore, this is the most affected area in the tube. Erosion at the muzzle could critically influence the exterior ballistics, but the muzzle erosion is generally very little as compared with O.R. erosion. Some of the important processes which result from the above listed reacting parameters in the area of the origin of rifling are summarized in Fig. 3 and very briefly discussed below.

Thermally Altered Layer: Heat and pressure cycling result in the transformation of martensite ($> 750^{\circ}C$) $\rightleftarrows$ austenite, which, on cooling, depending upon the rate of cooling, revert back to martensite. The thickness of this layer, which is also called the thermally altered layer and has the same composition as that of the unaltered layer, varies along the bore of the tube.

Heat Checking: Consequent to the volume changes on rapid heating and cooling of the surface, also involving phase transformation, stresses are developed at the bore surface which are relieved by the cracking of the surface. This condition is called heat checking (Fig. 3b). It is further aggravated by the combined chemical interaction and high temperature (higher than the m.p. of the product formed at the surface) causing pebbling (Fig. 3c), especially in the forward part of the chamber.

White Layer (Fig. 3d): The powder gases react with the thermally altered layer and form a thin layer of the product called "white layer". Its composition varies with the history of firing, nature of the propellant, and the tube temperature. With a single base propellant, the major products

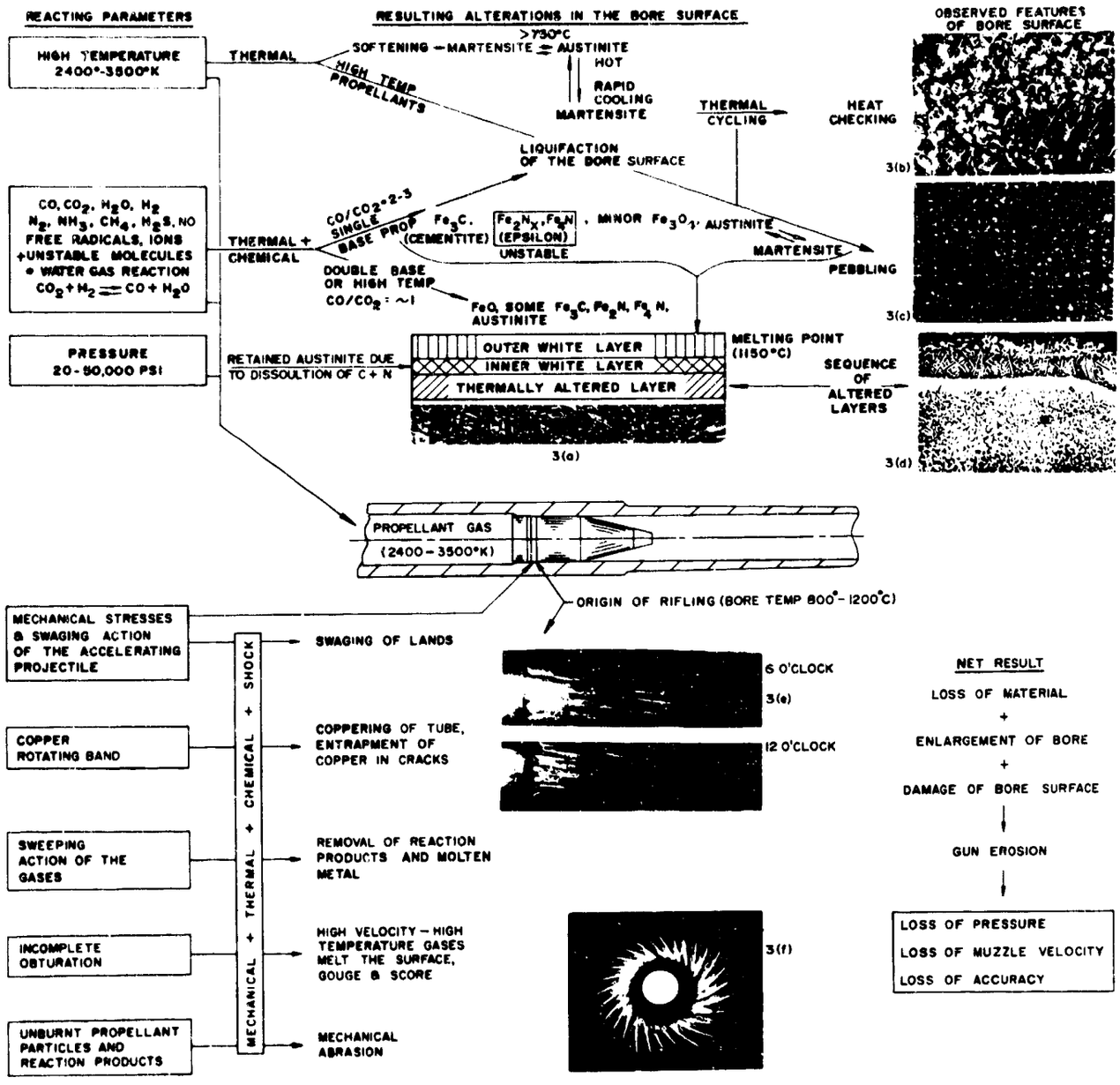


Figure 3. Summary of the Processes Leading to the Erosion of the Gun Tube at the Origin of Rifling.

formed are Fe_3C (cementite), Fe_2N_x (epsilon)*, and Fe_4N (γ' prime)*, some austenite stabilized by the dissolved C and N, and martensite phase formed on rapid cooling of austenite. Another layer between the thermally altered and white layer (called the inner white layer) is also observed. It is generally austenite stabilized by the dissolution of C and N, and is sometimes partly melted. Apparently, the formation of the inner layer precedes the formation of the outer one. The morphology of the layer is schematically represented in Fig. 3a.

With double base powders, the predominant end products are austenite and FeO which, however, because of the high temperature may melt along with the bore surface and be removed by the gases.

Mechanical Action of the Gases and the Projectile: The high velocity gases following the projectiles, heat the surface and sweep the softened or molten material from the bore surface and enlarge its diameter (Fig. 3e). Under extreme conditions, actual rippling or formation of "tongues" of molten material is observed. Frequently, incomplete obturation by the rotating band results in a streaming of very high velocity gases past the projectile, and gouge or score the material (Fig. 3f). They will also soften the copper rotating band, which, as the projectile moves, results in coppering the bore especially towards the muzzle end. Some of the entrapped copper in the heat check cracks may accelerate their

* Fe_2N_x and Fe_4N are unstable at the temperatures of firing. Therefore, these possibly form during the cooling time by the interaction of NH_3 with the bore.

propagation in the body of the material. Further, the accelerating projectile swages the bore, especially the land at the O.R.

Influence of Other Parameters on Erosion: It has been shown that the rate of erosion increases with 1) increased rate of fire; 2) CO_2/CO and H_2O/H_2 ratios; 3) flame temperature of the propellant; 4) muzzle velocity and increase in chamber-to-bore diameter ratios. The lands are eroded more than the grooves. There is more erosion at the 12 o'clock position than at the 6 o'clock, at the origin of the rifling which is the worst affected area of the bore.

NET RESULTS OF EROSION AND WEAR LIFE OF CANNONS

The net results of the combined action of the above conditions are:

1. Enlargement of the bore.
2. Loss of fire accuracy.
3. Loss of muzzle velocity.
4. Also, decrease in fatigue life, as the physicochemical environment can accelerate the rate of propagation of cracks formed initially by heat checking.

The extent of this damage can be appreciated from the fact that, except for the howitzers (in which low temperature propellant, e.g., M1, and low muzzle velocities are used) the majority of the cannon tubes manufactured at the Watervliet Arsenal are wear limited. The ballistic characteristics of some of them are summarized [12] in Table II. The point is easily made in the case of the 175mm M113. This tube, in 1966, was fatigue limited and had a life of 400 EFC rounds. Watervliet Arsenal's R&D efforts resulted in the successful application of autofrettage

Table II. Condemnation Limits of Some Cannon Tubes.

Caliber	Wear Limit In(***)	Wear Life EFC Rds	Estimated Fatigue Life EFC Rds	Muzzle Velocity Ft/Sec	Propellant	Isochoric Temp T°K	Maximum Pressure 70°F kpsi	Charge (Lb)/ Projectile (Lb)
40mmM1	0.052 (13.75)	12,000		2870	M1(AP-T M81)	2433	50.5	0.6/1.96
76mmM32 Tank Gun	0.100 (24.75	350		3200	M30(TP-T)	3040	55.2	14.5/14.5
*90mmM41 Tank Gun	0.197 (25.25)	700	3000	3000	M17(TP-T)	2974	57.7	9.0/24.0
" " "	0.197 (25.25)	240		3950	M30(HEAT M431)	3040	57.7	8.0/12.0
105mmM68 Tank Gun	0.075 (25.25)	100	4500	4850	M30(APDS-T)	3040	61.8	12.0/12.8
" "	0.075 (25.25)	400	4500	4850	M30(APDS-T) (Additive)	3040	61.8	12.0/12.8
" "	0.075 (25.25)	125	1500	3850	M30(HEAT-T)	3040	61.0	11.5/22.3
" "	0.075 (25.25)	1,000	1500	3850	M30(HEAT) (Additive)	3040	61.8	11.5/22.3
**105mmM137E1 Howitzer	0.070	20,000	5000	1621	M1	2433	36.7	3.0/33.0
**155mmM126E1 Howitzer	0.080 (47.75)	30,000	7500	1841	M1	2433	36.4	13.0/95.0
**175mmM113	0.200 (64.50)		400	3000	M6(Additive)	2583	47.0	57.25/147.75
175mmM113E1	0.200 (64.50)	1,200	2350	3000	M6(Additive)	2583	47.0	57.25/147.75

*Plated **Tube primarily condemned on metal fatigue. ***Measured at distance in inches forward of breech shown in parenthesis.

process on these tubes. This increased the fatigue life of the tube as high as 2350 rounds. However, now the wear became a problem because its wear limit of 0.2" reaches at about 700 rounds. Even this is an order of magnitude of improvement on the 1966 tube life. Yet it shows that, roughly, 2/3 of the potential tube life is wasted. Similar consideration on other wear limited guns adds up to, on the whole, wastage due to erosion to a mammoth dollar value.

Measures to Reduce Erosion: A critical review of the various causes of erosion would suggest the following as some possible measures for its reduction:

1. Using wear reducing additives to propellants.
2. Formulate propellants such that CO/CO_2 and H_2/H_2O ratios are high at a given flame temperature.
3. Devise systems in which the heat is quickly conducted away from the bore, either by cladding the tube with material of high thermal conductivity, or cooling the tube from the inside by the injection of a fluid or from the outside by air or water.
4. Design a better system for gas obturation.
5. Make a tube from a material more resistant to erosion than gun steel. Or, use such a material as a liner or as a coating in the tube to protect the gun steel tube.

The first measure has been successfully used by a Swedish firm [9] by the introduction of a TiO_2 wax-impregnated overwrap for the propellants charge, whereby the wear life of the gun tubes has been markedly improved. This has now been officially adopted by the U.S. Army and Navy for many guns.

Other additives like talc [13] and urethane [14] foams have been investigated and found to be effective. This work will be reported in the afternoon session. However, the mechanism of the action of these additives in reducing wear has not yet been fully understood and needs further study. Addition of deoxidants (the second measure) such as ferrosilicon [15] to the propellants was shown to give encouraging results. This approach should be explored further. Considerable effort has also been expended in the development of the third measure, i.e., fast removal of heat from the tube. It has been adopted in the provision of cooling systems for some of the rapid firing automatic weapons. Yet, it is not very convenient and restricts the mobility of the system. While incomplete obturation by the rotating band is a serious problem, very little is being done to remedy it (fourth measure). Efforts must be made to both improve the material and design of the rotating band.

Erosion Resistant Materials (Fifth Measure)

One of the most important conclusions arrived at as a result of extensive investigations under the NDRC in 1941-5 was that with double base powder and high rate of fire, steel, regardless of its type, will be severely eroded. Only a marginal improvement can be made by improving the composition of the tube. Therefore, a material better than steel must be found. The following are some of the most important requirements of such a material.

1. High melting point $> 1500^{\circ}C$ (this is the most important single factor in erosion).
2. High specific heat.
3. High thermal conductivity.
4. Low coefficient of thermal expansion.
5. No volume change as a result of thermal or pressure cycling.
6. High resistance to powder gases especially CO/CO_2.
7. Resistance to thermal, mechanical, and chemical shock.
8. High temperature mechanical strength.
9. Resistance to abrasion.
10. It should be ductile enough to resistance cracking, yet hard enough to resist swaging by the projectile.
11. For lining or coating, the thermal and elastic properties of the material should be compatible with the steel. For coating, good adhesion is another requirement.
12. Fabricability.
13. Available in economic quantities.

An ideal material with all these properties is, as yet, to be found. Under the sponsorship of NDRC, more than 100 materials were evaluated by erosion vent plug tests, firing of material particles with the propellants, and actual test firing of some of the material in the form of barrels, lining, and coatings. Efforts on a reduced scale on similar lines during the last 20 years did not add much to their conclusions which were approximately as follows.

1. No amount of alloying or other measures of improving gun steel could give a satisfactory material to resist erosion by high temperature propellants at a high rate of firing.
2. Of the high m.p. materials,Mo with 0.1% Co (or Ni) was the most promising material. But, difficulties of fabrication of liners or application of coating were technical barriers, which could not be completely overcome.
3. The next best material was Stellite 21 (64% Co, 28% Cr, 6% Mo, 2% Ni, and 0.25% C) which was found to be excellent when a single base powder was used. With high temperature propellants, its low m.p. of 1200-1300^{o}C made it unsatisfactory.
4. Chromium with its high m.p. and excellent chemical resistance is, in fact, second best to Mo. Yet, it is very brittle and when applied by electroplating has microcracks due to residual stresses. It is the only material which has been used to protect bores from erosion in spite of these weaknesses. No method has yet been found to improve its ductility and obtain its coating crack-free.
5. Indications of a good promise were also obtained in the case of Co-W (97:3) and "as-rolled" silichrome XCR, but their complete evaluation was not achieved.

In fact, the suitability of a material is prescribed by the conditions under which the gun is designed to be fired. For example, for howitzers in which Ml propellant and low muzzle velocity are usually employed, there

is no problem of erosion and, therefore, nothing here can beat steel. The same is true for mortars, where because of extremely small residence time of erosion conditions and low pressures, fatigue rather than erosion is the life limiting factor. In guns where the melting point of the bore is expected to go high, but not very high ($< 1100^{\circ}C$), materials like Stellite 21 will be better than steel. Yet, they will not be suitable with double base propellants and rapid rates of fire. Chromium (m.p. $1895^{\circ}C$) or chromium alloys (with improved ductility) will perform better than Stellite 21 under these conditions. Still, at higher temperatures it becomes imperative to use refractory metals and alloys based on metals such as Mo, W, Cb, V, Ta, Re, Rh, Cr, etc.

Results of a number of investigations on the evaluation of such alloys and coatings will be presented tomorrow in the third session.

During the last 25 years, tremendous progress in the development of new techniques of fabrication, application of coatings, and evaluation has been made. Also, a number of new high temperature alloys have been developed and come into the market. They must be evaluated.

CONCLUSIONS

1. Although exhaustive work on the mechanism of erosion of gun tubes has been in progress for the last three-quarters of the century, it is still far from being adequately understood.

2. Because of the continuous efforts of improving the fatigue life of the tube and a side-by-side increasing demand of higher muzzle velocities, the problem of erosion will always be present. Therefore, a

continuous and coordinated activity must be maintained in the DoD laboratories to gain a deeper insight into this phenomenon.

3. A number of measures to reduce erosion have been considered. Encouraging progress has been made in the use of wear-reducing additives. Yet, the mechanisms involved are not fully understood. Very little has been done on the use of deoxidants and improvement of material and design of the rotating band. These areas must receive due attention of the investigators who are interested in reducing wear of gun tubes.

4. In the field of materials, the problem of brittleness of plated chromium remains unsolved. It is of interest to state here that very little attention has been paid to the nitrogen embrittlement [16] of chromium plated in the gun tubes. In the literature, addition of 0.1% yttrium has been suggested as a possible remedy. The problem of fabrication of suitable liners or application of coatings of refractory materials such as Mo and its alloys are also yet to be overcome. A refractory alloy better than chromium plated steel is yet to be found. Therefore, evaluation of new high temperature alloys as gun tube materials, liners or coatings and application of new technologies must continuously be explored.

5. To achieve fruitful results in a reasonable length of time, all these R&D activities must be carried out under a well prepared and coordinated plan.

ACKNOWLEDGMENT

Thanks are due to R. Imam for his fruitful discussion of the subject matter of this paper and also for providing a number of photographs of eroded bores, some of which are included here. Figures 3a and 3d were kindly supplied by R. B. Griffin and Mrs. T. V. Brassard of the Physical and Mechanical Metallurgy Laboratory.

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1.1 DISCUSSION:

R. Weigle (comment): Dr. Ahmad has stated that the wear limit of the 175MM M113E is 700 EFC rounds. I wish to add that this figure has now been modified to 1200 rounds.

Karl H. Meyer: Why is a stellite liner not compatible with a double base propellant?

I. Ahmad: The melting point of stellite 21 is low and cannot stand the high flame temperatures of double base propellants.

REFLECTIONS ON THE WEAR AND TEAR OF GUN BARRELS

Peter R. Kosting, US Army Materiel Command,
Washington, D. C.

Abstract

Comments are made based on observations extending over many years. Studies of the wear and tear of gun barrels and of the phenomena involved are multi-faceted and interdisciplinary in nature. Physical scientists, ballisticians, gun designers and systems engineers have different approaches to the problems of understanding the phenomena of erosion and wear and the improvement of the performance of guns. Different organizations within the Army become involved in full scale erosion investigations and their contributions must be timely for the maximum benefit to be obtained. Many lessons are relearned periodically, particularly regarding the importance of the mechanical properties of the gun barrel material and the design parameters. The phenomena of melting of the bore surface are important but not always controlling in erosion. Chemical changes and subsequent loss of the gun barrel material from the bore surfaces are also important. Yet, additions to the propellant powder and control of the design of the propellant powder grain have profound changes on the erosion rate of some gun barrels. Much remains to be learned about gun materials; propellant powders and gases; and design of guns, propellants and projectiles.

Introductions

The first Chief of the Ordnance Corps selected cast iron instead of bronze for the manufacture of cannon. Two reasons were given. The first was that weapons made of iron lasted longer than those made of bronze. The second was that iron was cheaper than bronze. The year this selection

was recorded was 1812, 158 years ago. It is no idle statement that the life of its cannon has long been an important concern of the Army.

Reflections on the wear and tear of gun barrels based on personal observations cover three periods of time, namely: prior to World War II; World War II; since World War II.

Period Prior to World War II

The early studies of the parameters affecting the life of gun barrels were usually unidisciplinary in nature. The ballistician, the designer, the metallurgist, the physical scientist, etc. evaluated relatively independently their own sets of parameters until the late 1930's. Metallographic studies of eroded barrels were concerned with thermal checking, carburization, the copper mouthful theory of crack propagation and so forth. Carbon pick up in the Hard Layer was established. Such type of studies were also carried out at Watertown Arsenal, the predecessor of the Army Materials and Mechanics Research Center at the time it was under the command of General Tracy Dickson. Dr. H. H. Lester reported in 1929 upon constituents of the Hard Layer, which is around 0.003 inch thick at the bore interface of eroded steel gun barrels. He found alpha and gamma iron were present and postulated the presence of iron-nitrogen solid solution. The next commander at Watertown Arsenal was Colonel Glen F. Jenks who stimulated continued study of erosion in the early 1930's. It was found necessary that improved methods of preparing metallographic specimens be used, otherwise evidence of the true nature of the bore interface was lost. The term Hard Layer was used to describe the hard surface skin and the term White Layer was used for layers which were found at the extreme bore interface. Some of these White Layers were less than about 0.00005 inch thick. These White Layers resisted ordinary etching much more than did

the Hard Layer. Two White Layers were sometimes observed, mechanical loss of which could account for much of the erosion. Along the side walls near the mouth of some cracks were found layers with eutectic-like structures. These were postulated to be the iron-iron oxide eutectic with melting point much less than that of steel. X-ray chemical analysis identified the presence of iron oxide. Evidence of other unidentified constituents existed in the X-ray diffraction pattern. Clues lead to experimentation with ferrous cyanide, for instance, but with inconclusive results. Chemical reactions of steel with propellant gases to form gaseous carbonyls were considered.

The study of eroded chromium plated gun barrels and liners revealed that chromium metal would break off from itself but leave the chromium-steel interface intact. Numerous but not all cracks in the chromium plate extended through to the steel. Chromium was more resistant to the chemical attack of propellant gases than was the steel which somehow disappeared from beneath the plate at many of the cracks. Also chemical changes in the steel were found to have occurred, extending longitudinally at depths greater than the thickness of the Hard Layer at places where the propellant powder gases had access through cracks to stringers of inclusions. Needless to say, poorly processed chromium electro-deposits would flake off in toto during proof firing of plated gun barrels. Diffusion of carbon, hydrogen and nitrogen into the steel was considered.

In machine gun barrels, deep cracks were preceded by chemical changes in the steel as revealed by metallographic etching. Bainitic microstructure of the Hard Layer was identified.

Elsewhere work was also going on. Frankford Arsenal and Springfield Armory were developing chromium plated machine gun barrels. At Aberdeen

Proving Ground, the thermal history of and temperature distribution along gun barrels were being calculated and experimentally determined; a massive molybdenum metal liner was found to be erosion resistant; life of various cannon was being predicted, and so forth.

It was concluded that direct melting of steel was not the best explanation of erosion in well designed guns, particularly when using single base propellants as suggested by many prior investigators. However, it can take place when conditions are suitable. Scoring of gun barrels is considered to be caused by too great leakage of gas and melting of steel.

Period of World War II

At the beginning of World War II, the problems of gun erosion were suggested to Dr. J. B. Conant during his visit to the United Kingdom in order to determine what military research the United States of America should undertake. The National Defense Research Council undertook this work and carried out a broad program. At the end of the war most of the work was stopped precipitously.

The contributions were numerous and valuable. One piece of intricate work was done at Johns Hopkins University in collaboration with Aberdeen Proving Ground and Frankford and Watertown Arsenals. Several new iron carbonyl compounds were discovered and synthesized, and their decomposition reactions were determined. The objective was to determine the tendency for iron carbonyl vapor formation during firing of gun barrels. This was done by capturing and quickly cooling the bullet and propellant powder gases after they had passed the length of the gun barrel and emerged from the muzzle. Some iron carbonyl was detected but not nearly enough to account for the weight loss of the barrel. But iron carbonyls decompose quickly, and though the end reaction products are usually iron and carbon monoxide,

iron oxide and iron carbide are the results of several types of side reactions. The end of the war stopped further work on improving the quenching of the gases and identifying the sources of any iron oxide and carbide particles. These particles could form also because of direct oxidation and carburization of gun steel by the propellant powder gases.

During part of this period, Colonel H. H. Zornig was Laboratory Director at Watertown Arsenal. He introduced the systems approach to the studies. His concept was that the study of erosion in all of its ramifications required a back up facility of broad capabilities to make and alter: propellant powder and igniters, etc; projectiles, rotating bands, and cartridge cases, etc; breech rings and breech blocks, etc; chambered and rifled gun tubes, etc; carriages, recoil mechanisms, etc. In addition, there should be but one size of gun in which all ideas were first tried out. This became known as the "One Caliber Gun". The size should be small and standard in the interest of economy of ammunition required for firing tests. The 37MM gun system was such a weapon and much erosion information was obtained with it. This gun was available with at least two variations in chamber size, two types of propellant powder, fully developed projectiles, cartridge cases and propellant powder, and a big supply of complete rounds. The initial development by Battelle Memorial Institute of thick electrodeposited chromium for erosion resistance was done with the 37MM gun. This size was also used in the Carnegie Institute of Technology program on steel quality, the initial plan of which required about 90 tubes.

Another concept of Colonel Zornig was that in a well designed gun tube and projectile system, the military characteristics would all deteriorate beyond usefulness at about the same time in the erosion life of the

weapon. Thus, dispersion and frequence of prematures should not become intolerable while range and muzzle velocity remained relatively unchanged.

Among other developments were chromium plated nitrided machine gun barrels and Stellite lined machine gun barrels. The Stellite has a lower melting point than steel but much better hot hardness. The development of strong ductile tough chromium and chromium base alloys and of molybdenum was started.

This was also the period when band pressures were first measured extensively, also there were observed squashing of lands in guns made of soft steel, deformation and shearing of side wall of lands in guns made of hard steel, annular growth of side branches from the radial bore cracks leading to stripping of short lengths of lands in regions adjacent to the origin of rifling. The resultant changes in the bore diameter were not attributed to erosion.

Period After World War II

Among the many endeavors which were continued after the close of World War II were: improvement of chromium plate and the plating process; development of strong, ductile, tough chromium and chromium alloy castings or forgings having a large cross section; development of strong ductile tough molybdenum pieces having a large cross section; development of these and other refractory metals for thin liners for machine gun barrels.

Obvious potential for improvement in chromium plating included increasing rate of deposition by a factor of 10, decreasing the crack system, improving the hot hardness, measuring non-destructively the quality of adhesion. The quality of adhesion and the capability of reproducing good results were impaired by most changes in the existing chromium electroplating process. The development of fundamental criteria for measuring

adhesion was impaired by the desire to evaluate "working" electroplating solutions used in production. Although both college researcher and government engineer were interested in the results, time and money ran out before necessary standards could be evolved. The initial obvious improvements still remain to be achieved. A recent study of the dispersion hardened nickel plate at Watervliet Arsenal is most interesting. The improvement in erosion resistance of the nickel under conditions found deleterious to steel under chromium plate remains to be established. The Army undertook the development of large forgings of ductile tough chromium base alloys. The Navy undertook not only the development of molybdenum but also the design for cannon of a liner made of brittle materials. In essence, the latter endeavor was the design of a liner with separations (cracks) located in tolerable positions. All in all, although small pieces such as wire and turbine blades for aircraft engines were prepared from ductile metal, large pieces suitable for military usage were not obtained.

The policy of developing a tough alloy before firing tests are begun is still considered correct. Although it can be demonstrated that several barrels of non tough material may be fired successfully, stoppages occur due to the passage of the projectile being blocked by dislodged fragments of the liner. The fragments are formed by the growth of annular cracks as well as longitudinal and transverse radial cracks. These stoppages affect the reliability and safety of the weapon.

More hopeful progress was made at Springfield Armory with thin liners for machine gun barrels. The first columbium alloys tested gave outstanding evidence of success only to be snagged on reproducibility. Interest in tantalum alloys evolved soon thereafter. The development of such alloys is continuing.

More recent developments at Picatinny Arsenal has shown the potential for fiber reinforced plastics in the manufacture of very light weight tubes (81mm in diameter). Means to overcome the thermal checking and to withstand the internal pressure have been demonstrated. In the meantime, fibers and plastics capable of withstanding high temperatures are being developed by the sister services. Metal may no longer be indispensable for cannon.

The idea conceived at Aberdeen Proving Ground of enveloping the hot gases with a layer of cool gases flowing past the bore interface seems to have found a modification in the new ball small arms ammunition. A plug of cool gases immediately behind the projectile at the instant of start, and engraving of the rotating band by the rifling, may be the key. The recent development, of course, is the successful wear additives for use in some, although not all, cannon systems. This development was extremely valuable at this time in the history of our Nation. At first glance this appears to negate need for metallurgical improvements. On second thought, however, it hopefully permits upping the performance characteristics of future cannon systems, the low cost accuracy of which is their chief military usefulness. It may be helpful for the light weight problem. For these reasons the correct explanations of the successful and unsuccessful applications of wear additives and layered propellants are important areas for research.

A change in concentration of the main alloying agents in the surface layers of eroded gun tubes has been indicated by means of adaptation of new methods of instrumental chemical analysis for light weight elements. Further adaptation should be helpful in tracing mechanisms of erosion.

New procedures for measuring erosion and expressing the results are definitely needed. The caliber .30 erosion gage weapon is one simple

improvement. The degree of erosion is a function of the severity of test. It is not enough to identify the severity and then compare weight losses. This variability of severity should somehow be incorporated in an erodibility factor for any material. This should minimize misinterpretation of data about the relative erodibility of materials.

Close

Only a few of many endeavors have been mentioned for the purpose of showing the military implications of many basic and applied problems associated with Gun Tube Erosion and Control. Such problems are a continuing challenge to the military scientists and engineers. There is no final solution because as soon as one goal is reached, the designer will require that more energy be introduced into the system. Metal is not necessarily supreme. Fiber reinforced plastics will continually challenge metal on the basis of weight and even temperature of service. Wear additives and layer propellants enlarge the scope of future opportunities.

Quantification of knowledge for computer retrieval and reuse when military characteristics are truly specified should make design of a gun-projectile system more reliable in the initial stages and eliminate much, but not all, of the test firing now required.

The stakes are high in erosion research.

1.2 DISCUSSION:

Ernest L. Bannister: What were the effects of Carbonyl Erosion?

P. R. Kosting: There is metallographic evidence of deterioration of gun steel by propellant powder gases at discrete but small distances from the bore interface. In machine gun barrels which presumably are very hot during firing the entire length of some bore cracks is affected. In both cannon and m.g. barrels the steel is affected along stringers of non-metallic inclusions adjacent to the bore and intersecting cracks. Loss of steel from beneath electroplated chromium metal has also been demonstrated. Search for explanations of this type of evidence included the work on iron carbonyls by Evans Fraser and Horn. But carbonyls may not be the actual deterioration agent and certainly is not the only one.

Paul Netzer: 1. Were there not studies on thickness of chromium in excess of .0005 inch?

2. What were results of the gas study components continued after John Hopkins? Did not sulphur contribute significantly to erosion?

1.2 DISCUSSION CONT'D:

P. R. Kosting:

1. Battelle Memorial Institute, under contract, developed the application of thick chromium plate for erosion retardation. It was determined that with thick plate, new barrel performance could be maintained for quite a long time. Thickness up to .010 inch and more were used.
2. Undoubtedly small additions can catalyse chemical reactions appreciably.

GUN EROSION AND METHODS OF CONTROL*

Mrs. D.J. Taylor and Mr. J. Morris
Royal Armament Research and Development Establishment
Fort Halstead, Seven Oaks
Kent, England

Various aspects of gun erosion with a special reference to the United Kingdom experience are reviewed. Methods of controlling heat transfer, mechanical effects caused by the rotating band, muzzle and spiral wear are discussed.

DESCRIPTION OF EROSION

Bore Enlargement

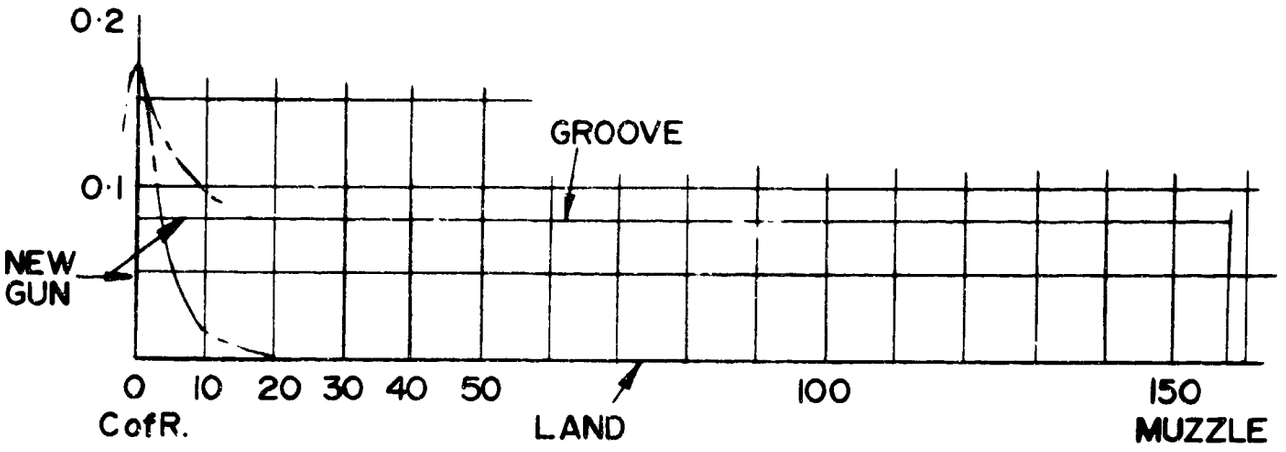
The most important feature of erosion is the enlargement of the bore. Erosion is a general term applied to the removal of metal from the bore of a gun by the action (thermal and chemical) of the propellant gases and also by the abrading action of the driving band of the projectile. Erosion due to gas action is greatest at the breech end of the rifled bore and decreases exponentially towards the muzzle, the extent varying with the nature of the gun and propellant.

Mechanical wear by driving bands of copper or plastics is relatively small and under conditions of rapid erosion the action of the propellant gases will over-shadow the wearing effect of the driving band. On the other hand driving bands made of cupronickel, steel, soft iron or sintered iron do not suffer the same degree of softening as copper bands due to frictional heating during the travel along the bore, and by their abrasive action progressively extend landwear towards the muzzle. In guns which fire metal cartridge cases, erosion starts from the mouth of the case and is most severe at this point which is just before the leed and the rifled part of the bore, ("Y" in Fig. 1.2). The cartridge case protects the chamber of the gun from erosion. In bag-charge guns where the chamber is not protected, erosion is most severe at the commencement of rifling and only extends rearwards a short distance in the chamber. These characteristics of bore enlargement are shown in Fig. 1.1.

The wear in the grooves is about half that on the lands. In some cases erosion may proceed at an enhanced rate at local points in the bore surface. Irregular pits or 'scoring' result. Scoring usually occurs, or is most severe, near the position of the driving band at the time maximum pressure is reached. A good example of scoring is shown in Fig. 1.2.

*(Based on a paper drafted by Mr. J.B. Goode, 1948)

Q.F. 3·7" MKS. 1-3 GUN
AFTER FIRING 1600 ROUNDS
(N PROPELLANT)



Q.F. 17 PR. GUN
AFTER FIRING 300 ROUNDS
(NM PROPELLANT)

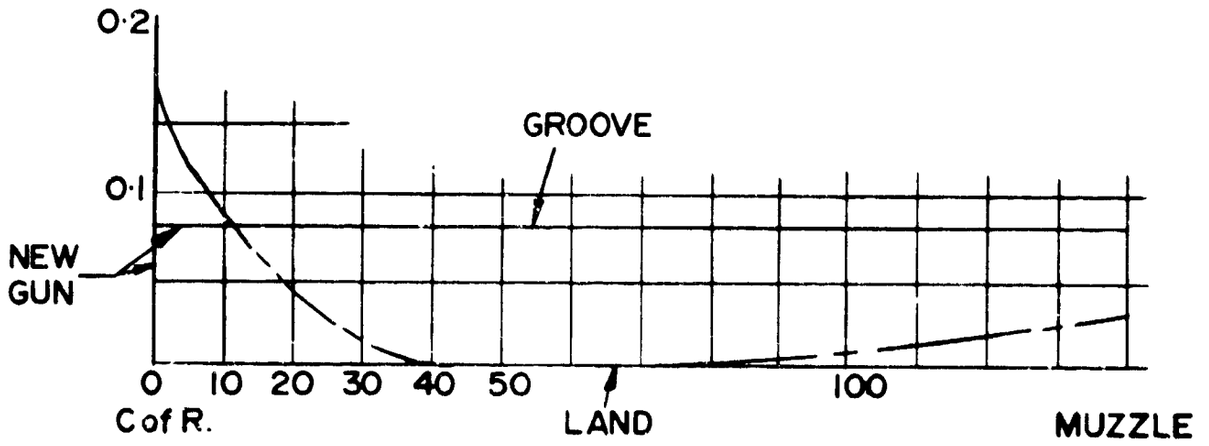


FIGURE 1.1. GUN WEAR CHARACTERISTICS

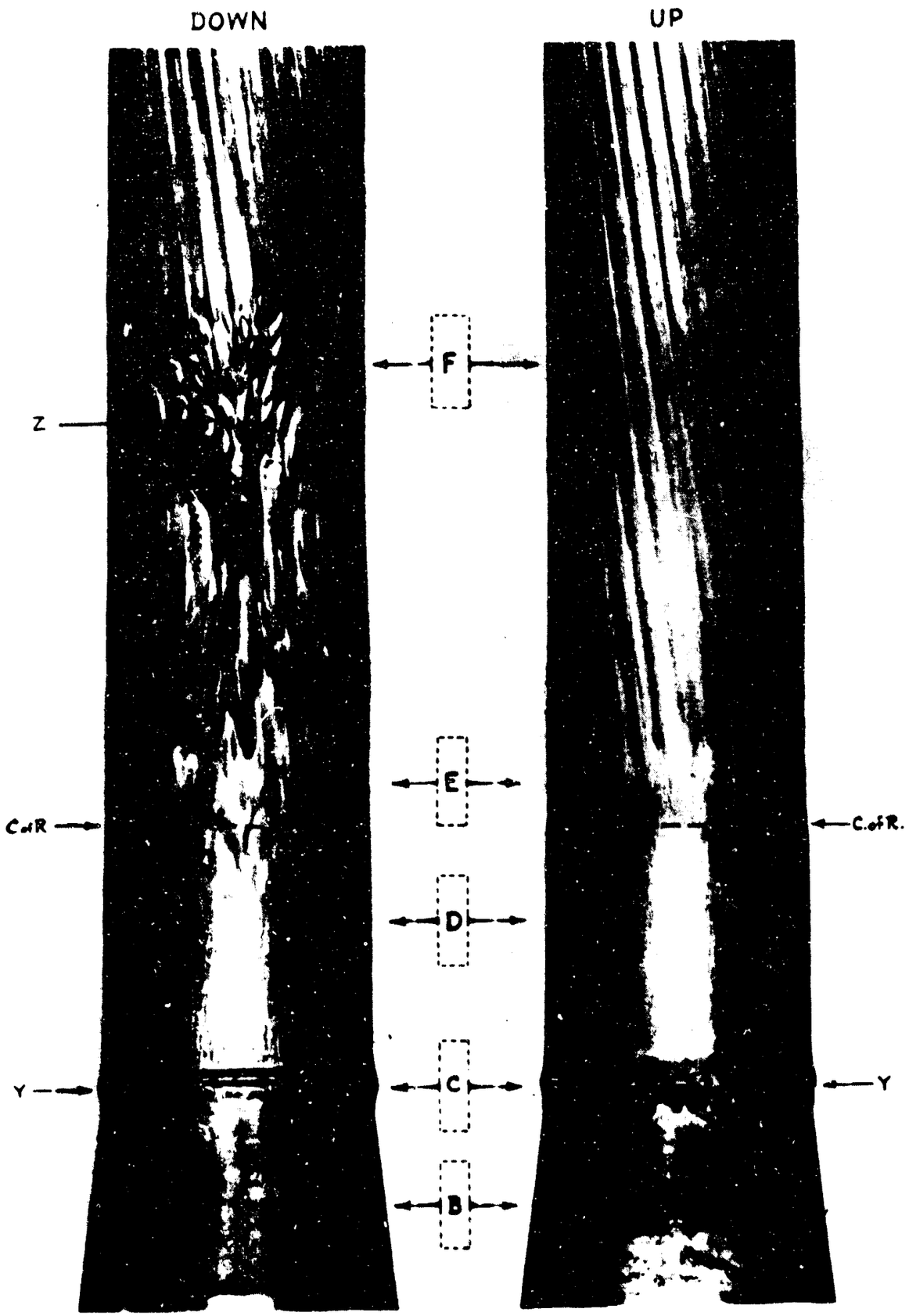


FIGURE 1.2. EROSION AT CARTRIDGE MOUTH AND LOCALISED SCORING IN RIFLED BORE OF 4.5 INCH GUN.

The rate of erosion, or bore enlargement, that is the percentage increase in bore diameter per round fired increases with the performance of the gun, gun performance being defined as the energy imparted to the projectile divided by the cube of the calibre. It also increases with the flame temperature of the propellant. There is a noticeable difference between cartridge case guns and bag-charge guns, the former having twice the erosion rate shown by the latter for equivalent conditions. It is usual to measure wear at one point in the vicinity of the commencement of rifling, (which is where the rifling attains its full depth). If this measurement is plotted against the number of rounds fired it is observed that while for some guns the plot is linear corresponding to a constant rate, in others the plot is curved showing a decrease in the rate of erosion as the amount of erosion increases. In these latter guns gas erosion is negligible and the bore enlargement at this measuring position is mainly due to abrasive wear.

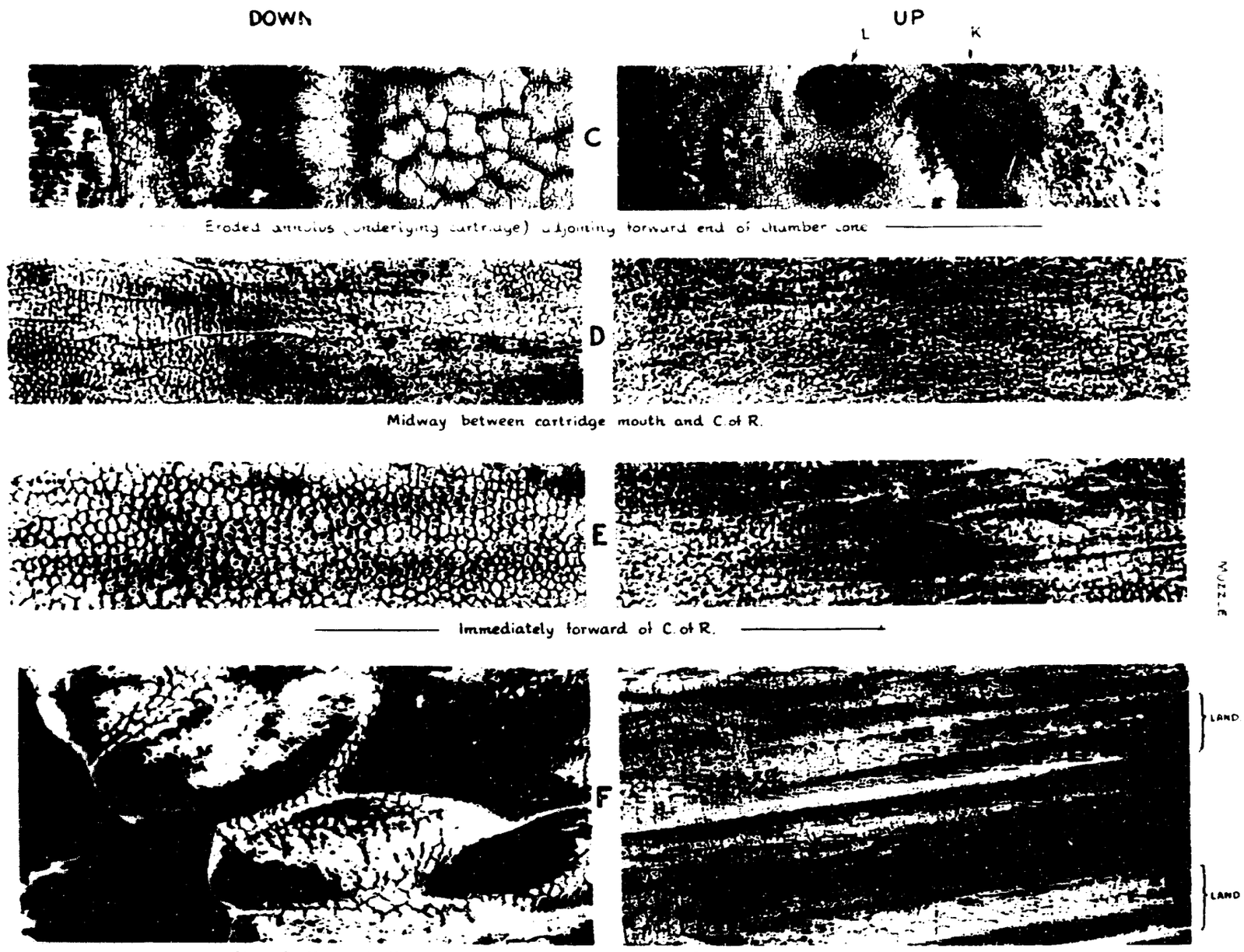
Bore Cracking

A notable feature of steel gun barrels is the craze-cracking of the bore surface which develops early in barrel life, and decreases in amount and depth as the rate of heat input to the bore surface decreases towards the muzzle. The pattern of these cracks exhibits a bias following the direction of the final machining of the bore surface, which is longitudinal in the grooves and transverse on the lands. As erosion proceeds some of the cracks become deeper and wider than others, and the pattern becomes one in which irregular shaped polygons are outlined by large cracks and contain a system of smaller cracks. At a latter stage distinct zig-zag cracks appear in the angles of the rifling grooves. In some cases the edges of transverse cracks are smoothed as if by gas flow. Illustrations of craze-cracking are given in Fig. 1.3. Surface cracking tends to be deeper and more prolific with cooler propellants, that is, under less erosive conditions.

In high rate of five, built up, guns, where the thermal gradient across the barrel wall is steep (particularly if water cooling is employed giving rise to high residual longitudinal tensile stresses at the bore), the major members of the crack pattern generally run in a circumferential direction and are most severe in the leed and early rifled bore. Progressive Stress Damage occurs when one or more members of an existing crack pattern increase in depth with subsequent firings and cause the barrel to fail in a fatigue mode.

The Altered Bore Layer

One of the changes which take place at the bore surface of a gun during firing is the formation of a thin hardened, or altered, layer. This layer is obvious in any metallographic section of a fired gun barrel. Its thickness depends upon the severity of the erosive conditions. At and near the commencement of rifling the thickness builds up fairly early in the barrel life. This thickness remains reasonably constant throughout the barrel life. As material is removed from the bore thermal penetration into the



1.3-4

FIGURE 1.3. ENLARGED VIEWS (x4, REDUCED 1/4) OF BORE AT LOCATIONS C TO F IN FIG 1.2.

barrel wall restores the original depth of the altered layer. The depth of this layer diminishes progressively towards the muzzle end of the barrel and in many guns it does not exist in the forward regions of the rifled bore. Etched sections through plated and unplated bores showing varying degrees of thermal penetration are reproduced in Fig. 1.4.

The altered layer has a structure similar to that of martensite, but there has been some controversy as to whether simultaneously the possible absorption of nitrogen or carbon might cause the quenched layer to remain in the austenitic condition. Although austenite has been identified in the surface layers it is still not certain to what depth it is present in the altered layer. Like other chemical alteration products it may be just present in the 'white layer' that overlies the thermally altered layer.

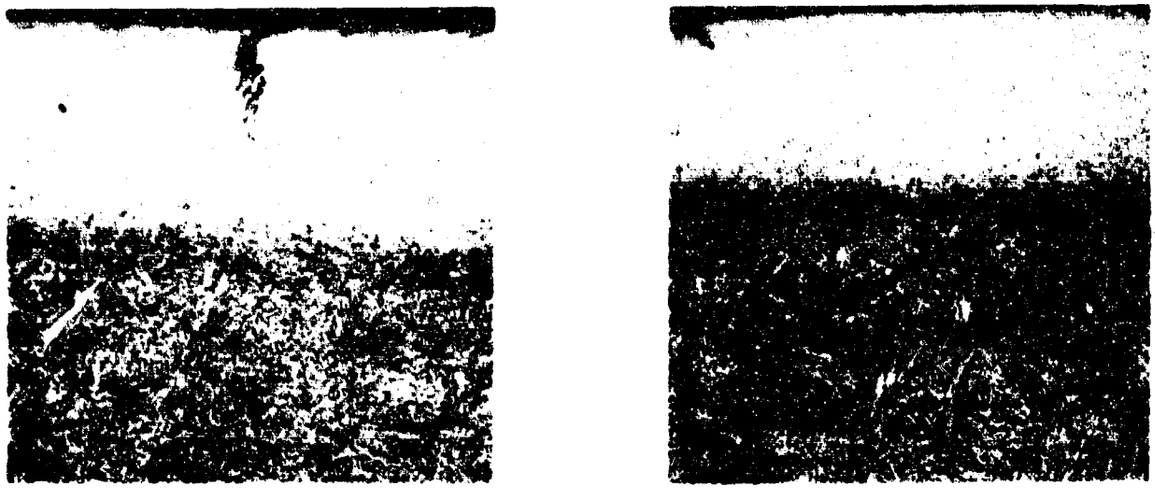
Erosion products

The products of erosion found on the bore surface can provide valuable information in the detailed study of the mechanism of erosion, particularly of the chemical reactions that take place. A considerable amount of work on the examination of these erosion products has been carried out by American investigatiors. (1).

The first stage in such an investigation is the removal of the erosion products from the bore surface. Material lodged in cracks can be collected if most of the barrel thickness is removed so that the curved bore surfaces can be flattened, thus opening the cracks. It was found that the coppering banded projectiles, was a 'store house' for erosion products that had been formed on the bore surface and swept forward. These entrapped products were released by dissolving the coppering with an ammoniacal solution of ammonium carbonate and hydrogen peroxide at a low temperature, 5°C, to prevent attack of the underlying stool.

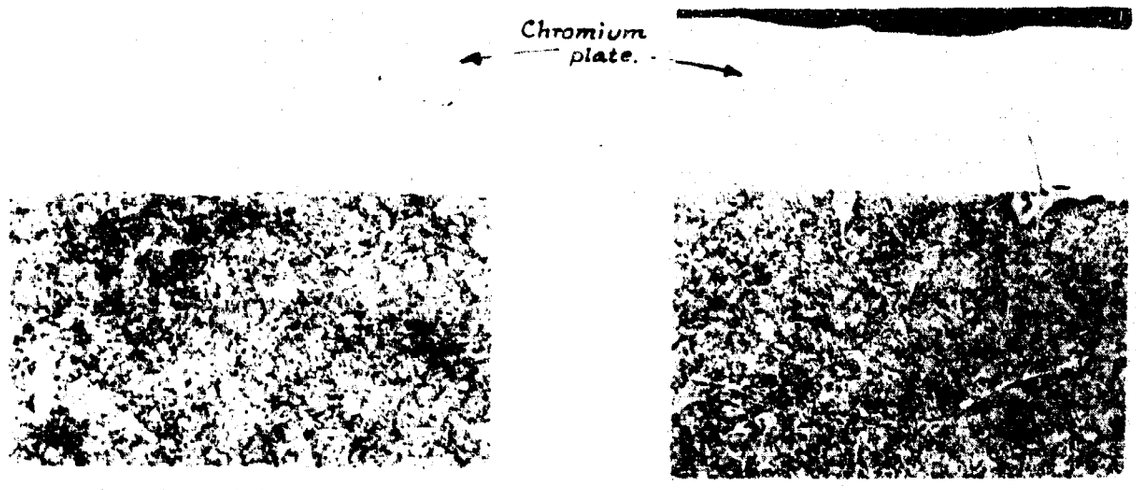
A special technique was used for disengaging flakes of cementite from the altered layer. A section of the decoppered bore was treated with a solution of copper potassium chloride containing a small amount of hydrochloric acid. This solution dissolves the underlying gun steel leaving disengaged flakes of cementite. The cementite of the unaltered steel may be separated in the same way, but in this case it is a very finely divided powder. The crystals of cementite obtained from the altered layer are so coherent that they can be removed as scales which comprise a cast of the crack system. An improved method of obtaining such a cast consists in coating with vinylite resin the eroded surface, then dissolving away the ferrite leaving the cementite flakes adhering to the vinylite.

For identification of the erosion products standard X-ray and electron diffraction techniques were used, the spectrograph and chemical analysis. The following table lists the chemical alteration products which were identified and the positions in which they were found.



On land. In groove

Thermally altered layers (×500) at 12 inches C. of R. in 4·5 inch gun barrel.



No altered layer Penetration down micro-cracks.

Chromium plated gun bores, (×100).

Penetration by decopperizing compounds. through micro-cracks (×100)

Altered structure under Cr. at corner of land (×100)

FIGURE 1.4. THERMAL ALTERATIONS IN BORE SURFACES, WITH OR WITHOUT PROTECTIVE CHROMIUM PLATING.

Alteration Product	Superficial surface layer	Surface layers near C. of R.	Entrapped in coppering	In cracks	Beneath cartridge case
Cementite Fe_3C		x	x		
Fe_2C			x		
Austenite		x	x	x	
Magnetite	x		x	x	x
Wastite FeO		x	x		
Iron nitride ϵ		x	x		
Iron nitride γ		x	x		
Chalcocite Cu_2S			x	x	
Wurtzite ZnS		x	x	x	x
Sphalerite ZnS				x	
Digenite Cu_9S_5				x	
Pyrrhotite FoS_x				x	
Barium carbonate				x	
Barium sulphate				x	
Barium nitrate					x
Chromium carbide		x			
Nickel carbide		x			

Muzzle wear

In some guns under certain conditions there occurs an enlargement of the bore at the muzzle. This is known as muzzle wear. It tends to occur in moderately high velocity guns firing copper banded shot. The bore enlargement is more extensive than that occurring at the breech end of the rifled bore; it usually develops over a bore length of 20 calibres or more becoming greater as the muzzle is approached. Muzzle wear is almost entirely confined to the lands, there being little or no wear in the grooves. Very frequently muzzle wear is asymmetrical, that is, a few adjacent lands are worn to a greater extent than the rest. This asymmetry tends to be associated with the same group of lands throughout the region of muzzle wear; this type is often referred to as "spiral wear". The rate of muzzle wear increases exponentially with the muzzle velocity of the projectile. (2).

THE CONSEQUENCES

Muzzle Velocity

The enlargement of the bore brought about by erosion causes a deterioration of performance of the gun and eventually determines the end of its useful life either by the extent of this deterioration or by consequent failure to function correctly. Muzzle velocity is the main factor which is subject to gradual deterioration. This is due to a falling off in the

initial frictional resistance to the motion of the projectile and, in the case of separately loaded guns the increased ramming leading to an increased chamber capacity, is also an important contributory cause. In the later stages of wear gas leakage may also be significant. (3).

Hump Effect

Even without actual enlargement of the bore the craze-cracking in the bore surface may alter the friction between band and bore and have an appreciable ballistic effect. This is apparent as a rise in pressure and velocity in the early stages of gun life, and is called the 'ballistic hump' effect. (4).

Band Stripping

In a worn gun, because of the obliteration of the rifling by erosion, the projectile moves some distance before its driving band makes effective contact with the rifling. This is particularly true with fixed ammunition, but is also the case with separately loaded projectiles. With any finite angle of rifling at the point of engagement, partial failure or stripping of the driving band is inevitable since owing to its inertia the projectile cannot instantaneously acquire the rotational velocity appropriate to its forward velocity and the twist of rifling. This partial failure of the driving band involves loss of metal, and as the gun becomes more worn this loss becomes greater until finally the band is completely stripped.

Fuze damage

Damage to fuzes arises from what is known as "side slap", that is the accelerations produced in the projectile by lateral motion. It will be obvious that enlargement of the bore will allow more scope for such motion and the accelerations produced by hitting the bore will tend to increase. The results of this phenomenon can often be seen a few calibres from C. of R. as local flattening of the lands caused by impact of the shoulder of the shell.

Arming of fuzes

Some fuzes require a minimum forward acceleration for arming. In the case of the bottom charges in howitzers the maximum pressure attained in a worn gun may be insufficient to provide this acceleration, especially if the charge temperature is low.

Inaccuracy of gun

Inaccuracy of shooting may be due to partial failure to impart spin causing a reduction in the stability coefficient of the projectile, or it may be due to the enlargement of the bore at the muzzle which will increase the initial angular dispersion of the projectiles.

Overtempering of barrel

The heating of the gun barrel, if excessive, will reduce its strength either by reducing the strength of the barrel material or reducing the magnitude of the built-in stresses in auto frettaged or shrunk-up gun barrels.

"Cook-off"

Heating of the gun barrel can also produce a temporary problem of some importance in rapid fire guns. The barrel may become so hot that if a round is loaded but not fired the propellant may 'cook-off' and ignite.

THE MECHANISM OF GUN HEATING AND EROSION

Theory (5, 6, 7 & 8)

The propellants referred to in the text are as follows:-

RDX - Experimental propellants, various types and temperatures
N, N/S - Picrite, flame temp 2450°K. WM - Double base, 3,200°K, obsolete
NH - Single base, US origin, 2680°K. NC - nitro cellulose base, various temperatures. Digl - Diethylene glycol dinitrate, various temperatures.

General considerations

The heating of a gun barrel during firing is brought about by the friction between the projectile and the bore, leakage of hot propellant gases past the driving band and by the main stream of propellant gases following behind the shot. There is little doubt that most of the heat is transferred to the barrel by forced convection through the turbulent boundary layer of the high velocity main stream of propellant gases, for, compared with this, the heat transfer by radiation from the gases is negligibly small,[5] and the heat produced by friction has no appreciable effect on the total heat transfer or on the maximum surface temperature.[6] The possible heating effect of gas leakage past the driving band is found theoretically to be small unless the leakage channel exceeds a certain size.

Heat transfer equation

The transfer of heat between the propellant gases and the bore is due to the exchanges of energy in collisions between the gas molecules and the wall. Since the mean free path of the gas molecules at the densities prevailing in ballistic conditions in very small - of the order of 10^{-7} cm - the motion of the gases can be treated by the methods of hydrodynamics and the type of flow depends upon the relevant Reynolds number. In ballistic conditions, the Reynolds number is always extremely high - of the order 10^7 to 10^9 - which means that the flow will always be of a highly turbulent nature, except possibly in a thin boundary layer adjacent to the wall. The thickness of this boundary layer under ballistic conditions will be of

the order of 10^{-5} cm which, though small compared with the gun dimensions, is large compared with the mean free path. It follows that the accommodation coefficient will be of the order of unity and that at the bore surface the gas will have zero flow velocity and the same temperature as the surface. Under these conditions there exists a relation between heat transfer and mechanical friction first discovered by Reynolds.

The heat transfer is accordingly given by the equation -

$$q = 1/2\ \lambda\ s_p\ \rho u(\theta_g - \theta_g)$$

where
- q is the heat transfer
- ρ and u are the gas density and velocity respectively
- o_p the specific heat of the gases at constant pressure
- θ_g and θ_s the temperature of the gases and surface respectively
- λ is a hydrodynamical factor - the Fanning factor - related to the mechanical friction of the walls.

Friction Factor

In order to obtain numerical values for the heat transfer it is necessary to know the value of the friction factor λ ; the other factors are either physical factors or can be deduced by standard internal ballistic theory. The friction factor depends upon the type of flow. The thickness of the boundary layer as deduced from hydrodynamical theory is of the order of 10^{-5} cm. A boundary layer of such dimensions has a meaning only if the wall is sufficiently smooth. Irregularities of larger dimensions in the surface will prevent laminar flow and a rough regime will exist. This will certainly be the case for gun bores. This result introduces two considerable simplifications to the heat transfer theory; firstly a constant value of λ can be used, since with a rough regime λ is independent of velocity, and secondly there is no need to investigate the viscosity of the propellant gases. On the other hand the value of λ cannot be obtained 'a priori' from theory alone and must be determined by comparison with experimental results on the heating of guns.

The above considerations apply to the case of minimum disturbances of flow. Any deviations from ideal conditions, such as variation in the cross sectional area at the mouth of the chamber or the presence of sharp corners at the mouth of cartridge cases, will always tend to increase the friction factor.

Calculation of bore temperatures

The heat transfer equation having been established, the resulting temperatures and heat flow in the barrel can be calculated by the Fourier equation of heat conduction in solids. Such calculations show that the bore surface near the commencement of rifling attains the highest temperature and that the value of the peak temperature attained at positions further forward falls quite rapidly with the distance from the commencement

of rifling. (Fig. 3.1) To be more precise, the part of the bore which attains the highest temperature is immediately to the rear of the gas sealing device, the driving band in most cases, in the loaded position of the projectile. The calculations also show that, owing to the relative slowness of the thermal conduction process, only a very thin bore surface layer is heated at all when the bore surface reaches its maximum temperature. And further it is only a thin layer which undergoes a large rise in temperature. A typical example is shown in Fig. 3.2.

Measurement of bore surface temperature

It follows from the concluding remarks in the previous Section that if the maximum bore surface temperature is to be determined experimentally, measurement must be made at a point extremely near to the bore surface. This is clearly fraught with considerable difficulty, but success on the small arms scale has been achieved[9]. Steel plugs were fitted to borings in a rifle barrel so as to be flush with the bore. Thermo junctions were formed in the bottom of the plugs by a very thin coating of nickel and the measurement was made at a distance of 0.002 cm from the bore surface. Corrections for this displacement were applied.

Measurement of heat transfer

The alternative approach is to measure the total heat transfer at a given point of the barrel, since the theory can be used to calculate either the maximum bore surface temperature or the total heat transfer. Three techniques have been used for this purpose by US investigators; they are known as the "calorimetric ring", the "calorimetric section" and the "calorimetric wall"[10]. The calorimetric ring technique employs a thermally isolated ring which forms part of the bore surface and of which the temperature rise is measured. This method has, however, been completely superseded by the calorimetric section which uses the actual gun barrel as a calorimetric section, as this avoids any possible disturbance of the gas flow and is obviously much simpler to apply. The method is satisfactory for most positions on the barrel because the temperature across the annular section of the barrel has evened out before there is any significant loss of heat from the section by longitudinal conduction or by external cooling. Measurement of heat input at the commencement of rifling is not possible with this method since considerable longitudinal heat flow takes place in this region. The calorimetric well technique in which the thermocouple is fixed to the centre of a flat bottomed boring near the bore surface overcomes this difficulty by reducing the distance between the bore surface and the thermocouple and therefore the time for the conduction of heat. Another technique is to deduce the total heat transfer from the residual external strain of the gun barrel measured by a strain gauge.

CORRELATION OF RATE OF EROSION WITH THERMAL EFFECTS

Critical isotherm theory

A simple theory of erosion was developed by C.K. Thornhill based on the assumption that, at a specific position along a gun barrel, the rate of erosion is directly proportional to the depth of penetration of one of

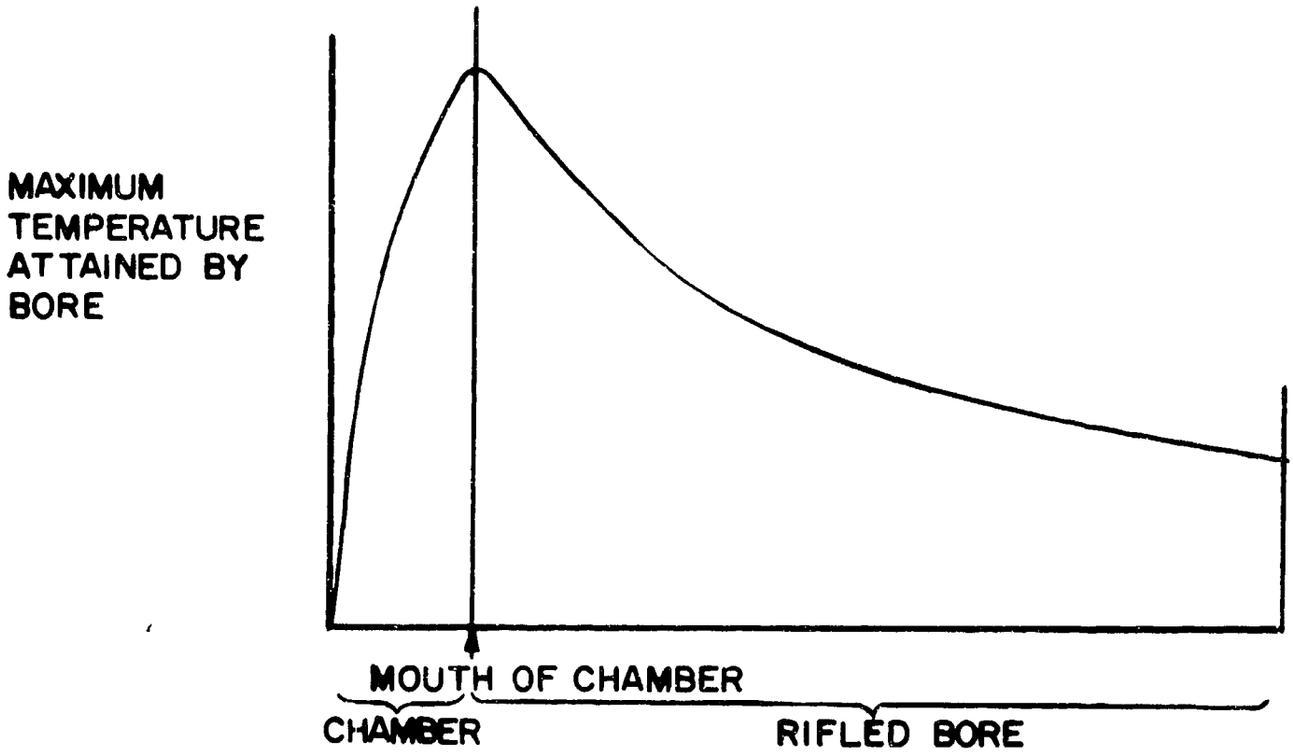


FIGURE 3.1

PEAK BORE TEMPERATURE DISTRIBUTION

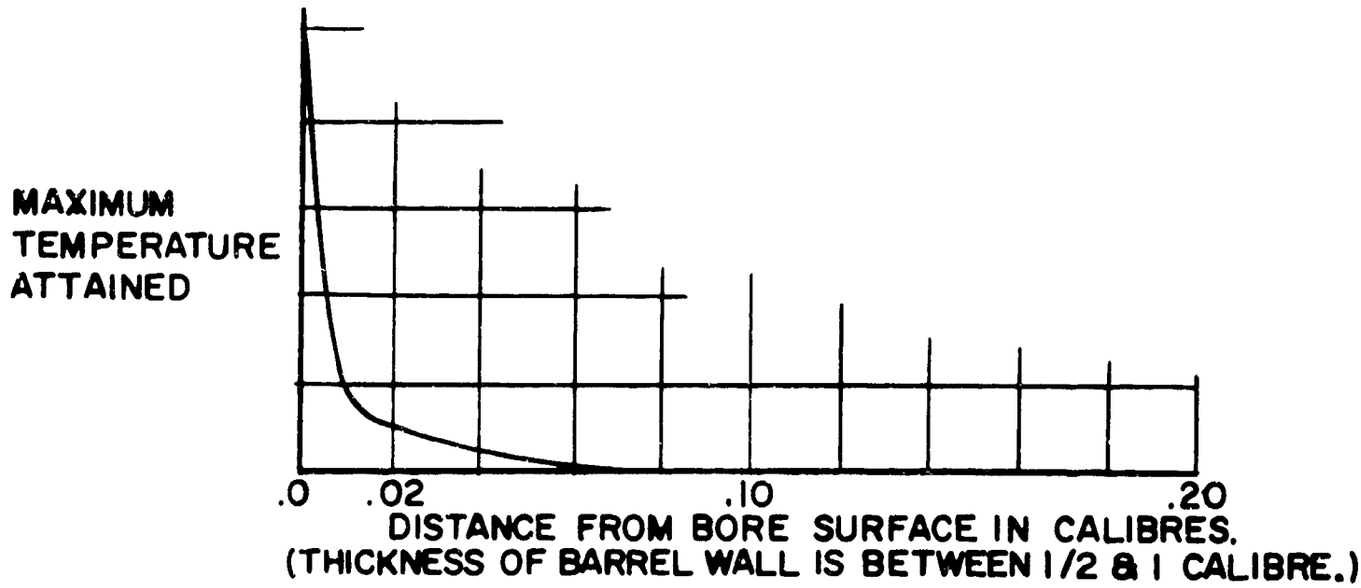


FIGURE 3.2

TEMPERATURE DISTRIBUTION IN BARREL SECTION

a number of critical isotherms. From the results of some detailed thermal calculations in a representative group of cases, semi-empirical formulae were derived for the estimation of the maximum bore surface temperature, heat transfer, and depth of penetration of temperature. Applied to the position of the commencement of rifling these formulae show an appreciable degree of correlation in service guns between the average rate of wear at 1 inch from C of R and the estimated maximum bore surface temperature at this point. Three regimes of erosion were identified. When the maximum bore surface temperature is less than 660°C erosion is negligibly small and probably entirely mechanical in origin; when the temperature is between 660° and 1,000°C the rate of erosion divided by the square root of the calibre increases steadily with temperature - this in theory is equivalent to the depth of penetration of the 660° isotherm. This critical temperature is, by its derivation, a theoretical figure in which no allowance has been made for the hydrodynamic roughness of the bore surface of the gun. The critical temperature is possibly associated with the AC temperature of phase change in steel - about 710°C for slow rates of heating, but higher for more rapid rates. When the maximum bore surface temperature is greater than 1060°C the rate of wear increases much more rapidly, and this may be associated with the melting point of cementite, 1150°C.

Melting Theory

R. N. Jones of BRL, has developed a theory of gun erosion by melting. Although the average bore surface temperature may never rise to that of the melting point, if the surface is rough, a large number of peaks may be presented to the heating action of the gases and raised to the melting point. Dr. Jones contends that this actually happens and that the material from the small peaks is melted and swept away, the bore surface maintaining a stable condition of roughness by fresh peaks being constantly formed during firing.

Erosion is therefore proportional to heat input and the proportionality factor is determined to give good correlation. The same constant applies to both guns and erosion vents.

THE PART PLAYED BY THE DRIVING BAND (ROTATING)

Band Pressure

It is now well known that copper driving bands exert a high radial pressure on the gun bore near the commencement of rifling and in some cases throughout the bore[12]. Initially, at any rate, this radial pressure must be accompanied by a powerful frictional drag on the bore surface, though later, as the surface of the driving band becomes heated, this drag will diminish with the falling coefficient of friction. The combination of these high radial and longitudinal forces acting on the bore will tend to break up and remove any bore surface layers embrittled or otherwise damaged by thermal and chemical action. Laboratory experiments have shown that when copper slides on an unlubricated steel surface there is not only a marked tearing out of copper fragments from the copper surface, but also a plucking of minute particles of steel out of the steel surface.

The most abundant and general evidence is in the shape of the wear curves for guns. For certain guns the rate of wear at 1 inch from commencement of rifling decreases with increasing wear until the amount of wear roughly corresponds with the height of the driving band. Since the forces exert by the band will tend to become smaller with increasing wear while the other conditions will remain substantially the same, it is concluded that the difference between the initial and final rates of wear must be due to band action. The magnitude of this effect varies considerably; for instance in the Q F 3.7-inch gun Marks 1-3, there is no effect if WM propellant is fired, while with the cooler propellants NH and N/S the effect is pronounced, the final rate of wear being only one third of the initial rate.

Pre-engraved and unbanded projectiles

More direct evidence is furnished by US experiments with pre-engraved projectiles[13]. These projectiles, which were designed to eliminate the driving band forces referred to above, gave about half the rate of wear experienced with conventional copper banded projectiles. A limited investigation of this subject has been carried out in a Q F 17 pr. gun, in which projectiles with reduced bands and without bands were fired and the rates of wear obtained compared with the corresponding figures for Service projectiles[14]. The comparison showed for the unbanded shot a decrease in the rate of wear of 50% at 1 inch from C of R and increasingly larger reduction further forward, that is, with a banded shot the wear was not only greater but extended further down the bore towards the muzzle.

THE FORMATION OF BORE CRACKS

Residual Stresses and phase changes in the bore

The craze cracking of a gun bore is due to the rapid changes of temperature which occur in a very thin superficial layer of metal when successive shots are fired from the gun. At the peak temperature the compressive stress in the surface exceeds the yield of the material and plastic flow occurs. On the subsequent rapid cooling the surface layer is thrown into tension, the stress tending to exceed the yield, and tensile rupture occurs. The depth of metal involved is very small. Cracking is facilitated by phase changes in the bore layers with accompanying volume changes which occur (in steel barrels) on passing through the critical range 730-800°C. Picrite propellants accelerate the incidence and increase the severity of craze-cracking owing to the high nitrogen content (order of 30 per cent) of the propellant gases and the fact that absorbed nitrogen depresses the M_s temperature and exerts a stabilizing influence on austenite. Investigation of M_s temperatures of 3 in. Mk:N1 gun liners, where steep thermal gradients across the liner wall were present, indicated that M_s temperatures bore some relation to the propensity of liner bores to develop cracks[15].

Thermal Cycling Experiments

Experiments in this Establishment showed that craze cracking in metal surfaces could be produced simply by the application of repeated thermal stress. The tests involved repeated heating by H F induction of one edge

The omission of decoppering compounds from the ammunition of the 3 inch Mk N1 gun reduced the rate of wear in the early rifled bore and doubled the gun life, thus indicating that bore cracking can have a significant role in the rate of removal of material from the bore.

CHEMICAL ASPECTS OF EROSION

Erosion Test Gun and Erosion Vent Plug Experiments

Although the rate of erosion shows a strong correlation with temperature, erosion is certainly partly due to chemical action of the propellant gases on the bore surface. Consequently the chemical side of erosion is important and particularly any variations in the chemical reactions with different propellants. The erosive power of propellants has usually been investigated either by erosion vent-plug tests or in erosion test guns. These devices were instituted to obtain a high rate of erosion so that results could be obtained quickly and economically. It is now recognized that very high rates of erosion, which imply melting of the metal, do not yield information which is relevant to gun conditions, and the rate of erosion must be related to that of guns if valuable results are to be obtained.

US experiments with erosion vent-plug apparatus in which the severity of erosion was adjusted so as not to be excessive, on a series of RDX propellants with flame temperatures from 2290° to 3265°K showed that some RDX propellants are more erosive with respect to gun steel than some single base propellants of the same flow temperature, thus demonstrating the importance of the chemical factor in erosion[19]. For example it was found that, under matched ballistic conditions including flame temperature, an RDX propellant was nearly twice as erosive as the standard single base propellant NH-M1. With increasing severity of erosion, however, the difference between these two propellants decreased. A notable feature of other US experiments using an erosion test gun was the marked effect of coating the propellant with centralite in reducing erosion.

Theoretical considerations

The nature of the products to be expected from the chemical reactions at the bore surface have been determined by C F Curtis and N L Johnson using the standard methods of thermo-chemistry[20]. For single and double base propellants and different loading densities the ultimate products were derived. An ultimate product is one which would be formed if chemical equilibrium were established between a finite amount of steel and an infinite quantity of reacting gases. It was found that there were three ultimate products for both low and high surface temperatures; these were Fe_3C, FeO and Fe_3O_4, the proportions depending upon the assumed temperature; Fe_3C predominating at low temperatures but disappearing at high temperatures to give place to FeO. When 0.1% sulphur was assumed to be added to either propellant, the ultimate reaction product at low temperatures was FeS, while at high temperatures it was FeO just as if the sulphur were not present.

The principal difference between the ultimate products to be expected from single base and double base propellants arises not from their chemical compositions but from their difference in flame temperature and consequent difference in bore surface temperature. With high surface temperature FeO is more likely to be formed than Fe_3C; this is in agreement with observation.

The reaction $3Fe + 2CO \rightarrow Fe_3C + CO_2$ is so strongly exothermic that enough heat is liberated to melt the Fe_3C. The reaction $Fe + H_2S \rightarrow FeS$ is also strongly exothermic, though a rise in temperature tends to inhibit the reaction.

It is also interesting to note that in addition to Fe_3C, FeO and Fe_3O_4 which have been commonly found in the erosion products of worn guns, iron nitrides have also been repeatedly found, but the thermo-chemical calculations show that these are not ultimate products.

PROPELLANT GAS EFFECTS

General

One of the problems in the investigation of the chemical causes of gun erosion is to determine which of the constituents in the propellant gases is responsible for the chemical reactions at the bore surface. American investigators have applied isotopic tracer techniques for studying the reactions of nitrogen, carbon and sulphur. The penetration of nitrogen into the bore has been studied by using a heavy isotope of nitrogen (N15) and determining its percentage in different layers of the steel by the mass spectrograph[21]. Similar studies for carbon and sulphur have been made using radio-active isotopes and measuring the radioactivity introduced into the steel[22].

Nitrogen

The experiments with nitrogen showed that nitrogen of single base propellant gases penetrated to at least 0.05 inch below the bore surface after 10 rounds. Other indications were (i) that some of the original nitrogen in the steel was replaced by the "tagged" nitrogen, with migration of the original nitrogen elsewhere, (ii) that the "tagged" nitrogen had two peak concentrations, one in the bore surface and the other at a depth of about 0.03 inch and (iii) that the total nitrogen content of a layer within 0.003 inch of the bore surface was increased not only by the "tagged" nitrogen but also by ordinary nitrogen; this might be due to migration from deeper layers or reaction with nitrogen from propellant gases diluted with air.

Sulphur

Sulphur is present to the extent of about 0.1% in the propellant charges of most guns. Experiments with radioactive sulphur in a rifle showed that 4% of the sulphur in the charge became incorporated in the bore surface after firing a single round and that only 5 per cent of this sulphur remained after firing an additional 40 rounds of normal ammunition. Other experiments carried out in a vent-plug apparatus showed that erosion was significantly reduced by the elimination of sulphur from the primer and charge[23].

of a test piece the main mass of which was continuously water cooled. A wedge shaped test piece, the narrow edge of which was subjected to repeated heating, was designed to restrain thermal expansion in the direction of this edge and thus produce uniaxial strains which approached the maximum values. To this end the edge was made narrow to minimize transverse strains, the length of the edge was made large compared with the depth of heating, and the base of the test piece, which was cooled by a high velocity stream of water passing through its length, was made relatively massive[16].

Effect of decoppering agents on bore cracking (17 & 18)

Serious cracking was experienced in a 3 inch Nl barrel which was subjected to repeated cycles of severe thermal stress. However the estimated stresses did not seem large enough to explain the observed rate of cracking and it was suspected that traces of lead or lead-tin alloy, which were known to be present on the surface, were accelerating cracking. Some thermal fatigue tests were therefore put in hand using the above equipment.

Notched specimens of 2-1/2% Ni Cr Mo steel were used to investigate the rates of crack propagation and it was found that with a cycle of 40 - 600°C contact with lead increased the initial rate of crack propagation by a factor of 7 (Fig. 3.4). Contact with a lead-tin solder increased the factor to 25. Expressed in another way, the contact with a lead-tin alloy had greater effect on the rate of cracking than an increase in the peak temperature of 100°C. The cracks produced were intergranular. Fig. 3.5 shows intergranular penetration by decoppering compounds in the bore of a 4.5 in. gun barrel.

However it appeared that neither of the low melting point metals had any effect when the peak temperature in the cycle was less than 500°C. This was interpreted to mean that a critical tensile stress is required to produce the intergranular penetration. The tensile stress increases as the temperature falls but at some point the contaminating metal solidifies and can then have no further effect. This is probably one reason why lead, with its higher melting point, is less damaging than the lead-tin alloy, and presumably zinc would be less harmful than lead.

Experiments with un-notched specimens, showed that the contaminating metals did not eliminate the induction period before the first cracks were observed, but the lead-tin alloy greatly reduced it. Lead was not nearly as effective in starting the cracks, and an atmosphere of hydrogen had to be used to preserve the lead until cracking started. Once started it proceeded very rapidly and the molten metal could be seen to exude in droplets when the cracks closed up during the heating part of the cycle, and to be sucked back into the crack on cooling.

With a cycle of 40° to 850°C, giving repeated phase changes, the effect of contaminating metals on crack initiation was not so pronounced but crack growth was very rapid. When a crack eventually started it would proceed through the martensitic layer in two or three cycles and after a slight pause it would then set off into the underlying metal at a rate that was almost equally great.

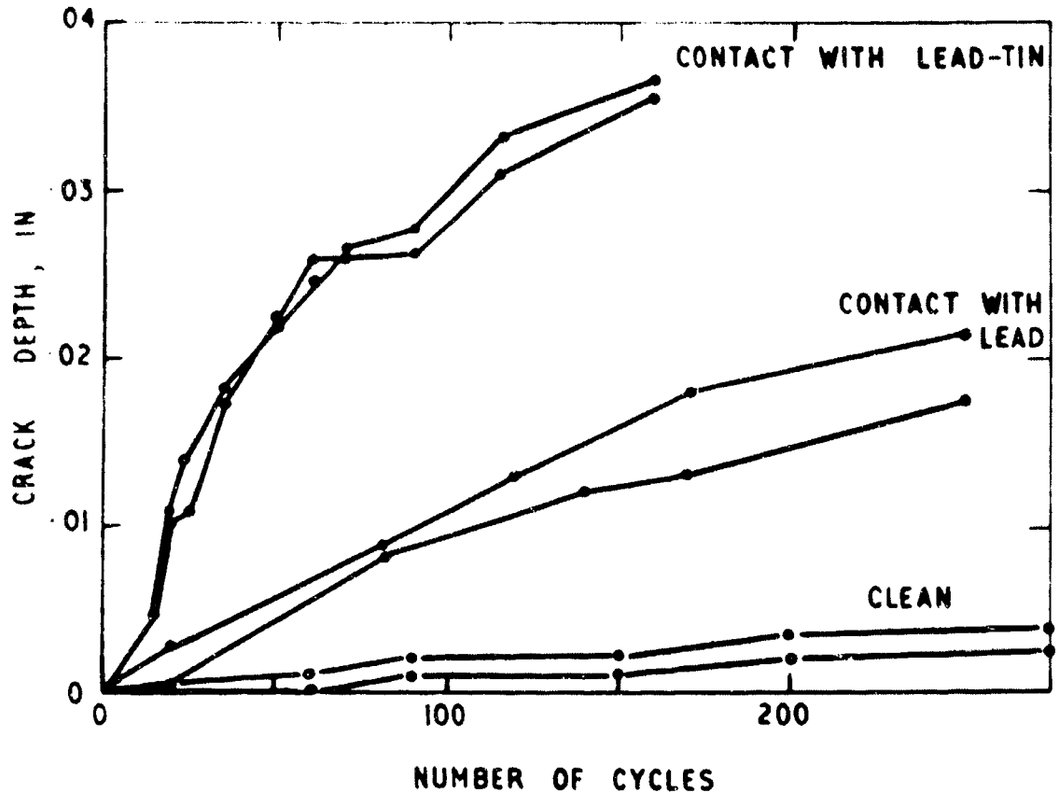


FIGURE 3.4. RATE OF GROWTH OF CRACKS IN NOTCHED SPECIMENS. THERMAL CYCLE 40° - 600° C, IN AIR.

FIGURE 3.5. (x500) DECOPPERING COMPOUNDS IN BORE SURFACE CRACK IN 4.5 INCH GUN BARREL.

Carbon

Radioactive tracer experiments showed that carbon of single base propellant gases penetrates the bore surface during the first round, that is, before a crack system has developed. The depth of penetration was not greater than 0.0003 inch. At the surface the percentage of the total carbon derived from the propellant was about 8 but passing to deeper layers the percentage dropped rapidly. The penetration was found to increase with the temperature attained by the bore. With double base propellant the carbon did not penetrate the bore surface and was only present in a very thin surface layer. This result is in agreement with independent observations that with such propellants iron oxide rather than cementite is the principal chemical alteration product in the bore surface, and it is also in agreement with thermochemical calculations.

Carbon monoxide

The reaction of carbon monoxide with steel has been studied by exploding mixtures of CO and O_2 at various high initial pressures and allowing the products of explosion to pass through steel erosion vent plugs[24]. The erosion was found to increase with the percentage oxygen in the original mixture, but this also increased the flame temperature of the explosion. In other experiments the same products of explosion were obtained but at reduced flame temperature by diluting with CO_2. These experiments showed that erosion was insensitive to the composition of the gases as long as the CO was in excess of CO_2. When the proportion of CO_2 was nearly as high as that of CO erosion was enhanced, apparently because oxidation of the steel became important. In further experiments minute quantities of H_2S, NH_3 or H_2 were added. These caused considerable increase in erosion. The increase was most pronounced with H_2S when the flame temperature was low. These results were provisionally explained by the hypothesis of formation of volatile iron carbonyl. This was confirmed by experiments in which iron carbonyl was identified in gases collected from the erosion vent. Further the amount collected was shown to be increased by the presence of sulphur, which is known to be a catalyst for the formation of iron carbonyl. Similar results were obtained by collecting the gases from a rifle firing ordinary NC propellant.

Free radicals

The existance of free radicals in the flame region of burning cordite is a necessary postulate in all existing theories of the mechanism of burning. At gun pressures the thickness of the main flame zone is very small, of the order of a few microns. That is to say, the main reactions of combustion are completed within this short distance from the cordite surface; consequently it is not to be expected that a significant concentration of the radicals participating in the main burning-mechanism will be found much beyond this distance from the cordite surface. It does not seem possible to form a quantitative estimate of the likely concentration of radicals in the vicinity of the walls since little or nothing is known as to the nature, distribution,

and conditions of motion of the intermediate decomposition products, as a whole, in the gun. And it must be borne in mind that other highly-active bodies besides free radicals will be present in a gun-chamber, e.g. electronically excited potassium atoms, and other atoms and molecules such as CO_2 in high-energy states.

THE ROLE OF THE ALTERED LAYER

Chromium plated bores

There is considerable evidence that the thermally altered layer in a gun bore assists erosion. In chromium plated bores, where the plating is thick enough to provide an effective thermal shield, no altered layer is evident in the basis steel. Gases may however penetrate down the micro cracks in the plate and, by thermo chemical reactions, cause pockets of altered structure in the steel. Spreading of these areas may link up under the plate causing plateaux of chromium to be raised from the bore and subsequently pulled out to give rise to small areas of erosion. Thermally altered structure can obtain under thick plating at the corners of lands, (Fig. 1.4) and assist stripping of the plate.

Where plating is too thin to prevent overheating of the basis steel altered layers form under the plating causing rippling of the plated surface and early removal of same from the bore.

Mechanism of formation of altered layer

The role of the altered layer in the erosion of gun steel is thus probably as follows. During the early period of the firing of a single round, little happens except that the surface layer of the steel is softened as it is heating to the critical temperature. During the middle period, the surface layer becomes and remains austenitized. Concurrently, rapid chemical reactions occur between austenite and the powder gases, and carbon and nitrogen may diffuse inward. The chemical reaction products may actually be formed in a liquid or plastic state and be partially or entirely removed. During the late period, the surface layer is drastically quenched by the flow of heat into the cold metal away from the bore. The austenite transforms into brittle martensite concurrently setting up considerable transformation stresses which may actually crack the martensite. A cracked martensitic layer is left which is surmounted by a thin "white layer" which may contain austenite stabilized by products of the chemical reactions particularly carbon and nitrogen. During a subsequent round, removal of the "white layer" may start almost at once since the necessary ingredients are already to hand.

Effect of stress on rate of erosion

It seemed possible that the presence of stresses in the bore surface when it is subjected to the erosive action of the propellant gases right have some effect on the rate of erosion. An experiment to check this point was carried out by US investigators[25]. An erosion vent was stressed in such a manner that the vent surface was under known tensile stress on one

of its diameters and under known compressive stress on a diameter at right angles. The effect of the applied stress on the erosion seemed to be negligible. This result was confirmed by NPG in experiments with autofrettaged and non-autofrettaged 3"/50 barrels fired with N propellant.

Where residual longitudinal tensile stresses at the bore are sufficient to promote bore cracks preferentially in the circumferential direction, the lips of these cracks elevate above the normal bore surface and are readily eroded; these cracks may form sources of turbulence in the outer layers of the propellant gases and produce conditions of localized erosion or scoring.

MUZZLE WEAR

Muzzle wear is brought about by abrasion and is usually associated with groove marking on the projectile. The fundamental cause appears to be failure of the driving band to keep the rear of the projectile centered in the bore. While the projectile is centered the radial forces due to the gas pressure exerted on the surface of the projectile behind the driving band are in equilibrium. But if the band fails to keep the projectile centered and allows the base to touch the bore, then the gas is prevented from acting all round the circumference and there is no longer equilibrium but a resultant force tending to push the projectile into firmer contact with the bore. A high bearing pressure is thus set up between the base of the projectile and the bore, and this gives rise to abrasive wear of both the bore and the projectile, and muzzle wear and groove marking are observed.

It will be seen that owing to the rotation of the shot, this abrasive action, which is localized on one side of the bore, will tend to follow one group of lands. Further if the failure of the driving band is due to some local imperfection of the bore, such as scoring, the orientation of the abrasive action is likely to be repeated from round to round and thus lead to spiral wear.

Muzzle wear, in the absence of overall bore wear, sometimes occurs in guns which fire copper driving bands. It appears that the high thermal conductivity of copper enables such bands to be heated to an appreciable depth by the heat generated by friction at the band-bore interface, and thus softened. This softening is presumably responsible for the failure of the band to keep the projectile centered.

CONCLUSIONS

General Erosion

Summing up the conclusions of the previous sections we arrive at the following general picture of the erosion of gun barrels. The erosion of gun barrels is caused by a combination of a number of effects, the extent to which each one contributes being different for different ballistic conditions. The steel of the bore surface undergoes thermal alteration from the heating by the propellant gases and it reacts with certain constituents of these gases to form iron carbides, nitrides, oxides and sulphides. These compounds are liquified at temperatures below the melting point of steel,

and are brittle when cold. Hence in some cases they seem to be blown off the bore surface by the propellant gases while in a fused condition, while in other cases they seem to be rubbed off the surface by the projectile. Some of the iron has been shown to be removed by the formation of volatile iron carbonyl, but the extent to which this process contributes to the removal of iron is not yet known. Cracking of the steel surface by the thermal and mechanical stresses imposed on it by the propellant gases and the projectile is facilitated by its chemical and thermal alteration, and the cracked surface in turn is more susceptible to chemical attack.

Severe erosion

The severity of erosion is largely determined by the peak temperature attained by the bore surface. But the correlation of the rate of erosion with temperature does not indicate a purely thermal process but rather the influence of temperature on the rate and type of chemical reactions between the steel bore and the propellant gases. Severe local erosion known as "scoring" may result where bore cracks are deep enough to either permit gas escape past the driving band, or to cause local turbulence of the gas stream, thereby exaggerating the general bore thermo-chemical reactions which may be exothermic in character.

Enlargement of the bore at the muzzle

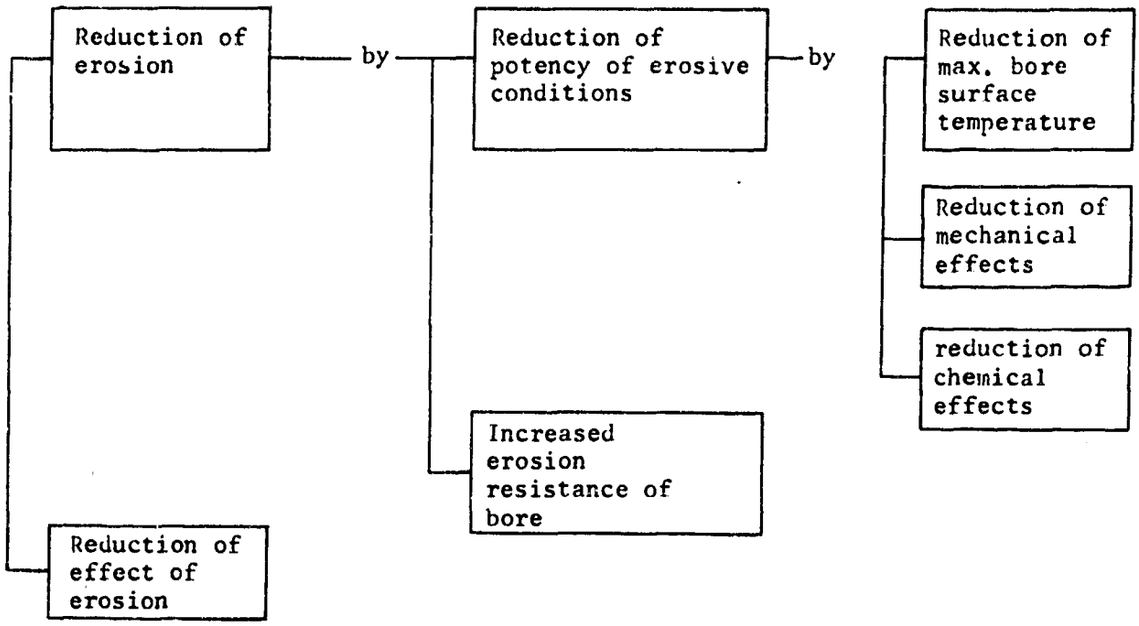
The erosion of guns at the muzzle differs fundamentally from that at the commencement of rifling. In general it is due to abrasive wear, either caused by the driving band, if of steel, or failure of the driving band, if of copper, allowing the steel body of the projectile to make contact with the bore. In the latter case groove marking of the projectile takes place.

MEASURES TO CONTROL EROSION

General Considerations

Erosion can be reduced either by reducing the potency of the erosive conditions or by making the bore more resistant to erosion. The alternative is to accept erosion as inevitable and to endeavour to reduce the effects of erosion on gun performance. It is found that these three lines of approach to the gun erosion problem are not independent and improvement on one tends to benefit the others. Consequently all are important.

It has been seen that the potency of the erosive conditions is predominantly controlled by thermal effects, in particular by the maximum temperature attained by the bore surface. Mechanical and chemical effects are by themselves less important. Muzzle wear is fundamently different from the erosion at the commencement of rifling since it is not due to thermal action of the propellant gases; it is therefore considered to be outside the following scheme and is treated separately. The above considerations in relation to the gun erosion problem can be summed up as follows.



Temperature is the general regulator of all erosive changes and is therefore of over-riding importance. The temperature achieved by a bore surface and underlying points during firing will control any melting of the bore surface or thermal transformation of the wall material. These temperatures will also control the nature and rate of chemical reactions at the surface and will influence the mechanical strength, ductility and hardness of the wall material and will thus affect abrasion, deformation and the cracking of the bore surface which occur during firing.

A reduction in bore surface temperature can be achieved by (a) use of cool propellants, barrel cooling, and boundary layer techniques (b) the super calibre principle and (c) mechanical design to reduce gas turbulence at commencement of rifling and to provide an efficient gas seal on the projectile.

A reduction of the mechanical effects can be achieved by a reduction of the frictional drag of the driving band either by design of the band or the use of a non-metallic band.

CONTROL OF HEAT TRANSFER

Cool propellants

One of the principal factors which determines the heat transfer to the bore is the temperature of the propellant gases. As a relatively small reduction in the maximum temperature attained by the bore surface produces a

large reduction in the rate of erosion, cool propellants, that is propellants producing relatively cool gases, provide a very powerful means of combating erosion.

The adiabatic flame temperature of a propellant can be adjusted over a wide range by relatively small changes in the proportions of secondary constituents. The other main characteristics of the propellant are not sensibly altered. The following tables gives the composition and flame temperatures of a series of piorite propellants with the same basic composition but with flame temperatures ranging from 1700°K to 2450°K.

% Composition	F.487/44	F.487/45	F.487/46	F.487/47
	(ERDE experimental compositions)			
Piorite	60	60	60	60
Gun cotton	20	20	20	20
D.G.N.	17.36	14.22	11.16	7.90
Dibutylphthalate	-	3.14	6.20	9.46
Carbamite	2.64	2.64	2.64	2.64
Flame temperature °K	2450	2200	1960	1700
'Force' constant (tons/sq in/gm/cc)	62.5	58.0	53.3	47.6
or (lb in/lb) x 10^6	3.87	3.60	3.31	2.95

Charge weight

The ballistic performance of a propellant is determined basically by the value of its 'Force' constant. It will be seen in the above table that the value of this constant decreases with decreasing flame temperatures. This is equivalent to stating that a cooler propellant has a smaller amount of potential energy per unit weight. It thus appears that the use of a cooler propellant will require a larger charge weight to obtain the same ballistic performance. The ballistic performance of cool propellants is not quite as simple as "the cooler the propellant the heavier the charge weight" though this is true. There are some factors inherent in the internal ballistics of guns which react favourably to cool propellants, which on this account can be used more efficiently than hotter propellants.

Gun Length

It should be mentioned here that a mere increase in charge weight without increase in gun length is not a satisfactory way of changing over from

a hot to cool propellant. The proportions, or the expansion ratio of the gun, should be preserved. On this basis the proportional increase in charge weight is rather less that the decrease in 'force' constant and about half the decrease in flame temperature. For the extremes of the propellant series quoted above the relevant ratios are:-

Flame temperature	1.44	:	1
Force constants	1.32	:	1
Charge weights and gun lengths about	1	:	1.25

Functioning

As regards the functioning of cool propellants in guns, there appears to be a greater chance of alternative reactions on burning so that there may be some variation in the resulting gas composition which may be responsible for inferior regularity in performance. Comparative trials in a Q F 3.7-inch Mks. 1 - 3 A A gun between German Digl propellant (T = 2125°K) and British N/S propellant disclosed no significant difference at 80°F but at 120°F the German propellant was markedly inferior[26]. The m. d. in M. V. was twice that of the British propellant and the drop due to charge temperature was much larger. On the other hand experience with British cool propellants also in comparison with N/S indicate good regularity and a lower temperature coefficient.

Effect in Q. F. and automatic fire

The effectiveness of cool propellants in reducing erosion was demonstrated in comparative firing trials: the amount of wear with propellant (F.487/46) having a flame temperature of 1960°K was only 1/50 of that with Propellant N which has a flame temperature of 2450°K.

Although cool propellants are effective in reducing erosion by lowering the peak temperature attained by the bore surface, the reduction in the total heat transfer to the barrel is not large and consequently cool propellants do not give much help in the problem of the heating of a gun barrel in a burst of fire.

Super-Calibre Principle

In the super-calibre system the diameter of the projectile in flight is less than the calibre of the gun from which it is fired. While in the gun the projectile is centered, driven and rotated by a light carrier of bore diameter. This carrier is either discarded at the muzzle, or deformed before the muzzle is reached, so that the calibre of the emergent projectile is less than that of the gun. The primary result of applying this principle is to reduce the length of the gun required to impart a given muzzle velocity to a given projectile. This is because it is volume linked with pressure which corresponds to the useful work performed by the gun, and consequently, by increasing the cross sectional area, the same volume can be obtained with a reduced length of gun.

In the semi-empirical formula developed by Thornhill, referred to previously, the value of charge weight divided by the square of the calibre is a most important factor in determining the severity of heat transfer. The Super-Calibre Principle by increasing calibre without significantly increasing the charge weight thus has a strong influence in reducing erosion. An example to indicate the power of this approach is provided by the Q.F. 6 pr 7 cwt and Q.F. 25 pr guns. Both impart about the same kinetic energy to their projectiles, but with the same propellant NH, the life of the Q.F. 25 pr gun is about 10 times that of the Q.F. 6 pr. This is because its calibre is about 50% greater making the charge weight over calibre squared factor about half that in the 6 pr gun.

CONTROL BY MECHANICAL DESIGN

Position of gas sealing device

The bore is not uniformly heated on firing; the part of it which is subjected to the most intense heating and which attains the highest temperature is that immediately behind the gas sealing device of the projectile when the latter is in its loaded position. The magnitude of the maximum temperature attained by other parts in the bore falls quite rapidly immediately forward of this position. One result, which has been noted, is that erosion is confined to the breech end of the rifled bore and becomes rapidly less as the point considered moves towards the muzzle. In the conventional design of ammunition for Q.F. guns, the sealing device is the copper driving band and the ammunition is assembled with this outside the cartridge case. The most severe heating conditions are therefore applied to the steel bore immediately in front of the cartridge case mouth. If, however, the driving band or supplementary sealing device is initially positioned inside the cartridge case, then it will be seen that the most severe conditions do not fall on the steel bore, but on the cartridge case, and, in view of the decrease of the maximum bore temperature with distance forward, an appreciably lighter heat load is applied to the steel bore. The results of a wear trial in a Q.F. 3.7-inch Mk. 1 A.A. gun with sealing cups showed a reduction of 40 per cent in the rate of wear, and this is probably indicative of the order of the advantage which can be obtained in this way[27].

Fisa protector (28)

Very similar to the above is the US Fisa protector which consists of a very thin, slightly tapered sleeve of soft steel slid over a complete round of ammunition so that one end surrounds the neck of the cartridge case and the remainder covers the projectile nearly as far as the bourrelet. The sleeve is locked to the cartridge case during firing by the expansion of the neck of the case, which is forced by the gas pressure into several square holes out into the cartridge case. American experiments, which were carried out with 0.50 in. 0.60 in. and 37 mm ammunition, showed that the scheme was successful in protecting the commencement of rifling and as a result there was very little pressure and velocity drop. It was found that for proper functioning of the sleeves it was necessary to cadmium-plate or Parco-Lubrize the steel sleeves to reduce the coefficient of friction between band and sleeve.

Countersinking the mouth of the cartridge case

Reference has been made to the severe erosion which takes place at the mouth of the cartridge case, and it has been suggested that the discontinuity of the surface over which the propellant gases flow is responsible for an appreciable increase in the value of the Fanning factor. It has also been suggested that the increased heating which would then result is responsible for the observed difference in the rates of wear between B.L. guns and Q.F. guns, Q.F. guns wearing at about twice the rate of similar B.L. guns. If this hypothesis is correct a substantial decrease in the rate of wear in Q.F. guns should result from countersinking the mouth of the cartridge case. This principle is illustrated in Fig. 5.1.

A countersunk cartridge case mouth was in fact subjected to trials in a modified Q.F. 4 inch Mark 16 gun, and it was concluded that this had been successful in reducing the rate of wear. But there were other changes in design, including the provision of sealing rings, which could have been responsible, or partly responsible for this improvement.

Heat transfer from bore to exterior

In firing a single round, barrel cooling can have no conceivable effect upon the maximum temperature attained by the bore surface and hence upon the amount of erosion. In a burst of automatic fire, each round imparts to the gun barrel an amount of heat which is sufficient to raise the temperature of the whole barrel by about 1 or 2°C.

During the firing of the first few rounds of a burst this considerable amount of heat is confined to the bore layers before dissipation to the rest of the barrel material. Even if the rate of fire is low the natural cooling of the barrel is so slow that only a small proportion of this heat escapes from the barrel. For the high rates of fire appropriate to AA guns still less heat can escape by natural cooling during a burst and there is insufficient time between rounds for the temperature across the barrel section to even out, and thus the temperature at the bore immediately before a round is fired is appreciably higher than for the previous round. This rise in the temperature of the bore surface at the instant of firing does reduce slightly the heat transfer from the hot propellant gases to the bore so that the peak temperature attained by the bore during firing is increased by rather less than the rise in the initial bore temperature. But the increase in the peak temperature is large enough to raise the rate of erosion appreciably.

Reduction in strength of material

The general heating of the gun barrel during a burst of fire gives rise to a new factor tending to cause bore enlargement. In firing a single round, the driving band acts on a cold bore, which may or may not have been damaged by the action of the propellant gases in the preceding round. In a burst of fire the temperature of the bore in contact with the driving band may be sufficiently high for the hardness and strength of the bore

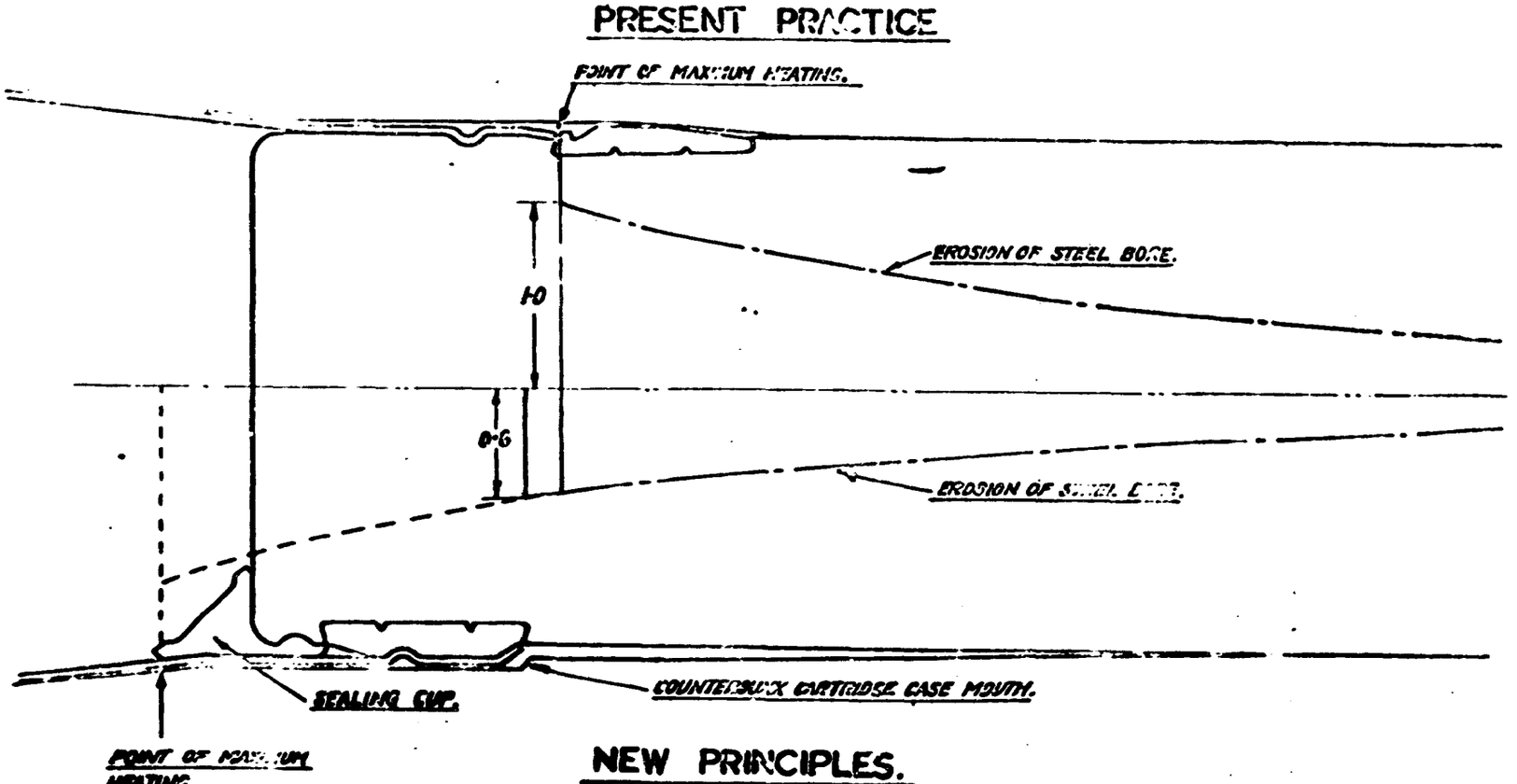


FIGURE 5.1. EFFECT OF POSITION OF GAS SEAL IN Q.F. GUN.

surface to be impaired. If this is so, then, independently of the erosion due to the peak bore surface temperature brought about by the propellant gases, appreciable bore enlargement may take place. Thus in a gun designed to fire at a high rate, there are two thermal conditions which may lead to rapid wear; the temperature of the bore surface immediately before the next round is fired and the peak temperature attained by the bore surface.

The peak temperatures attained by the bore surface, can be controlled adequately by the flame temperature of the propellant, but the general heating of the gun barrel cannot be controlled sufficiently in this way. The only courses available for this are (i) limitation of length of burst and (ii) forced cooling of the barrel.

Forced barrel cooling

Two principal methods of forced barrel cooling have been suggested; cooling of the bore surface by a liquid spray injected between rounds and forced convection cooling of the outside of the barrel. Injection cooling is a basically sound idea, for its object is to cool the bore surface directly. Several systems have been developed and tested experimentally, but none has been successful at really high rates of fire. It is difficult to inject a sufficient volume of fluid along the bore during the short time interval between rounds, but the main difficulty appears to be that only a small fraction of the available heat capacity of the coolant is usefully employed. Injection cooling has at least one important disadvantage; it causes increased band pressures.

The external surface of the barrel, can, in principle, be cooled by a stream of either liquid or gas, and some aircraft weapons are air-cooled. This is, of course, a convenient method in this particular case, but as regards Naval and Land Service weapons, liquid cooling is more convenient and far more efficient.

The possibilities of forced cooling of the barrel are mainly determined by the temperature gradient across the barrel section. The gradient is determined by the average rate of heat flow into the barrel, and is thus directly proportional to the rate of fire. In the conditions being considered, the temperature gradient is of the order of several hundred degrees Centigrade per centimetre. It follows that cooling must be made very near to the bore if it is to be effective. This limitation has led to the development of a modified method of forced convection barrel cooling in which coolant flows along a fairly large number of isolated channels within the barrel wall itself. These channels can be cut longitudinally in the outer surface of a thin liner which is then shrunk into the barrel. With this arrangement the coolant can be brought much nearer to the bore surface, but it is still difficult to have the cooling channels as near to the bore surface as appears to be necessary whilst maintaining the strength of the liner. This method is known as inter-face cooling. The problem does not end with the transfer of the barrel heat to the coolant flowing in the

channels. The amount of heat to be disposed of is very large and necessitates a rapid flow of coolant and a large radiator or reservoir for its eventual dissipation. Also the coolant must be recirculated to conserve additions such as antifreeze and anti-corrosion compounds.

High conductivity Materials

The problems of cooling stems from the slow nature of heat conduction. This could be accelerated if the barrel material had a higher coefficient of heat conductivity, and consequently some consideration has been given to the possibility and advantages of using such materials as liners for gun barrels.

The heat transfer per round and peak bore surface temperature occurring during the firing of a round are both affected by the thermal diffusivity of the bore material. Roughly the heat transfer is proportional to $K^{1/6}$ and the peak bore surface temperature to $K^{-1/3}$ where K is the thermal diffusivity. For steel K = 0.08 cm^2/sec; for copper K = 1.1: so that changing the bore material from steel to copper would halve the peak bore surface temperature rise but increase the heat transfer by 50%. This would increase the difficulties in the ultimate removal of the heat from the barrel. A liner of a high conductivity material with a bore coating of relatively low conductivity material such as chromium would avoid this disadvantage. The thermal conductivity of chromium is such that with it the heat transfer is only slightly greater than that for a steel bore. An analysis of high conductivity liners under conditions of automatic fire suggested that there is probably no advantage in the case of the uncooled barrel but there may be a definite advantage in the cooled barrel if thermal equilibrium is approached.

BOUNDARY LAYER COOLING

A variety of experiments have indicated that transverse mixing of the propellant gas stress down the bore of a gun takes place only to a limited extent. It is thus possible to have a relatively cool layer of gas in contact with the bore surface while the main stream is hot. In this way the advantages of cool propellant with regard to heat transfer can be realised without their disadvantage in having a intrinsically lower ballistic performance. Such a cool boundary layer can be obtained by surrounding the propellant charge with a suitable material, which burns with the propellant but produces far cooler gases.

The principle of using inert material to cool the boundary layer gases has been recognised for many years. Experiments with the charge contained in a silk bag or stocking showed a considerable reduction in wear. This may account in part for the difference in wear rate between Q.F. and B.L. rounds. A similar technique has been used by the Russians. Their cased charges are frequently contained in a cloth bag with a waxed paper liner between the bag and the cartridge case.

Lined cartridge cases

Extensive trials have been carried out by CARDE with high density polyurethane foam liners in the cartridge case to produce a cool boundary layer[30].

A considerable reduction in wear was obtained and in some guns it was reduced to negligible proportions. These trials confirmed that flow of propellant gases in a gun bore is laminar.

In the UK. trials in he 105 mm Tank gun have also shown an appreciable reduction in wear. The wear caused by 240 APDS rounds was .010 ins at 1 in C of R indicating a life of about 2000 rounds or a ten fold more use in life. However wear further along the bore would probably result in barrel being condemned for accuracy at some earlier stage. In the U.S. large reductions in wear have been obtained in large calibre naval guns. In the 6"/47 case gun a 60 fold increase in life was obtained.

Combustible cartridge cases

These also act as boundary layer coolants as the gas produced by the case is much cooler than normal propellant gases. In the 120 mm Tank gun combustible cased rounds reduce wear by a factor of 3 approximately compared to the bag charge round. The combustible case has the advantage that it is contributing some energy to the round and not merely occupying valuable space in the chamber. Limited experiments have shown that a thin cylinder of combustible case material used as a liner in a metal cartridge case produces substantial wear reduction without the disadvantage of an inert liner referred to immediately above.

Wear additives

The Swedish Wear Additive originally consisted of oxides of titanium or tungsten incorporated into paraffin wax in approximately equal proportions of oxide and wax by weight and coated onto a rayon cloth. The weight of material used was about 3% of the propellant charge weight. This liner is positioned in contact with the cartridge case wall at the front end of the charge. In the 105 mm Tank gun the U.S. obtained a 20 fold reduction in wear at C of R with tungsten trioxide and a 100 fold reduction with titanium dioxide. Experiments in the U.K. with titanium dioxide and in France with tungsten trioxide gave comparable results. The reduction in wear is greatest at the C of R region and after a few inches of shot travel wear proceeds at a more normal rate. This sometimes causes the position of maximum wear to be several inches forward of C of R. In recent work in the U.S. it has been shown that very fine magnesium silicate (talc) is even more effective in reducing wear than titanium dioxide. Further refinements have been a change from rayon to dacron as a substrate and the addition of a thin plastic film over the wax to protect it from the abrasive action of propellant granules.

The reduction in wear due to the Swedish Wear Additive is probably the result of a combination of effects. There will be a boundary layer effect from the cloth and the wax. It is also thought that the finely powdered oxides or silicates reduce the transmission of heat from the main gas stream across the boundary layer to the bore surface. The third effect is probably the protection of the bore surface by a coating of a grey white powder. This deposit has been found by all countries using the additive. A "memory" effect has also been noted by both the U.K. and the Netherlands.

Additives incorporated in the propellant

The Swedish Wear Additive can not be used in small calibre weapons and it sometimes leaves unacceptable residue in the gun. This has led to investigations into the effect of incorporating titanium dioxide or talc into the propellant. Work in the U.K. has shown that the addition of 2% TiO_2 to piorite propellant reduced its Force and the basic composition had to be "hetted-up" in order to match the ballistics of the service propellant. When fired in the 105 mm Tank Gun the propellant containing TiO_2 reduced wear to about 20 to 25% of normal. In Canada very large reductions in wear have been obtained in small calibre weapons when 2% Talc was incorporated into the propellant. Reductions in wear have also been obtained by coating the propellant granules with talc and by placing small bags of talc on top of the propellant charge.

SMEAR TECHNIQUES

Principle

A method of reducing heat transfer to the bore surface, tested extensively in the U.K., involved applying a film of a substance to the bore of a gun immediately after the passage of the projectile. The substance was to act as a temporary thermal barrier against the following propellant gases. Successive rounds would clear the bore of previous deposits and deposit their own film behind them. It was also considered that whilst acting as a thermal barrier the surface smoothness of the film would reduce heat transfer arising from micro turbulence at the gas/bore surface interface. A wide variety of substances were tested and the substances were referred to as "smears", (31).

Properties of a good Smear

There is little difficulty in specifying in general terms many of the properties desirable in a smear. It must wet steel; it should be sufficiently mobile to be spread easily, but must be sufficiently viscous to resist removal as spray; it should be a poor conductor of heat; it should have a low vapour pressure; it should have a high decomposition temperature; the vapour or the products of decomposition should themselves be effective as a thermal barrier; the life should be a big fraction of the "time up the barrel" but should not exceed it. Such considerations explain the wide variety of materials evaluated.

Silicone oil, method of application and results

The greatest reduction in heat input to bore was achieved by the use of silicone oil as a smear. The reduction was about 30%. The vehicle used as a rigorous test of the efficacy of silicone as a smear was the 3 inch Mark N1 gun. The fixed ammunition fired in this weapon was modified to carry 110 grams of a silicone oil (viscosity 60,000 centistokes) contained in a P V C capsule situated at the base of the projectile; the assembly is shown in Fig. 5.2.

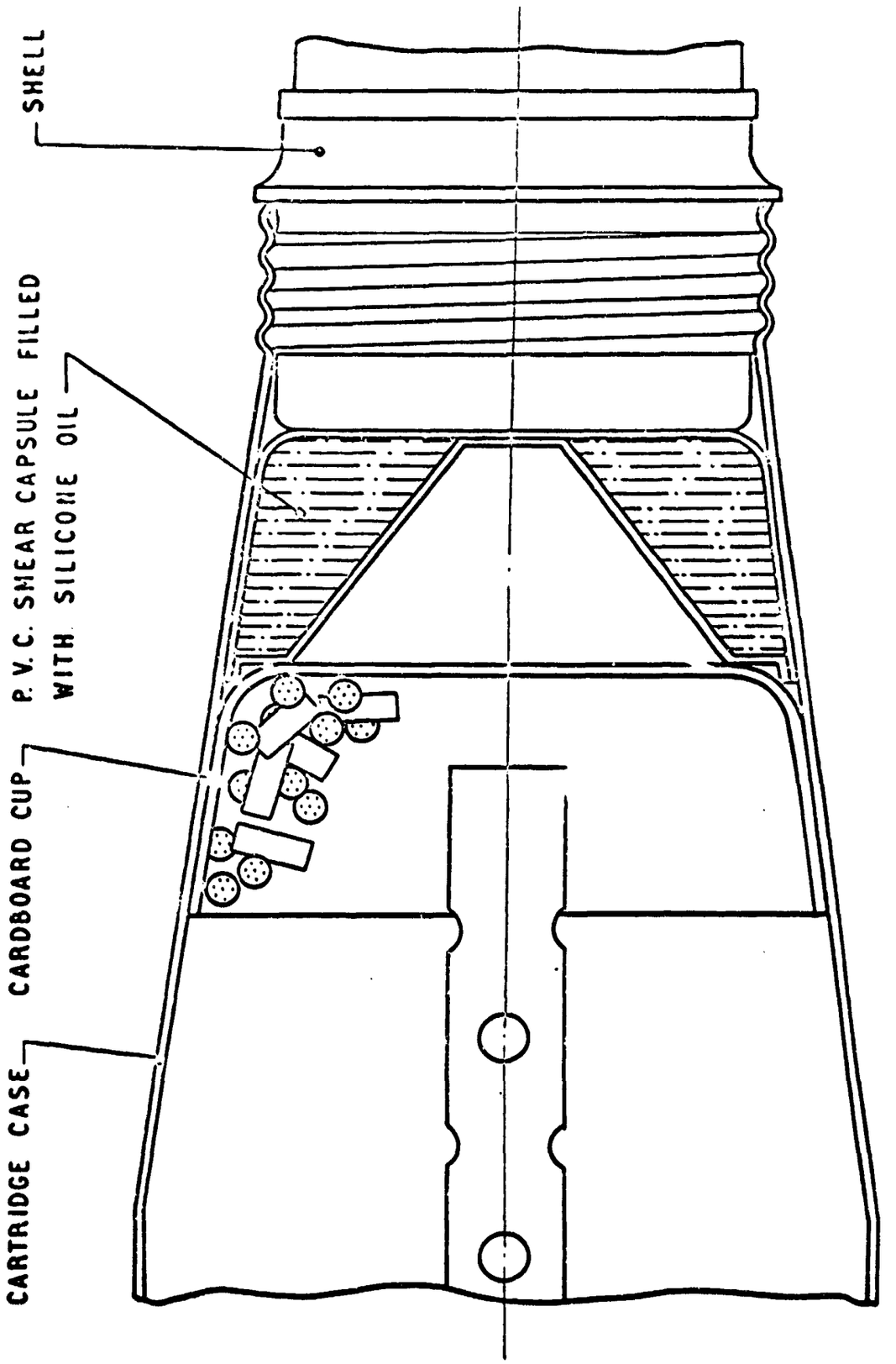


FIGURE 5.2. 3 INCH NI ROUND FITTED WITH SMEAR CAPSULE.

The gun barrel consisted of a relatively thin liner which was shrunk into a jacket, the jacket carried longitudinal water cooling channels in it's inner surface. The rifled bore was plated with chromium, 0.006 in. radial thickness, and the rifling was of the "disappearing" form. Sequences of 60 rounds each (4 x 15 round bursts) were fired at a rate of 120 r.p.m.; muzzle velocity was 3,400 f.s.

Initially the required gun life was 800 rounds and this was barely achieved with "traditional" ammunition. The omission of decoppering compounds from the ammunition reduced the rate of wear and increased gun life to about 1600 rounds. With the incorporation of silicone smear in the round wear was drastically reduced[32]. Nil wear was recorded over the first 40% of the rifled bore after firing more than 2,000 rounds. Figure 5.3 compares wear at C of R when firing ammunition (containing no decoppering agents) with and without smears. Muzzle velocity was well maintained with the smear ammunition and a comparison of this aspect when firing both types of ammunition is shown in Fig. 5.4. Wear was normal in the forward part of the bore.

The smear technique is effective over a greater length of the bore than cartridge case liners or additives. The only serious difficulty experienced with it was that the capsule was not strong enough to stand up to rough usage. This resulted in odd rounds giving velocities about 200 ft/s low when the silicone oil got mixed up with the propellant.

REDUCTION OF MECHANICAL EFFECT

Effect of driving band on erosion

Although the rate of erosion is mainly determined by the maximum temperature attained by the bore surface, the driving band can, and in many service equipments does, play an important part. For example in the Q.F. 17 Pdr tank gun, 3 ins calibre, the rate of wear in a new gun is reduced by about 30% with projectiles with lighter copper bands and by about 40% with projectiles without driving bands. As the gun wears the driving band effect diminishes.

The action of the driving band in promoting gun wear is mainly one of frictional drag. This action of the driving band can be reduced either by reducing the radial pressure of the driving band on the bore, or by reducing the value of the coefficient of friction, or both. Frictional drag of the driving band is the principal factor determining the velocity drop in a worn gun and consequently its reduction will not only reduce the rate of erosion but also reduce the velocity drop for a given amount of wear. Frictional drag can be reduced by the use of (i) Pre-engraved projectiles (ii) sintered iron bands (iii) skirt bands and (iv) Non-metallic bands.

Pre-engraved projectiles

A pre-engraved projectile is one which is already provided with teeth to match the grooves of the rifling before being loaded into the gun. Radial forces between the band and the bore are thus reduced to a minimum and the band can be coated with a material to reduce friction. This scheme received

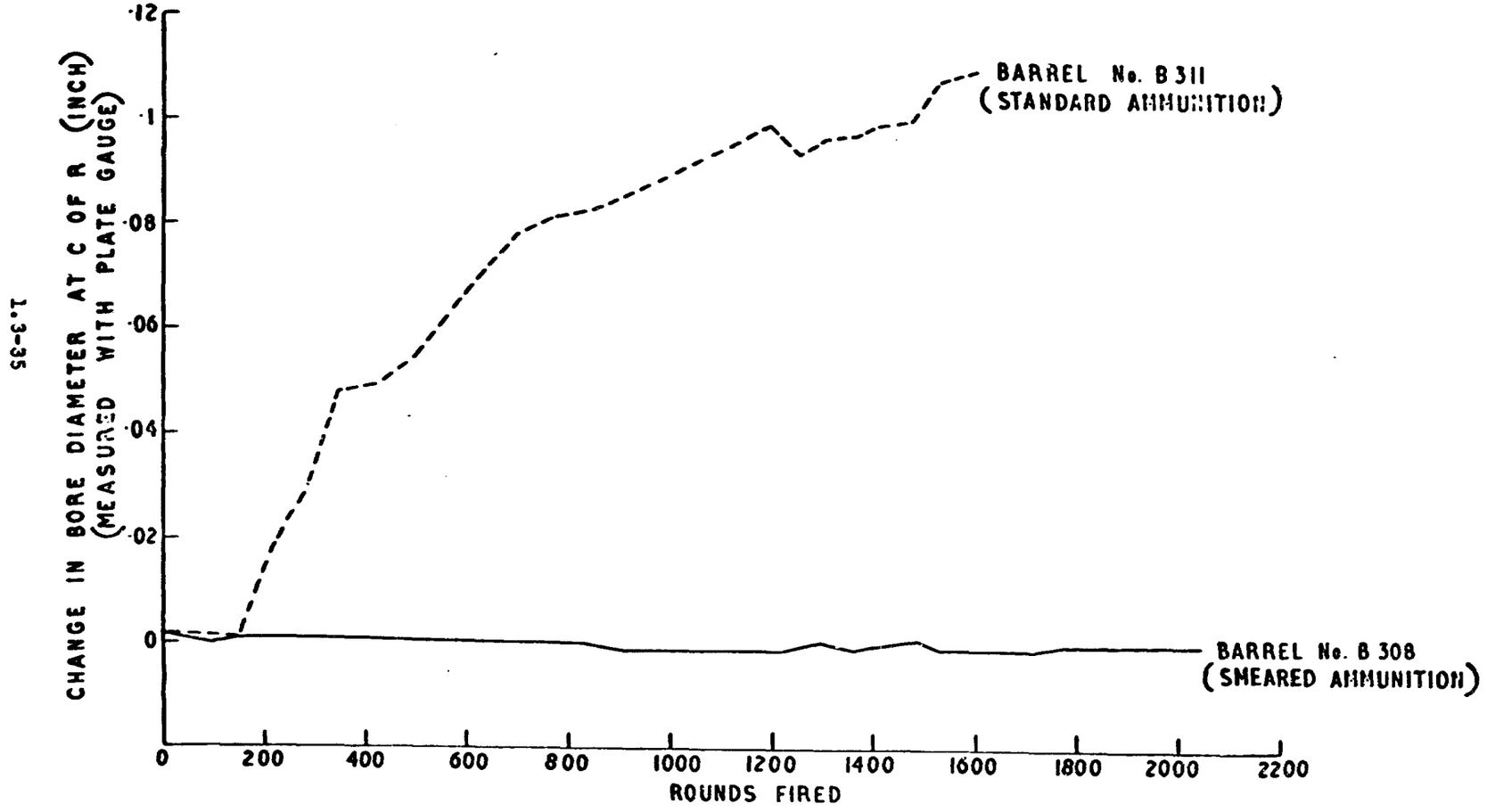


FIGURE 5.3. ROUNDS FIRED / WEAR AT C OF R.

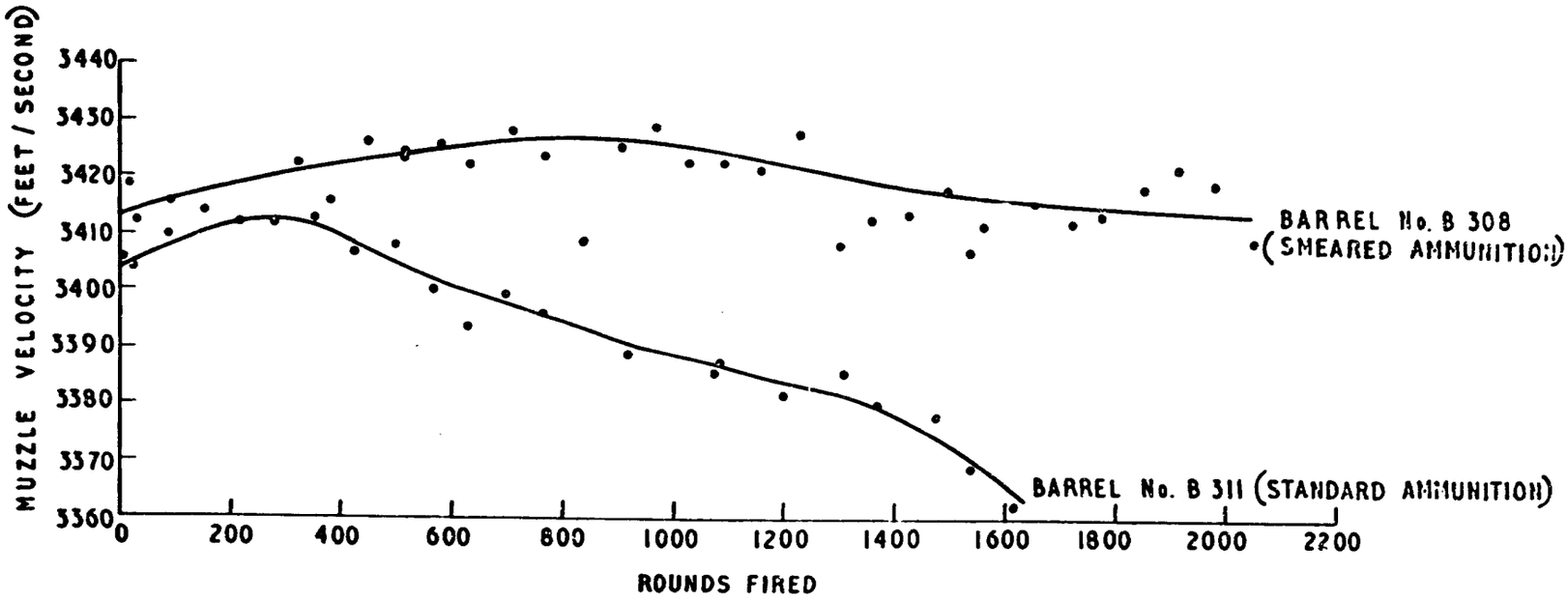


FIG.

FIGURE 5.4. MUZZLE VELOCITY / ROUNDS FIRED SINGLE SHOT SERIES CORRECTED TO 90° F.
(MEAN VALUES FOR R & A AND EROSION CHECK SERIES)

considerable attention in the U.S. and the expected reduction in the rate of erosion was achieved. For application to service weapons it is necessary to provide some means to ensure that the rifling of the projectile will mesh with the rifling of the barrel under service conditions. Although technical solutions tc this loading problem are possible it remains a disadvantage and must limit the amount of gun wear that can be tolerated.

Sintered iron bands

Sintered iron bands were introduced during World War II by the Germans because of shortage of copper. They then discovered that these bands gave appreciably less wear than copper bands at the C of R. This is due to a slightly lower band pressure and a small coefficient of friction. The use of sintered iron was investigated in the U.S. Canada and U.K. in a wide variety of guns. In general wear at C of R was reduced but abrasive wear occurred throughout the bore. As a result guns were frequently condemned for accuracy before the condemning limit for wear near commencement of rifling was reached. In these trials the design of band was the same as the copper band and only the material was changed[33]. Additional trials were carried out in the 17 Pdr gun with a specially designed band[34]. Wear was reduced by 22% at 1" C of R and there was practically no abrasive wear. There was no muzzle wear of the type associated with copper bands and velocities of 3000 ft/s and above. Another notable feature of these experiments was the absence of the ballistic phenomenon called "downward crash" with the sintered iron bands. Loss of MV with wear was also much improved.

Skirt bands

Skirt bands of mild steel also give less erosive wear than copper bands partly due to better gas sealing. In trials in the 2 Pdr David gun (40 mm calibre) wear at 1 in. C of R after 565 rounds was 60% of that given by the copper band and muzzle wear was negligible. Loss of M.V. with wear was reduced and accuracy remained good throughout the trial. Similar results were obtained in the 6 Pdr 7 cwt gun where wear at 1 in. C of R was halved with a skirt band. This type of band has the advantage that it will function at velocities of 3,000 ft/s and above where copper will normally fail.

Non-metallic bands

Non-metallic bands satisfy the requirements for minimizing the mechanical aspects of erosion namely low band pressure and low coefficient of friction. This type of band does not exhibit any signs of heating due to band-bore friction. This is due to the poor thermal conductivity of the materials normally used which prevents the heat generated penetrating to any appreciable depth in the band. When copper bands are fired at moderately high velocities there is evidence of softening and this is considered to be the primary cause of muzzle wear of the type exhibited by high velocity guns firing copper bands.

Most early trials with non-metallic bands were carried out with ebonite. In all cases a reduction in wear was obtained. The wear rate varied from 75% of normal in the 40 mm to 25% of normal in the 17 Pdr. Muzzle wear was insignificant and loss of M.V. with wear was considerably reduced. Similar improvements in wear were obtained in the U.S. where firings in .500 calibre machine gun gave a three fold increase in life with ebonite bands.

The only recent evidence in the U.K. on differences in wear rate between copper and non-metallic bands is in the 105 mm Abbot gun. As the gun is basically very slow wearing comparisons in rates of wear are very difficult. However with the super-charge non-metallic, asbestos/resin, bands give approximately a four fold increase in life.

Reduction of Muzzle and Spiral Wear

Muzzle wear is a roughly symmetrical enlargement of the bore of a gun at the muzzle. It is greatest at the muzzle and decreases rearwards. Spiral wear is a special form in which wear is not symmetrical but limited to a number of adjacent lands. Muzzle and spiral wear take place on the lands and not in the grooves. The cause is abrasion and in its most severe form is due to failure to keep the projectile centered in the bore. These phenomena are associated almost exclusively with high performance guns and copper driving bands. This type of wear can be enhanced by the substitution of brass or aluminum for copper but it does not occur with sintered iron, steel skirt or non-metallic bands. This suggests that the thermal properties of the band material are important but it is not clear whether melting point, thermal conductivity or strength at elevated temperatures is the important property.

The phenomenon is associated with high performance guns where the driving band is subjected to higher forces for a longer time than in medium performance guns. A reduction in these forces reduces this type of wear. One method of doing this is the use of rifling of increasing twist. Comparative wear trials have been carried out in 17 Pdr guns, one with service rifling of constant twist and one with cubic rifling starting from zero. In the gun with cubic twist muzzle wear was much less severe than in the service gun. The same trend was apparent in the results of trials with 6 inch experimental guns with uniform and increasing twists of rifling.

Another method of improving the functioning of copper bands at high velocities is the use of disappearing rifling to wipe off the softened copper as the projectile travels along the bore. This principle was used in the 3.7 inch Mk 6 gun in conjunction with a long forcing cone and a front centering band on the projectile. This gun functioned satisfactorily at velocities of 3500 ft/s and its accuracy was still good when the condemning limit for wear at 1" C of R was reached. Muzzle wear was not significant. Disappearing rifling does not appear to work so well in chromium plated barrels. A chromium plated 3.7 inch Mk 6 gun developed spiral and muzzle wear and failed for accuracy after 295 rounds. The life of the service barrel was

about 500 rounds. It is thought that the higher coefficient of friction between copper and chromium combined with a higher bore surface temperature because of the lower thermal conductivity of chromium resulted in a more rapid loss of copper, leading to early band failure. Disappearing rifling was also used in chromium plated 3"/70 cal guns which were made and used in both U.S. and U.K. In the U.K. guns, wear at the muzzle was slight but greater wear occurred between 40 and 80 inches back from the muzzle. U.S. guns tended to develop spiral wear.

ERODIBILITY OF VARIOUS METALS

Materials and method of testing (35, 36)

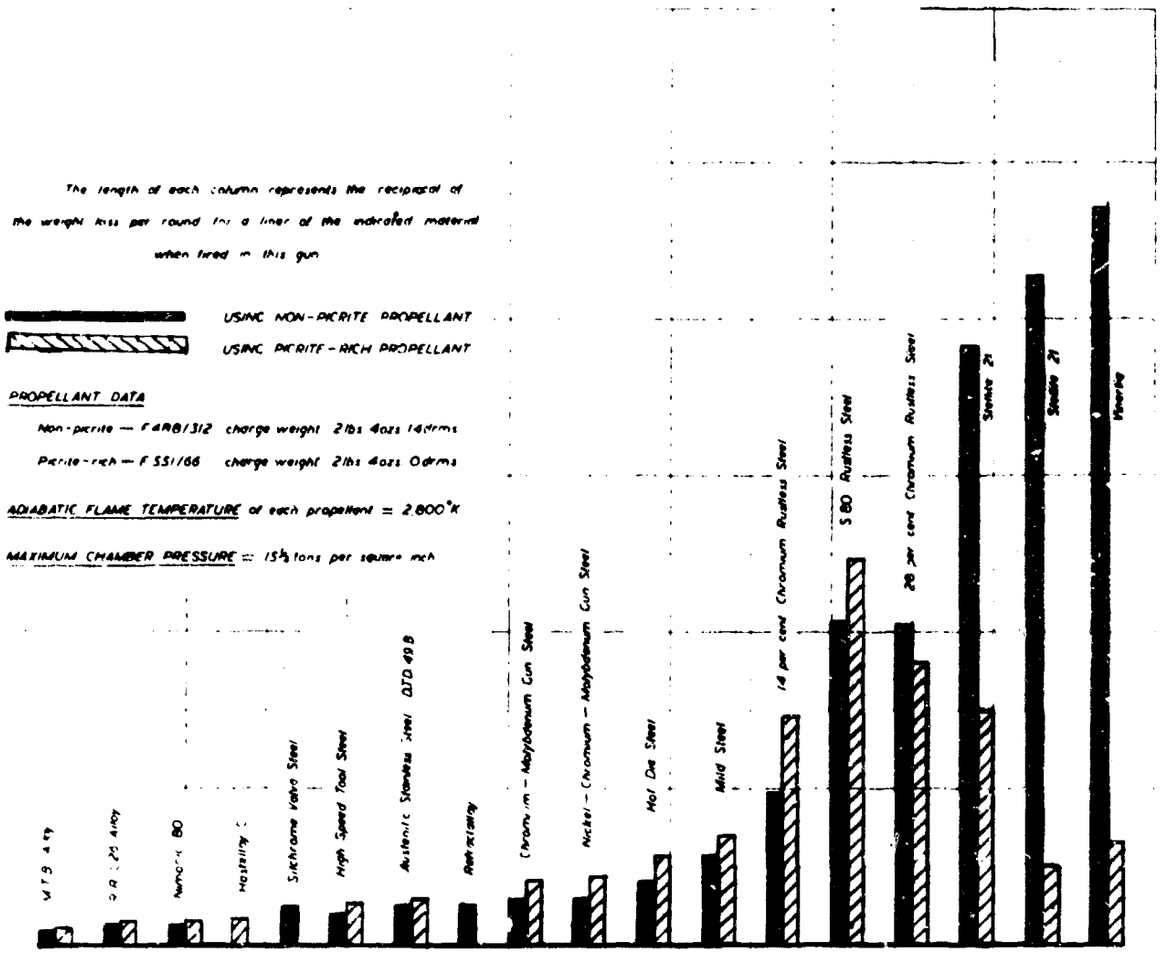
Nineteen different materials evaluated in the ARE Gun Erosion Programme comprised forged steels of various commercial types including mild, rustless, heat resisting and gun steels; highly alloyed materials of nickel-base and cobalt-base (including Stellite and Vinertia) types in the cast condition; "Nimonic 80", a forgeable, precipitation-hardening, 80/20 nickel-chromium alloy; molybdenum and titanium. Their relative erodibilities by propellant gases were tested in the form of extractable unrifled short-bore liners in a specially designed 6-pr/2-pr. gun barrel using plastic banded projectiles to ensure negligible mechanical wear by the band. The extractable liners were weighed before and after the firing trials, the weight loss (to 0.01 gm) thus providing a measure of the amount of erosion.

The main series of trials was carried out with piorite and non-piorite propellants of similar flame temperature (2800°K) and charge weights, with sizes adjusted to give similar chamber pressures (about 35,000 pounds per square inch) and muzzle velocities. The charge weight was about four times that of the service propellant (flame temperature 3300°K) used with the Q F 2-pr. barrel, and this large charge weight produced a disproportionately rapid rate of erosion in the 6-pr/2-pr gun.

Results

The high nickel alloys proved to be very susceptible to erosion when tested under these conditions. The molybdenum liner cracked along its length on firing one round and the liner in titanium alloy Ti 150A was heavily eroded after only 5 rounds. Under the conditions of testing the materials which proved considerably superior to standard British gun steels as regards erosion resistance were the heat-treatable chromium rustless steel B.S/S.80, and the two cobalt-base alloys named Stellite[21] and Vinertin, Fig. 8.1.

Similar comparative erodibility trials were carried out with N.C.M. gun steel and high chromium rustless steels using pairs of piorite and non-piorite propellants at flame temperature levels of 2450°K and 3400°K. When propellants of flame temperature 2450°K were used there was a large all round reduction in the rate of erosion, while the superiority of the high chromium steel over N.C.M. gun steel and the advantage of piorite over non-piorite propellants were both increased. When however propellants of



C.	0·15	0·15	0·05	0·17	0·48	0·85	0·50	0·15	0·30	0·31	0·39	0·27	0·20	0·14	0·07	0·45	0·48	0·50
Mn.	0·37		0·29	0·04	0·56	0·40	0·80	0·76	0·57	0·63	0·39	0·50	0·85	0·77	0·68	0·16	0·04	0·20
Si.	1·2	0·27	0·49	0·36	2·91	0·46	2·25	0·51			0·36	0·04	0·50	0·34	0·93	0·33	0·41	0·35
Ni	30·3	74·5	76·3	59·1		0·25	14·5	21·7	0·30	2·6				2·1	1·34	0·6	0·6	9·0
Cr.	20·9	10·2	10 4	13·6	7·0	4·8	13·5	20·8	3·3	0·6	3·4		13·8	16·6	28·0	30·2	31·0	30·0
Mo.	7·5	2·5		16·5	0·56			10·4	0·6	0·55	0·1				0·63	6·36	6·18	3·11
V.				0·22	0·13	1·77					0·34							2·41
W.	5·4			4·0		18·6	2·0	5·4			9·2					0·66	0·98	0·23
Co.	21·5					5·6		29·3								60·3	59·3	53·0
Al.		12·2	1·0															
Ti.			2·0												0·48			
Nb.	2·9							0·25			0·22							
Zr.													0·11					
Fe.	9·7			6·1	BAL	BAL	BAL	10·6	BAL	BAL	BAL	BAL	BAL	BAL	BAL	0·96	0·98	0·77

FIGURE 8.1. RELATIVE EROSION RESISTANCE OF VARIOUS MATERIALS USED AS SHORT-BORE LINERS IN THE 6pr./2pr. EROSION-TESTING GUN.

flame temperature 3400°K were employed the high chromium steels were found to be more erodibile than N.C.M. gun steel under the conditions of testing, a result attributed to incipient melting conditions.

Discussion of results

The relatively poor resistance to erosion exhibited by the high nickel alloys is possibly due to the sulphur content of the propellant gases.

Owing to their affinity for one another, penetration of a nickel surface by sulphur proceeds very rapidly at temperatures in the 500°C - 650°C region, so rapidly that any time effect is negligible. Penetration of nickel by sulphur has not been observed at temperatures below 400°C, but when it does occur it forms a very brittle surface layer. Also if sufficient sulphur is present at any local point on the surface to form a nickel/nickel sulphide eutectic (21.5%S), this constituent melts at the low temperature of 645°C.

The cracking of the molybdenum liner was no doubt due to its high modulus of elasticity compared with that of the backing steel. The titanium liner showed obvious signs that exothermic oxidation of the bore surface had occurred.

Titanium is more highly reactive than iron (1 gm of Ti oxidizing to TiO2 liberates 4,570 calories, 1 gm of Fe oxidizing to Fe_2O_3 liberates 1750 calories). Figure 8.2 shows the bore surface of the Ti liner after firing 5 rounds with piorite propellant, indicating ignition at point 'A' further heating the passing gases to continue the reaction and remove progressively more material in a fanwise fashion forward of the point of initiation. The use of non-piorite propellant would have produced more drastic erosion.

In order to confirm the exothermic oxidation theory, use was made of the 3.7 inch recoilless gun system. (The chamber pressure in this weapon was 3.0 t.s.i. compared with 15.5 t.s.i. in the 6 pr/2 pr testing gun). By this means it was possible to replace some of the service mild steel venturi throats with Titanium throats and erosion test both materials in the same environment. Figure 8.3 shows that, after firing only two rounds with either piorite or non-piorite propellant, the Ti throats were heavily eroded. In the case of the non-piorite firings the gases issuing over the Ti throats were super heated by exothermic reaction with the Ti to a sufficiently high temperature to attack the mild steel of the venturi trumpets. In contrast the mild steel throats suffered no obvious damage from either propellant.

Other than when melting conditions obtain, due to the use of very hot propellants, the trial results showed that the erosion of gun barrels by propellant gases is caused by exothermic reactions (particularly oxidation to form FeO) in the bore layers. This oxidation theory of erosion serves to explain the disproportionately rapid erosion which occurs when

Separate loading, inert filled, plastic banded ammunition
Charge - 2lb 1 oz 12 drm. of picrite propellant F 527/153
Adiabatic flame temperature - 2450°K
Chamber pressure - 13·7 tons per square inch

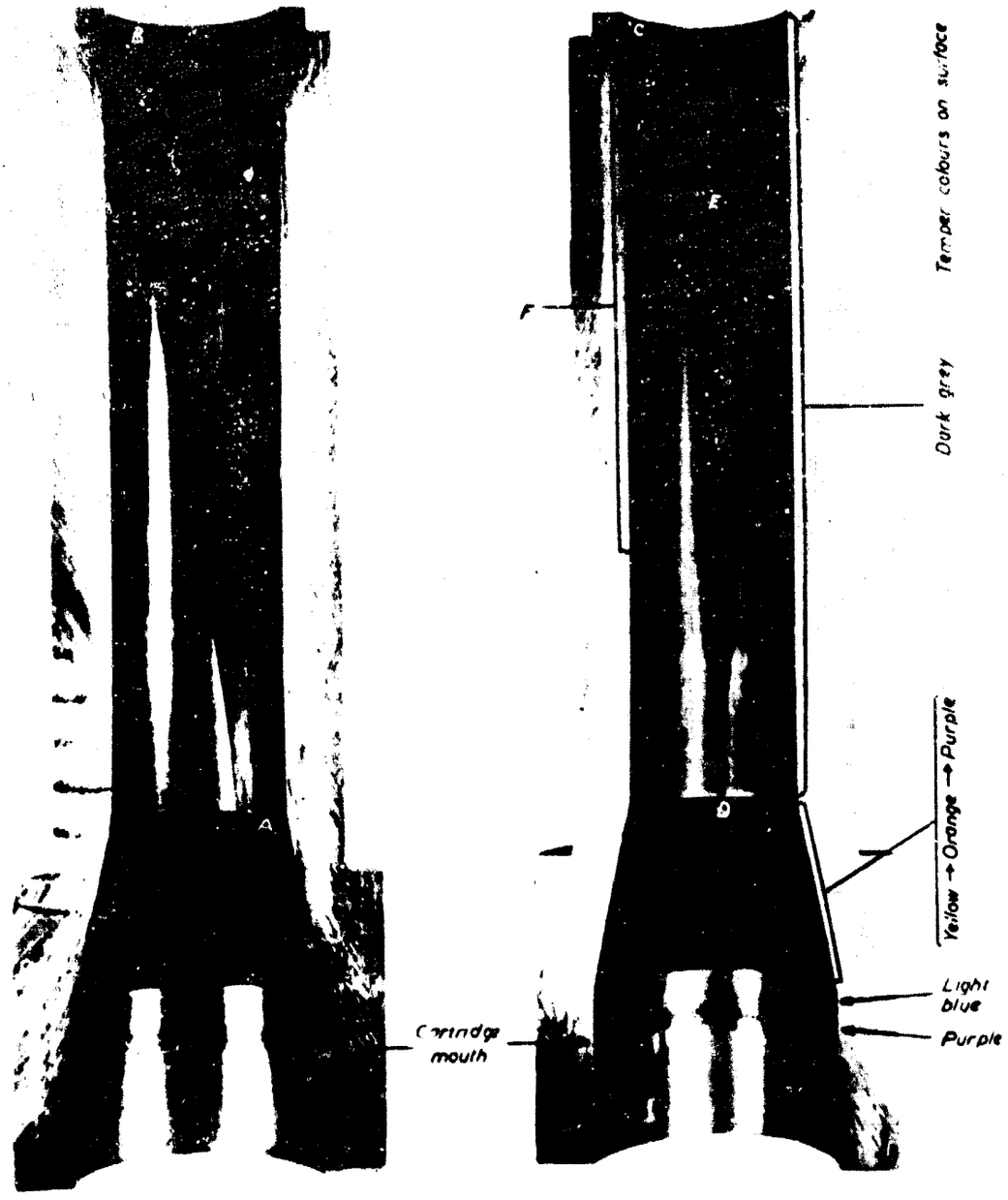


FIGURE 8.2. (x1/2 approx) AXIAL SECTIONS OF 6pr./2pr. UNRIFLED SHORT-BORE LINER OF TITANIUM ALLOY TI.150A AFTER FIRING 5 SINGLE SHOT ROUNDS.

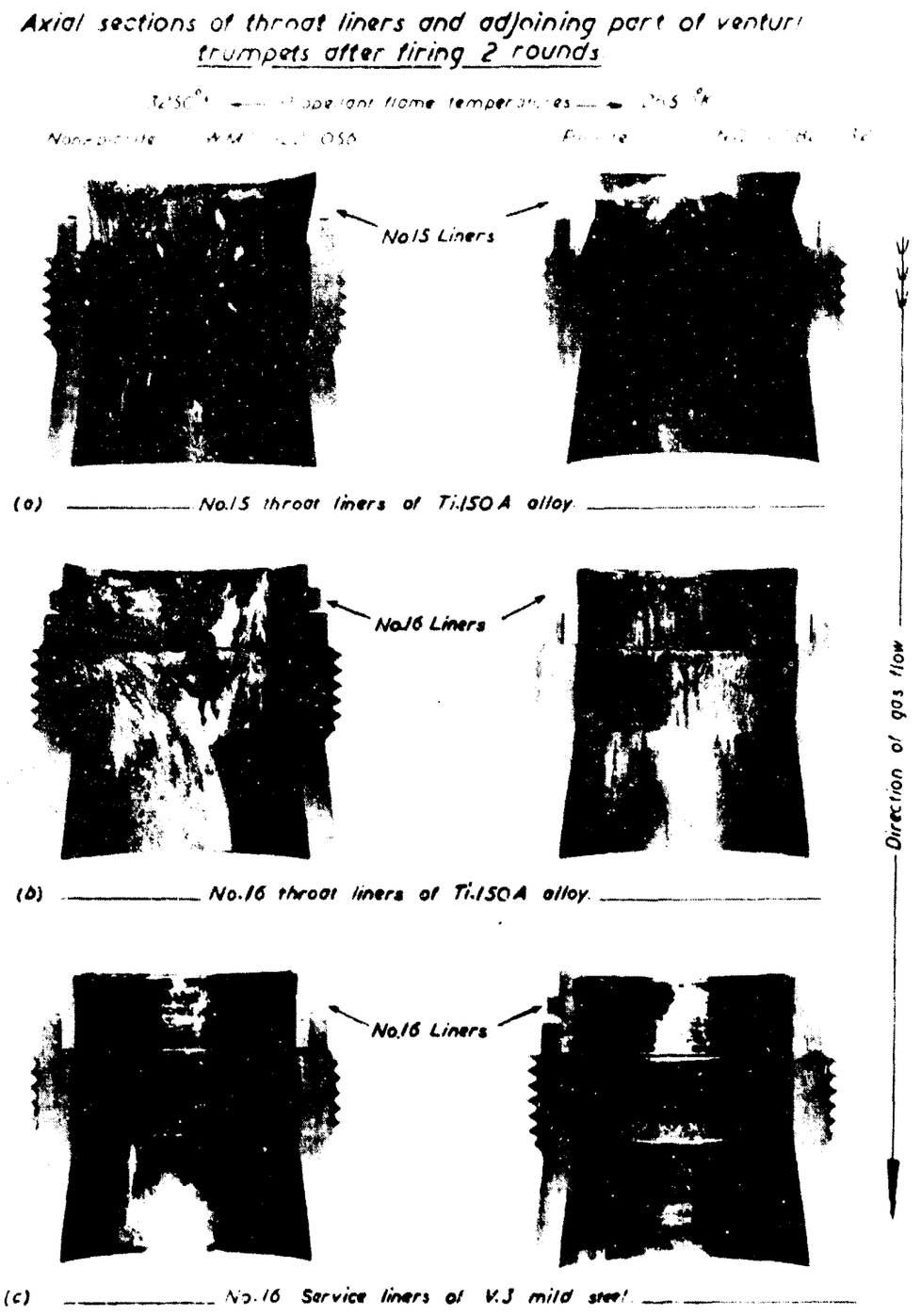


FIGURE 8.3. (x3/4 approx) AXIAL SECTIONS OF THROAT LINERS AND ADJOINING PART OF VENTURI TRUMPETS AFTER FIRING 2 ROUNDS.

flame temperature of propellant, charge weight or length of automatic bursts of fire are individually increased beyond certain values, which values presumably determine the incidence of rapid oxidation of the bore surface. This theory also explains why piorite-rich propellants are less erosive than their non-piorite equivalents since the high nitrogen content of the former would have a diluent effect on the oxidizing potential of the gases.

Chromium plating

Chromium plating is often used for its excellent resistance to wear, but in some service components it is also subjected to severe thermal stresses. To investigate the behaviour of the plating several test pieces of En 25 steel were obtained and the 0.05" wide faces were plated by standard methods with a layer of chromium 0.006" thick. One of the side faces was then polished and examined during thermal cycling.

The deposit was found to crack very readily and the cracks often appeared suddenly without evidence of gradual propagation. Cracks were evident after 1 cycle from 40° to 500°C, after 100 cycles from 40° to 400°C, or after 5000 cycles from 40° to 350°C. The initial cracks often appeared to stop just before reaching the steel interface, probably because of the support received from the steel. Perhaps for the same reason it was found that a much thinner deposit (0.002") did not crack so readily as the thicker one.

No other metal has been found to crack quite so readily in this test, not even white cast iron. One reason for this extraordinary weakness is that the plating is full of microcracks before testing is started. In addition the deposit contains a residual tensile stress in the as-plated condition. The stress can be reversed by a heat treatment of 1 hour at 500°C and this treatment gave some improvement in the resistance to cracking.

Despite the readiness of the deposit to crack the subsequent rate of propagation of cracks into the steel was not greatly increased. In fact this observation prompted the tests which have been mentioned on the influence of multiple notches, and it was confirmed that the multiple small notches on the surfaces of the steel had a similar effect on the rate of cracking to a layer of chromium.

Although the chromium deposits are weak in tension they have some strength, and a thick layer presents considerable resistance to compression. When appreciable plastic deformation occurred in the steel a thick deposit of chromium had the effect of localizing the deformation in the steel onto planes of shear which began at the cracks in the plate. The effect of repeated phase changes in the steel was eventually to break up the plating into blocks but the blocks adhered to the steel until they were undermined by oxidation.

In high rate of fire guns chromium has been observed to give a bonus in barrel life by delaying the onset of bore wear. However when the plating flakes from the bore, pockets of gas turbulence may be initiated and local erosion may commence. It is therefore considered that the use of chromium plating in the rifled bores of guns gives only a limited increase in barrel life.

MITIGATION OF THE EFFECTS ON EROSION

Effects of Erosion

The main effects of erosion are:-

(i) Drop in muzzle velocity
(ii) Failure to impart spin
(iii) Inaccurate shooting
(iv) Fuze damage
(v) Failure to arm fuzes.

Loss of muzzle velocity

One reason for the loss of muzzle velocity with wear for separately loaded projectiles is the increase in chamber capacity due to the increased ramming distance. This can be minimized by making that part of the forcing cone on which the band seats as steep as in consistent with ensuring a firm grip, say 4°, and by making the diameter of the gas check on the driving band as great as is permissible for resistance to handling and the avoidance of damage due to rough usage.

A more important reason for loss of muzzle velocity in all types of guns is the change in initial resistance to the motion of the projectile. This resistance has a marked effect upon the ballistics of the gun, and its variation due to wear is responsible for more than half of the drop in velocity. Resistance to the motion of the projectile in the latter stages of motion is far less important, and thus the reduction of the initial resistance by allowing the projectile to travel freely for a few calibres before the driving band is engraved shows a marked improvement in maintenance of muzzle velocity.

Part of the loss of muzzle velocity in worn guns is caused by the escape of gas past the driving band. This can be prevented by fitting to the base of the shot a plastic sealing ring which can expand to make contact with the bore and produce an effective seal.

Failure to impart spin

The obvious solution to this effect of erosion is to increase the size of the driving band, and this has in fact been done in most British guns since few guns are condemned for failing to impart spin. While a large band is successful in imparting spin in conditions where a smaller band fails,

this simple solution is not without disadvantages. Firstly, in some conditions at any rate, the larger band will be responsible for a higher rate of wear. Secondly the larger band will exhibit a greater drop in velocity for the same amount of wear. There is thus scope for other methods.

Rifling of increasing twist provides a means of easing the difficulty of imparting spin without increasing the size of the driving band. Increasing twist implies a higher torque to be transmitted by the band in the latter stages of motion up the bore; it appears that this need not be a disadvantage.

Another line of attack is the substituting of a different material for the driving band which for the same spinning ability has a smaller effect on wear and ballistics. This result can be achieved by the use of non-metallic bands.

Accuracy life

The accuracy of a gun can deteriorate due to variability in muzzle velocity, instability due to lack of spin or to excessive muzzle wear. The cure for variability in muzzle velocity is thought to be same as for drop in muzzle velocity. The disturbing influence of muzzle wear is due to the eccentric motion of the projectile and also the consequent asymmetry of the action of the propellant gases on the projectile after ejection. The cure for this is to centre the projectile in the enlarged bore, and some type of front centering band is required in addition to a satisfactory rear band which should be of some material other than copper.

Fuze damage

Fuze damage due to 'side slap', that is, lateral motion of the projectile in the enlarged bore can be reduced if the projectile is fitted with a front centering band which limits this lateral motion. It has also been shown that improved gas sealing, by sealing caps, is effective in reducing 'side slap'.

Fuze arming

This is due to drop in maximum pressure. This is really the same problem as maintenance of muzzle velocity and can be solved by the same methods.

Summary

The method of controlling erosion and its effects are summarized in the table attached.

Phenomena and Cause	Effects of Bore Enlargement on Internal Ballistics and Gun Functioning	Effects on External Ballistics and Accuracy	Control of Erosion and Mechanical Wear	Mitigation of Effects of Erosion on Ballistics and Accuracy
Enlargement of bore near chamber. Caused by heating and chemical action of propellant augmented by mechanical action of gas and driving band.	1) Combustion is retarded and the maximum pressure developed in the chamber is decreased due to (a) increase of chamber capacity with separately loaded projectiles (b) reduced engraving resistance (c) leakage of gas past the driving band and (d) increase of cross sectional area of bore	1) The muzzle velocity and regularity of M.V. are reduced and the tendency to flash is increased.	1) Control of bore temperature by (a) Use of cool propellants (b) Use of super calibre principle (c) Countersinking neck of cartridge case to reduce turbulence (d) Use of a gas sealing device to prevent leakage (e) Barrel cooling for automatic fire (f) Use of Smear (g) Use of Boundary layer techniques.	1) The loss of muzzle velocity and flashlessness may be reduced by the following expedients (i) The use of a high diameter ramming stop on the driving band to preserve chamber capacity. (ii) The use of a limited free run followed by gradual engraving to eliminate the effect of engraving resistance. (iii) The use of a gas sealing device to prevent leakage.
	2) Side slap and vibration of projectiles is increased due to increase of windage and gas leakage.	2) Fuzes are damaged causing blinds and inaccurate functioning.	2) Reduction of mechanical effects Relief of band pressure and friction (a) Pre-engraved projectiles (b) Skirt and sintered iron bands.	2) Fuze trouble may be prevented by efficient gas sealing in conjunction with positive centering of the projectile.

Phenomena and Cause	Effects of Bore Enlargement on Internal Ballistics and Gun Functioning	Effects on External Ballistics and Accuracy	Control of Erosion and Mechanical Wear	Mitigation of Effects of Erosion on Ballistics and Accuracy
			(c) Visa device (d) Non-metallic driving bands.	
	3) The capacity of the barrel to impart full rotation to the projectile is eventually lost.	3) Accuracy fails when the rotation of the projectile is inadequate for stability in flight.	3) Increasing resistance to erosion by use of an erosion resistant liner or an erosion resistant bore coating.	3) The rotational capacity of the barrel may be preserved by reducing the intensity of the thrust on the driving surfaces in the rotating band. Deep rifling, optimum number of grooves, increasing twist, maximum practicable working material in driving band and the use of the super calibre principle are factors which assist. For H.V. weapons the use of an efficient driving band is also required.

Phenomena and Cause	Effects of Bore Enlargement on Internal Ballistics and Gun Functioning	Effects on External Ballistics and Accuracy	Control of Erosion and Mechanical Wear	Mitigation of Effects of Erosion on Ballistics and Accuracy
Enlargement of forward part of the bore. This tends to be symmetrical when caused by the abrasive action of the driving band and spiral when caused by the bodies of eccentrically moving projectiles.	1) The eccentricity of the C.G. of the projectile during shot travel is increased. 2) The capacity of the barrel to impart the full rotational torque up to the muzzle may be impaired	1) The initial yaw of the projectile and the angular dispersion of fire are increased. 2) The gun is condemned for inaccuracy before the condemning limit for wear is reached at C. of R.	Erosion can be reduced by 1) The use of increasing twist or disappearing rifling with copper bands and forward centering rings. 2) The use of steel skirt, sintered iron or non-metallic driving bands.	NIL
Bore Surface Cracking. Due to tensional stresses at the bore on cooling Phase changes in bore layers Prevalence increased with piorite propellants.	Craze cracking in early life can cause ballistic "hump" Prolific cracking aids removal of material from the bore. In high strength barrels incipient cracking may initiate fatigue cracks and drastically shorten barrel life.	Increase in MV due to "Hump" effect.	Incidence of bore cracking can be reduced by 1) Use of non-piorite propellants* 2) Smear or Boundary Layer techniques 3) Elimination of low melting point metals from propellant charge 4) Thin walled barrels.	*All cool propellants are of piorite type. Using non-priorite will increase bore temperature and aid oxidation of the bore. Hump effect may be overcome by firing a few rounds with hot propellant and eroding crack types to reduce drag on the band (Wear will increase slightly.)

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FOLLOW ON CONTRIBUTION

S. W. Hollingum
Royal Armament Research & Development Establishment
Fort Halstead, Seven Oaks, Kent, England

Mrs. D. J. Taylor has presented the main conclusions of this review paper. In amplification of the erosion research, Mr. J. Morris has provided examples of the associated metallurgical work completed a number of years ago. Illustrations from investigations of erosion in 4.5 inch gun barrels show the phenomena of deep erosion at the cartridge case mouth and in an area just forward of the commencement of rifling. The typical features of surface erosion and various degrees of craze cracking, and the observations on the altered surface layer and the influence of chromium plating are similar to those given in other papers.

Particular studies of the factors which influence thermal fatigue were completed about 10 years ago, and were summarised by H. G. Baron and B. S. Bloomfield in a paper published in the Journal of the Iron and Steel Institute, Volume 197, March 1961. They used a wedge-shaped test piece which was water-cooled through the centre and heated in repeated cycles at the narrow end of the wedge by an induction coil. This test was used to study the influence of the maximum and minimum temperatures in the cycle on the thermal fatigue properties of a number of different steels, some heat resisting alloys, and cast irons. The research emphasised the importance of the austenite $\rightleftharpoons$ martensite transformations which are accompanied by a volume change. If this is

suppressed, as in the copper-silicon steels, the thermal fatigue life can be improved. The technique also showed the effect of decoppering agents.

In previous contributions mention has been made of limiting the life of gun barrels on the basis of fatigue properties. The UK barrels wear out, but with the use of stronger steels and success in reducing gun erosion and wear, fatigue crack propagation becomes a dominant factor. Researches at RARDE on fatigue and fracture toughness of gun steels are similar to those at Watervliet Arsenal.

In later papers reference is made to liner materials, and the RARDE review paper gives results obtained for unrifled short bore liners in a specially designed 6-pr./2-pr. gun barrel. These showed the relevant resistance of liner materials to non-picrite and picrite rich propellants. It is important to note that the nickel alloys and nickel rich steels were inferior to the current nickel-chromium-molybdenum-vanadium gun steels. This indicates the problems which might occur if Inconel 718 is used for the 81mm mortar on display in the exhibition. The UK has a preference for steel, which is less expensive and more easily worked, although the good elevated temperature properties of Inconel 718 cannot be disputed. Dr. Ahmad has mentioned Stellite 21, and its good erosion resistance to non-picrite propellants has been shown.

It will be seen that similar observations have been made by investigators on both sides of the Atlantic. Unfortunately in recent years RARDE has done very little metallurgical research into gun erosion and its control. Our techniques are now greatly improved and we have a

greater understanding of the properties and behaviour of materials in the service environment. Hence we welcome this opportunity of participating in this review of the state of the art and appraisal of the needs for future research, particularly in such topics as surface reactions, with new additives and coolants, and the influence on crack propagation of the propellant gases and deposits, the rate of strain and the temperature cycle. Also it is necessary to consider the need for development of improved materials and the associated techniques for component production.

1.3 DISCUSSION:

Jerome M. Frankle (comment): Mrs. Taylor has expressed an interest in test results which showed the detailed wear pattern produced in the 105MM Tank Gun when projectiles with vulcanized fiber bands were fired without the bands in the cartridge case. This information exists in BRLM 1879.

INVESTIGATION OF EROSION IN 7.62MM MACHINE GUN BARRELS

W. T. Ebihara, Ph.D.
Science and Technology Laboratory
Research and Engineering Directorate
U. S. Army Weapons Command
Rock Island, Illinois

Metallurgical analysis was conducted on 7.62mm machine gun barrels, in the chromium plated and unplated conditions, to characterize the erosion process. The chronological analysis involved the examination of severely eroded gun barrels as well as those experiencing test firings of 1 to 3000 rounds. Inherent defects in the form of cracks are noted in the chromium plate prior to firing. These cracks are extended to the chromium/steel interface as early as the first round, thus exposing the underlying steel to the reactive environment. Continued firing results in the propagation of these cracks into the steel substrate followed by crack branching. Branching proceeds until link-up is achieved, resulting in the removal of chromium plate/steel fragments. The factors considered to be responsible for crack extension include gaseous and liquid metal reactions. The character of erosion in unplated steel gun barrels is contrasted from the plated barrels in that substrate cracking is delayed and land wear occurs much earlier in the firing sequence.

Introduction

Deterioration of the bore surface resulting from erosion remains a major problem in the performance of rapid-fire, high velocity weapons. Generally, gun erosion is defined as the result of processes which lead to a change in bore dimensions. In

this paper, erosion is described as a change in the bore cross section resulting from material removal or structural alteration. In the initial stages, erosion may manifest itself in the decrease of projectile velocity or accuracy, thereby reducing the effectiveness of the weapon. Loss of velocity or accuracy becomes increasingly apparent as erosion progresses until the gun is retired.

The advanced stages of erosion introduce areas near the breech which are particularly susceptible to catastrophic failure. A cross section of such an area is shown in Figure 1. This segment is taken from a barrel which actually failed at the breech end, causing the damage shown in Figure 2. Failures of this type not only completely render the weapon useless but also may be fatal to personnel in the vicinity of the weapon.

Previous attempts to combat erosion in weapons have enjoyed only moderate success. Approaches to solving the erosion problem have dealt mainly with techniques to reduce erosion by

(a) the utilization of erosion resistant materials,

(b) the reduction of the bore surface temperatures, and

(c) reduction of chemical and mechanical effects.

The first of these was achieved with some form of plating or lining on gun barrel steel. The latter two items have, in general, resulted from utilizing lower combustion temperature propellants, wear reducing techniques and design changes of internal rifling configuration. However, large gains in erosion reduction are still limited by the lack of fundamental knowledge concerning the mechanisms of erosion and the erosion rate-controlling parameters for any given

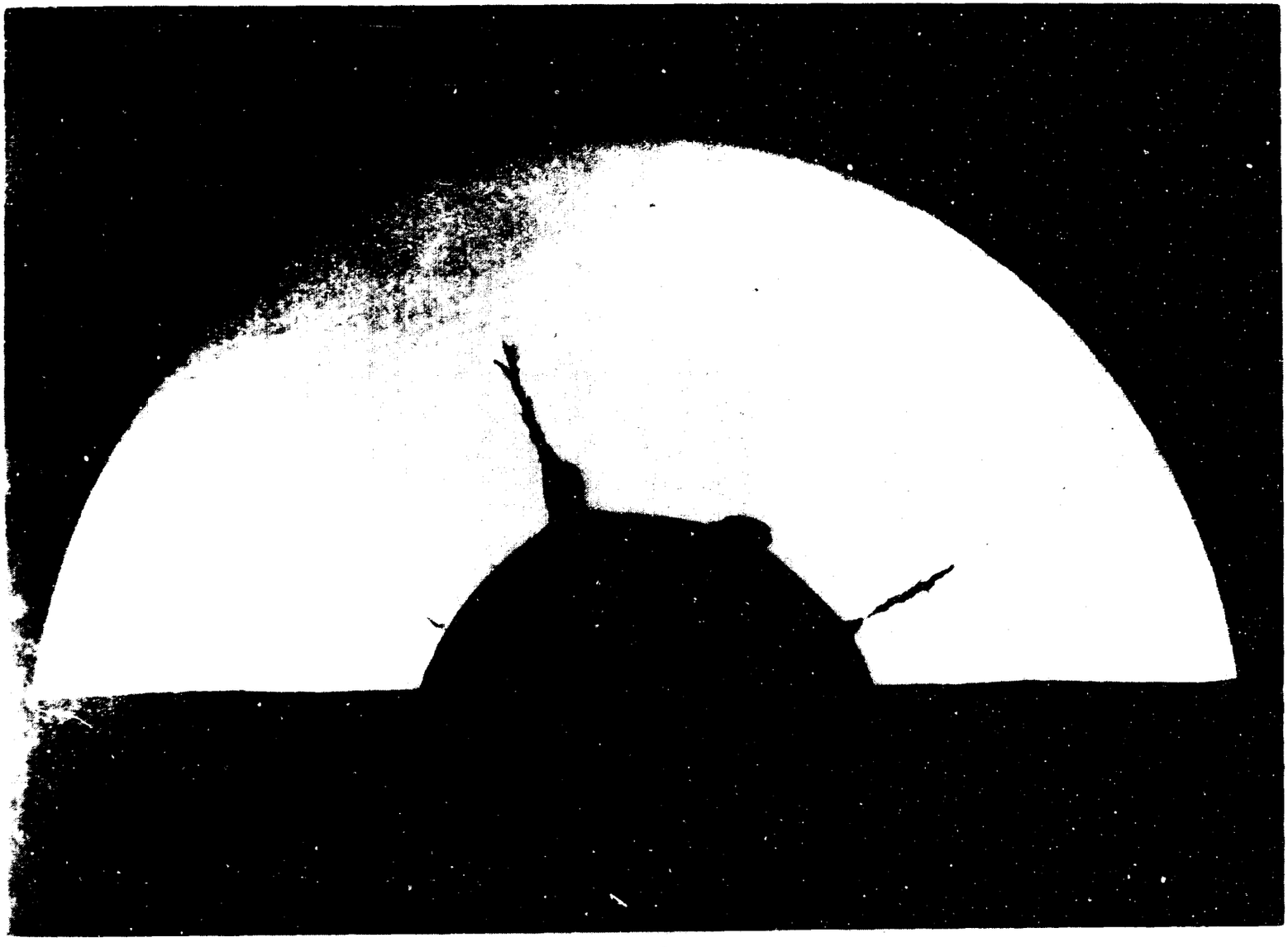

FIGURE 1
Transverse Section of Failed Barrel Near the Breech End.

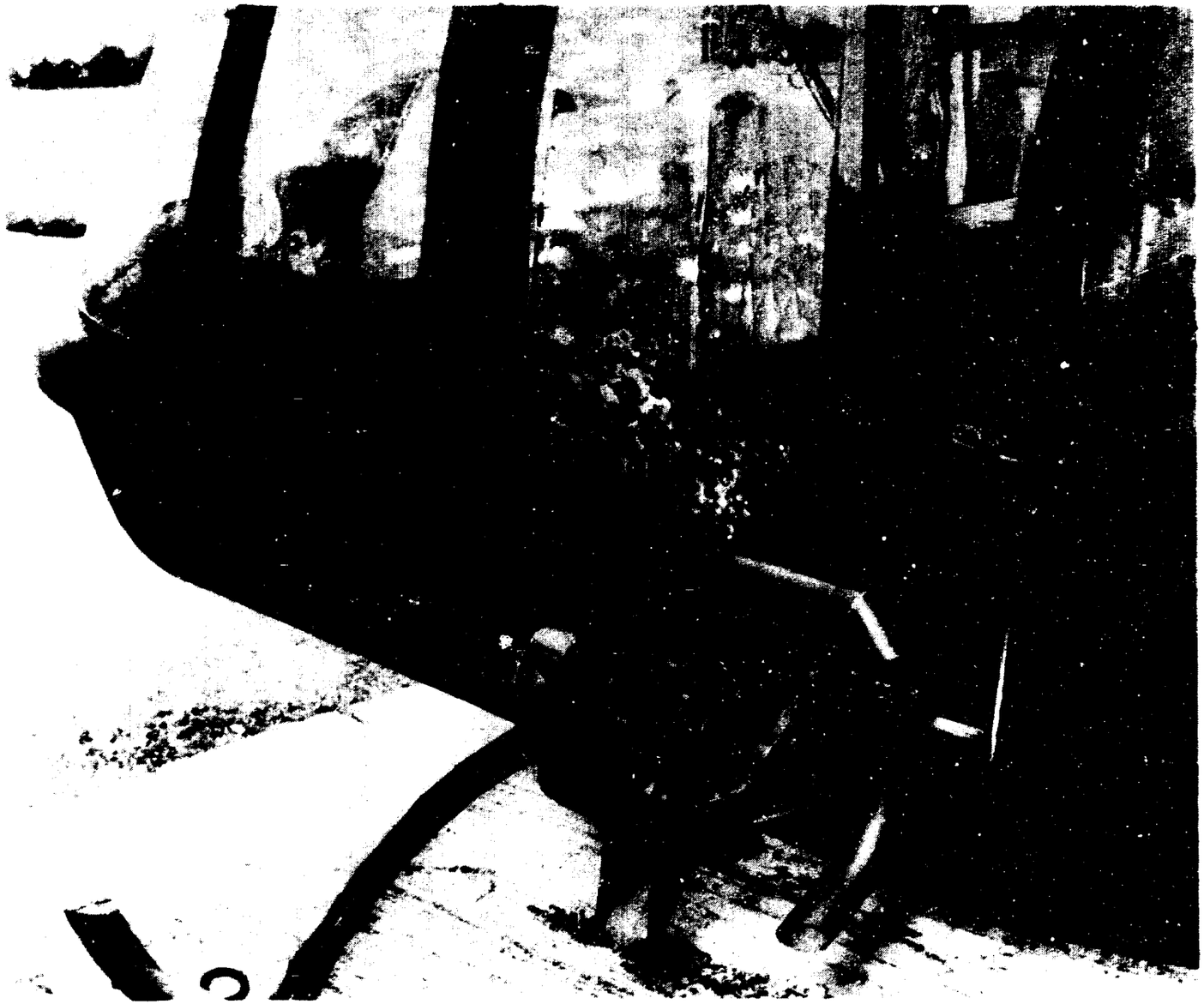

FIGURE 2
Weapons Carrier after Breech End Failure of Minigun Barrel.

weapons system. Once these are established, a combined approach utilizing materials, propellants, and configurational design considerations can be effectively applied to optimize weapons performance as well as to the selection of a testing criterion to evaluate candidate materials for use in gun barrels.

Erosion studies in the past, on small caliber weapons, were generally conducted with emphasis on weapons of caliber .50 or larger.[1] The studies were concerned with the inspection of severely eroded structures on barrels of a homogeneous structure. Little basis for comparative analysis could be established since nonuniform firing schedules, propellants of varying composition and different weapons systems were often used. Tests conducted to isolate various parameters were limited and, generally, were terminated soon after 1946. Although the results of these studies are extremely helpful in the present study, many of the conclusions were too general in content for specific applications to solve erosion problems of contemporary weapons systems.

The intent of the present effort is to determine the rate-controlling processes involved in the erosion of small caliber weapons systems so that satisfactory methods can be adopted to prevent or control this deterioration process. The first phase of the study involves an intensive analysis of the eroded structures to describe the character of the erosion phenomenom. The characterization of the chronological development of the erosion,

1. Hypervelocity Guns and the Control of Gun Erosion, Summary Technical Report of Division 1, NDRC, Volume 1, Washington, D. C., 1946.

as well as the description of eroded structure, are the objectives of this phase. The object of the second phase will be to investigate the effects of the various erosion parameters, both individually and in combination, through selective laboratory tests and, then, with the correlative findings of Phase I, arrive at the predominate erosion mechanism for the particular weapons system and propellant.

This paper describes the progress of the study to characterize erosion in the 7.62mm M134 gun barrel. Previously endurance-fired gun barrels, with documented firing schedules, were analyzed initially. These data, characterizing the advanced stages of erosion, were then compared with results of selectively chosen test barrels, having been fired from 1 to 3000 rounds, to show the chronological development of erosion. Emphasis is placed on the characterization of erosion in chromium plated 7.62mm barrels although comparisons are made with erosion of the same barrels in the unplated condition. The bulk of the analytical work was performed at the University of Missouri - Rolla under Contract DAAF01-69-C-0541. These results are considered preliminary and are provided for information only. The investigation is continuing and the final results and analysis will be provided at the conclusion of the program.

Experimental Procedure

7.62mm gun barrels, in the chromium plated and unplated conditions, were procured for test firing purposes on the GAU-2B/A Minigun. This weapon houses six gun barrels and was fired at a rate of 4000 rounds per minute or approximately 667 rounds per minute for each of the six barrels. In most cases, duplicate

tests were performed for both the unplated and the chromium plated barrels. Continuous bursts of 1, 10, 50, 100 and 200 rounds were provided. To provide barrels experiencing 300 rounds or more, the firing schedule per barrel consisted of a 100 round burst, 15-second cool, 100 round-burst, 15-second cool, a final 100 round burst followed by a cooling period of 30-minutes. Multiples of this 300-round firing sequence were then used to provide gun barrels experiencing a total of 900, 1500, 2100, and 3000 rounds. The ammunition used in these tests was the standard NATO M80, Lot TWL 18068 67 with WC 846 propellant.

The test fired gun barrels were cleaned by rinsing with ethyl alcohol and then dried. Silicone replicas were made to non-destructively examine the condition of the interior bore surface.

The gun barrels were sectioned longitudinally and the interior bore surface was again inspected. The majority of the samples for study were obtained from the first four inches from the origin of rifling since this area exhibits the maximum damage. Unless otherwise stated, the transverse cross section represent a zone approximately one inch from the origin of rifling. Two types of specimens (a transverse section and a section polished at a low angle to the bore surface which is referred to as a bore surface specimen) were prepared for examination purposes. The bore surface specimens were necessary to enlarge the area of damage because the depth of erosion was not always appreciable and, consequently, could not be observed satisfactorily on a transverse section. These specimens were subjected to metallurgical analyses utilizing the optical microscope, scanning electron microprobe and X-ray diffraction techniques.

Results

Initially several barrels which had been fired under severe schedules and, thus exhibited the advanced stages of erosion, were studied. The bore surface of these barrels had an appearance as shown in Figure 3. Much of the chromium plating has been removed and copper has filled cracks in the barrel. The extent of copper extrusion into the cracks is better observed in the polished section of Figure 4. The cracks observed on the bore surface extend through the chromium and well into the underlying steel as shown in Figure 5. Not all of the cracks in the steel exhibit copper but microprobe analysis did reveal copper in some of the most minute cracks (Figure 6). The cracks grew primarily in the radial direction, with some bifurcation noted. It was observed that an altered zone was associated with the cracks in the steel. Figures 7 and 8 contain examples representative of the appearance of the altered zone. The zone appears to consist of more than one phase and resists attack by common etchants (nital and picral) as depicted in Figure 9. Identification of this zone or of the phases present is not yet complete. However, it is generally characterized as being considerably harder than the unaffected steel. Microprobe analysis revealed that this zone is of a different chemical composition than the unaltered steel as evidenced by the scan shown in Figure 10.

The results of the investigation on the prescheduled test fired barrels will now be presented. Inspection of the bore surfaces at 40X showed a gradual accumulation of residue up to 300 rounds. However, no significant difference could be observed in the quantity of residue when comparing 900 round barrels to 3000

FIGURE 3
Scanning Electron Micrograph of Eroded Bore Surface.

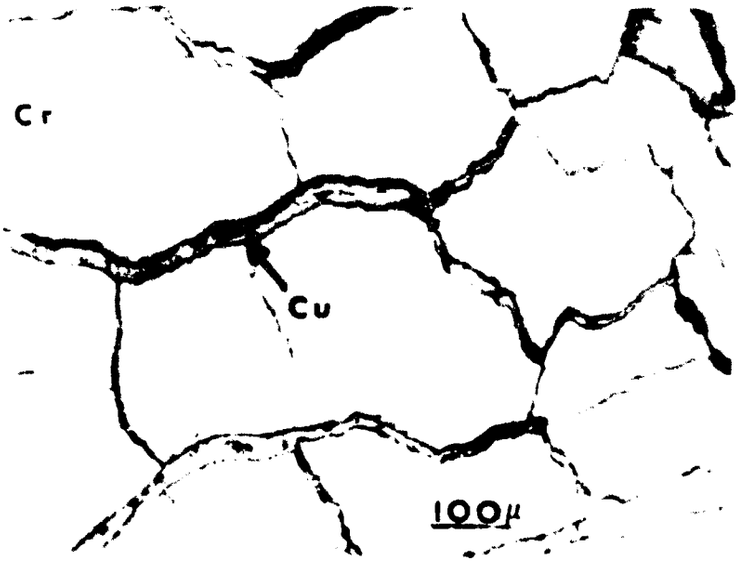

FIGURE 4
Copper Filled Crack Network in Chromium Plating. Unetched

FIGURE 5
Scanning Electron Micrograph Showing Extension of Cracks into the Underlying Steel.

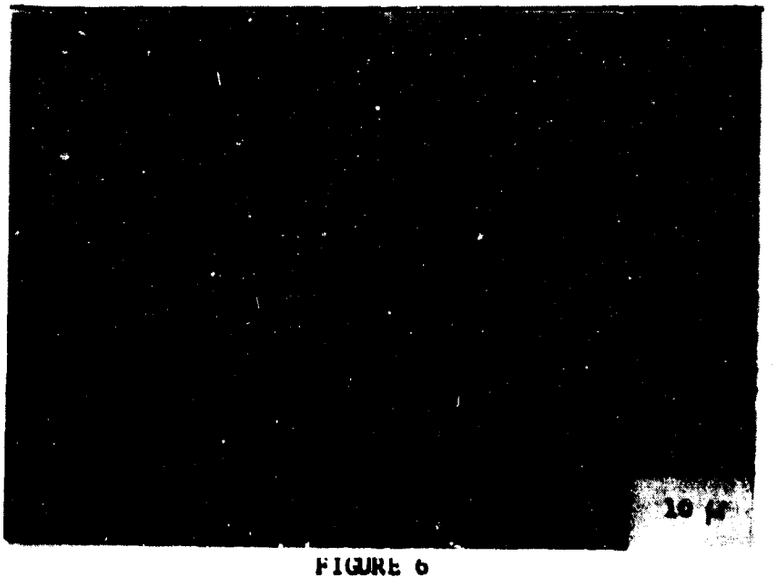

FIGURE 6
Electron Microprobe X-Ray Display Showing Copper in Minute Cracks in Steel

FIGURE 7
Optical Photomicrograph
of Altered Zone Surrounding a Crack.

FIGURE 8
Scanning Electron Micrograph
of Altered Zone Surrounding a Crack.

FIGURE 9
Structure Overetched to Reveal Altered Zone.
Etched in Nital.

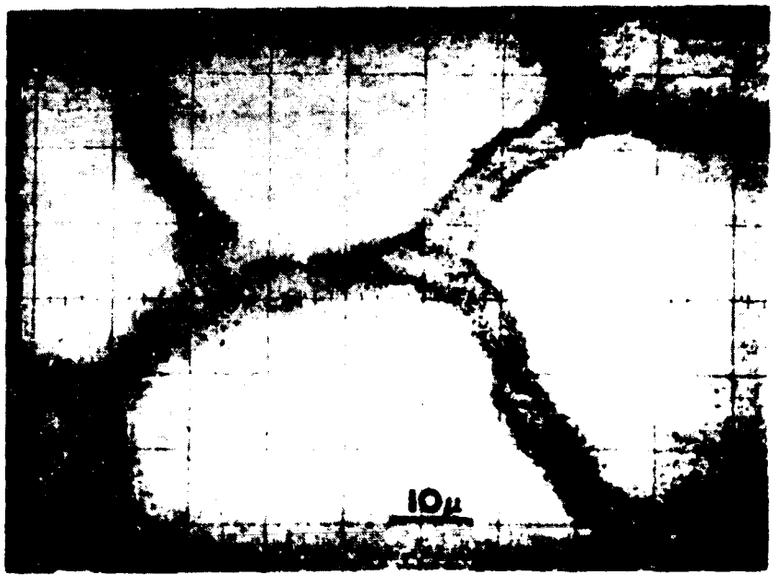

FIGURE 10
Microprobe Analysis by Back-Scattered Electrons
to Define Altered Zone.

round barrels. The residue appears to be a mixture of copper, which is heaviest in the corners between land and groove (Figure 11) and a fused crust (Figure 12). X-ray diffraction results indicate the major phase of the crust to be calcium carbonate, $CaCO_3$. The bore residue is accumulated more in the latter two thirds of the barrel toward the muzzle end and is more prevalent in the chromium plated barrels.

Cracks appear to be inherent to the hard chromium plating as shown in Figure 13. These cracks begin to open up during repeated firing so that a crack network is obvious at a magnification of 40X even after only 50 rounds. Figure 14 illustrates that the underlying steel is exposed to attack after only 10 rounds. Here, reaction pits in the steel are always traceable to cracks in the chromium plate. After 100 rounds, copper is observed to fill the cracks and decorates the network (Figure 11). The copper in the cracks on the bore surface appears as if it were extruded as the barrel material contracts following a pressure pulse. After 200 rounds, definite cracks are observed in the steel (Figure 15). It should be noted that not all cracks in the steel originate at a pit underlying the chromium plate. However, both the pit and crack in the steel are always associated with cracks in the chromium.

As firing progresses to approximately 1500 rounds, the grains of chromium plating become displaced and ultimately detached near the breech end of the barrel. In most cases, removal of the underlying steel is always associated with the detached chromium fragments. By 3000 rounds, much of the plating in the

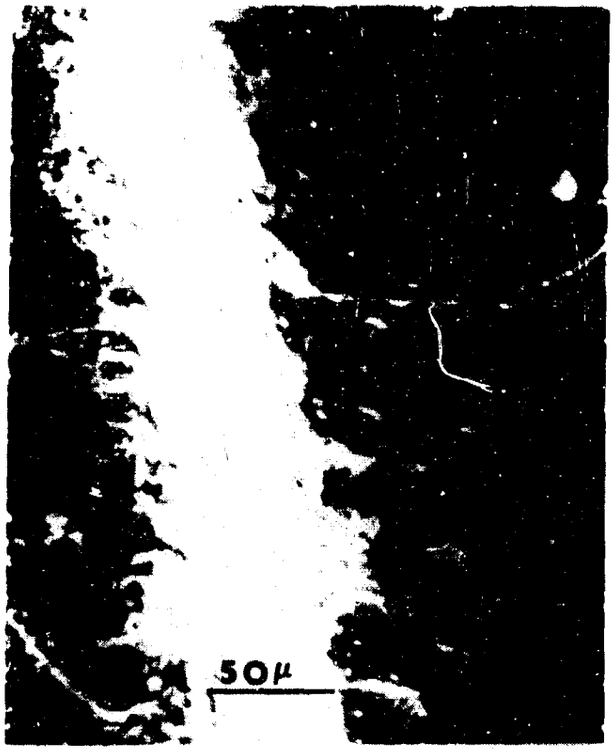

FIGURE 11
Scanning Electron Micrograph Showing Copper Collected into Cracks and Corners of Bore Surface.

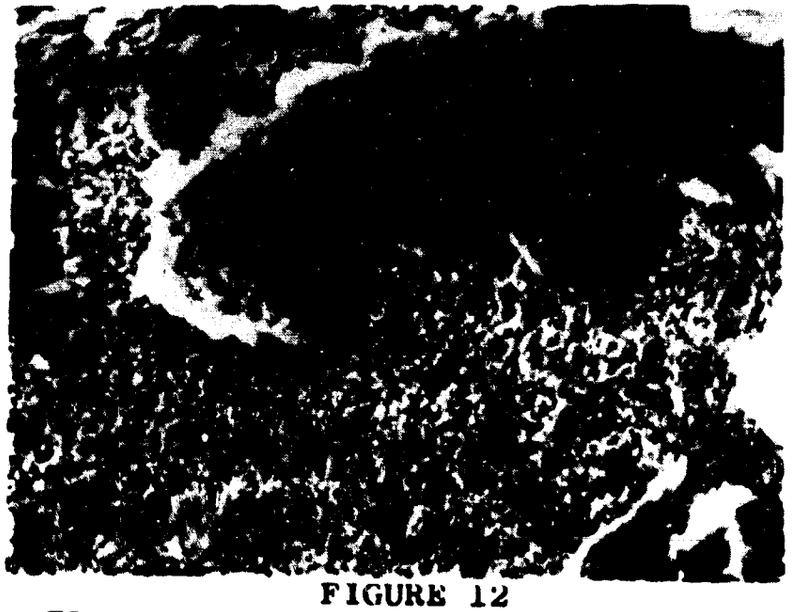

FIGURE 12
Scanning Electron Micrograph Showing Noncoherent Fused Crust on the Bore Surface of Unplated Barrels.

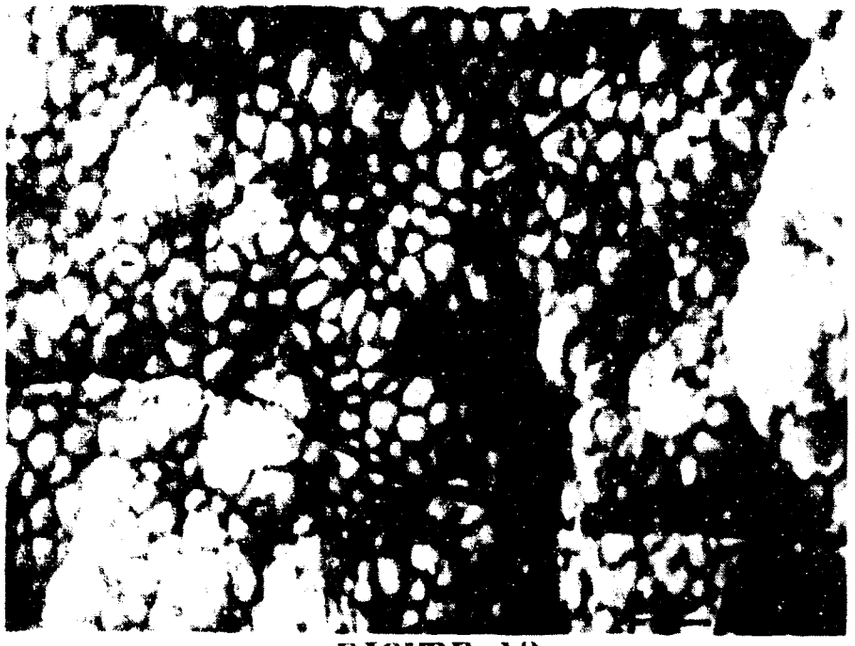

FIGURE 13
Scanning **Electron Micrograph Revealing**
Crack Network **Inherent in the Chromium Plate.**

FIGURE 14
Scanning **Micrograph Showing Pitting in Steel**
Beneath Cracks **in the Chrome Plate after 10 Rounds.**

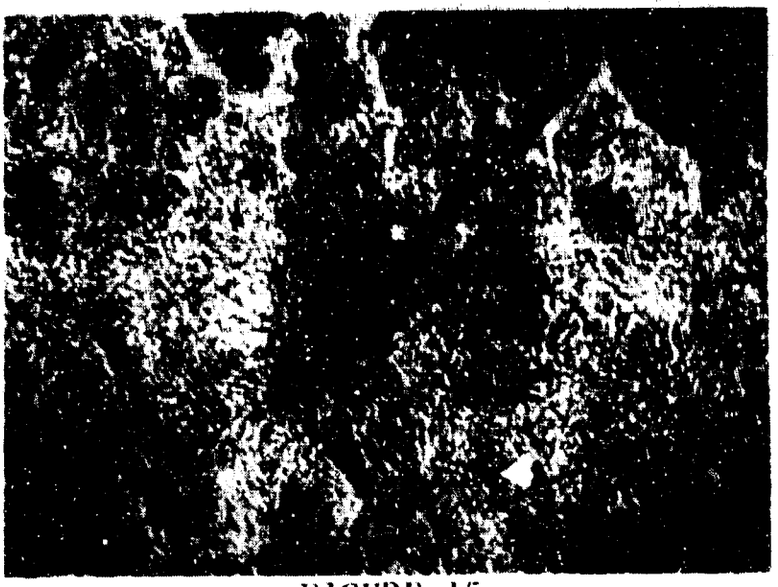

FIGURE 15
Scanning Micrograph of Crack
Propagating Intergranularly into Steel
after 200 Rounds.

FIGURE 16
Scanning Electron Micrograph
Showing Fragmentation and Removal of Chrome Plate
after 3000 Rounds.

first few inches near the breech has been removed as shown in Figures 16 and 17.

Altered zones surrounding cracks are not observed in test barrels until approximately 300 rounds. After 600 rounds of firing, the altered zone structures are well developed and new cracks are initiated while the primary cracks continue to propagate into the steel. Other than the altered zone, there is little evidence of significant structural alteration of the steel near the bore as shown by hardness surveys or by metallographic examination (Figure 18).

The unplated barrels exhibited no acute erosion features other than a gradual wearing away of the lands until light checking was observed on the bore surface at 900 rounds. The first checking was concentrated on the edges of the lands. After 1500 rounds the checking is fully developed, and after 3000 rounds, the surface structure is quite perturbed as shown in Figure 19. The rifling is almost entirely removed in the first few inches of the barrel after 1500 to 2100 rounds.

The first cracks in the unplated barrel were observed in a bore surface specimen experiencing 200 rounds of fire. Only a few, shallow cracks were found in the barrels fired less than 900 rounds. The progress of the cracking can be observed in Figure 20. The unplated barrels also exhibited an altered zone - not only in connection with the cracks (Figure 21) but also over the entire bore surface (Figure 22). Again, gross structural alterations are not observed for these barrels. However, some tempering of the steel near the bore surface is evidenced by microhardness surveys - approximately 4 points Rc after 3000

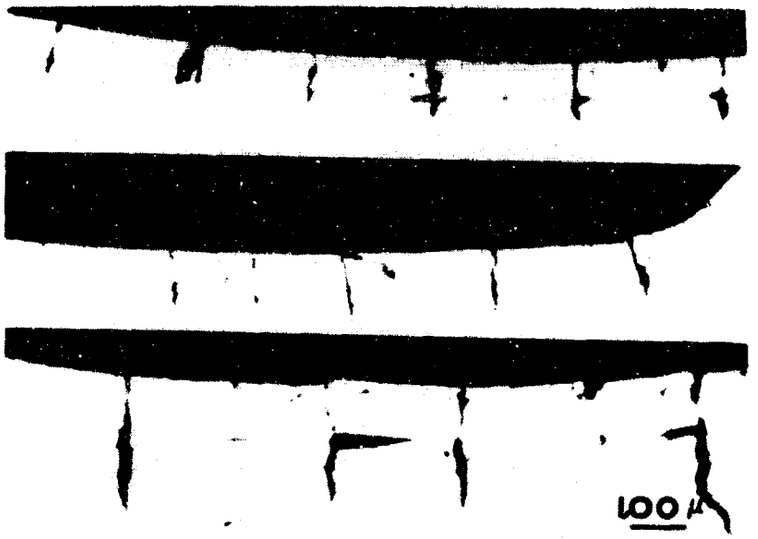

FIGURE 17
Optical Photomicrographs of Transverse Barrel Sections after 900, 1500 and 3000 Rounds.
Unetched.

FIGURE 18
Optical Photomicrograph of Altered Zone Surrounding Cracks after 3000 rounds.
Etched in Nital.

FIGURE 19
Appearance of Bore Surface of Unplated Barrel after 3000 Rounds. Scanning Electron Micrograph.

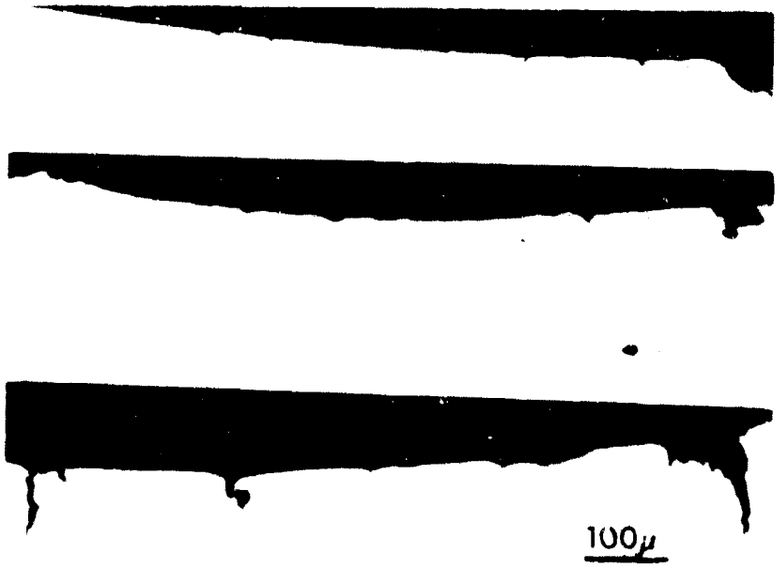

FIGURE 20
Optical Photomicrographs of Transverse Sections of Unplated Gun Barrels after 900, 1500 and 3000 Rounds. Unetched.

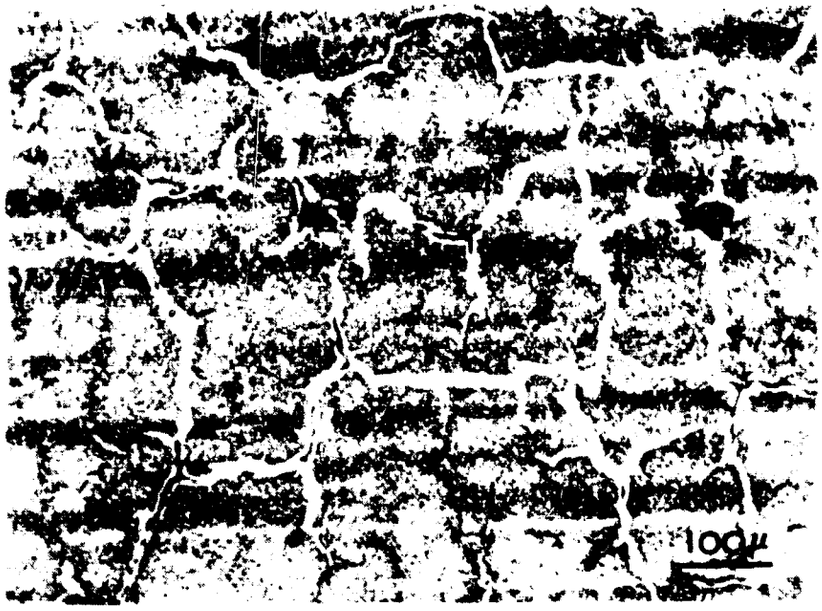

FIGURE 21
Optical Phctomicrograph Showing Crack Network
Beneath the Bore of Unplated Steel after 3000 Rounds.
Etched in Nital.

FIGURE 22
Optical Photomicrograph of Altered Zone
Formed on Bore Surface of Unplated Barrel
after 900 Rounds.

rounds.

No results of the dimensional changes accompanying the test firing were available at the time of this writing. These measurements are to be performed on the silicone replicas of the gun barrel bores.

Discussion

The initial stages of deterioration of the internal bore are traceable to the structure and properties of the chromium plate in the 7.62mm machine gun barrels. Cracks and/or incoherently bonded grains are observed in the plating prior to firing. These cracks open up quite early in the firing sequence, exposing selective areas of the underlying steel to the reactive environment. Reaction pits are formed at the root of the crack at the chromium/steel interface area. Cracks may either propagate further into the steel from these reaction pits or propagate continuously from its origin in the chromium plate. Therefore, the propagation of cracks into the steel substrate is not apparently controlled by the formation of reaction pits.

Altered zones, associated with cracks in the steel, generally remain inert to general etchants used to delineate structures in steel. These zones are thought to be formed in a reaction with the combustion gases. The exact identity of the phases associated with this altered zone is not available at this time. The role of this altered zone in promoting further crack propagation is also undefined. However, it does not appear unreasonable that crack propagation is in part enhanced by this brittle zone formation. Since the cracks are intergranular, preferential formation of the altered zone along grain boundaries is a

possibility.

Copper or brass from the rotating bands is extruded into existing cracks and, therefore, may have a wedging effect in opening the cracks. Liquid copper can rapidly attack Cr-Mo-V steel, and this effect in promoting embrittlement cannot be entirely ignored. Further, since the copper fills up much of the existing cracks, it may have a role as a transfer agent in the chemical attack of the underlying steel.

As the firing progresses, erosion cracks propagate into the steel. Crack branching in the steel is also noted, especially in the region near the chromium/steel interface. When the crack branches link up, fragments of the chromium plate with some bonded steel are detached and removed from the bore. When approximately 3000 rounds are experienced, much of the bore surface near the origin of rifling become devoid of the chromium plate and, consequently, the steel is directly exposed to attack. Additional firing results in further radial propagation of the primary cracks and eventually, unless the gun barrel is retired, the cracks will become supercritical in size and catastrophic failure will result.

The unplated steel barrels experience rapid land wear near the rifling origin early in the firing sequence. Cracks, however, are not observed until after approximately 200 rounds and are not of notable size and number until after 900 rounds of firing. Therefore, the modes of the initial stages of erosion are sufficiently different for the two types of gun barrels. Overall wear or erosion is observed for the unplated steel as contrasted from the localized attack of steel substrate through

cracks in the chromium plate. Although further firing results in noticeable altered surface zones as well as in a well defined network of intergranular cracks, unplated barrels would be retired much earlier than the chromium plated barrels because of reductions in accuracy or projectile velocity due to the early bore enlargement.

Conclusions

Chromium plating on 7.62mm machine gun barrels, designed to enhance erosion resistance, can also contribute to failure mechanisms associated with erosion. Inherent cracks in the chromium plate are propagated early in the firing sequence and expose the underlying steel to the reactive environment as well as to an avenue of continued crack growth. Crack branching, observed as the firing progresses, proceeds beneath the chromium plate until link-up occurs, causing removal of chromium/steel fragments from the bore surface. The advanced stages of erosion are concerned with further penetration of the primary erosion cracks as well as the complete removal of chromium plate near the origin of rifling. An altered zone surrounding most of the cracks suggests that chemical reactions with the combustion gases are primary causes for the deterioration of the underlying steel. However, these findings are quite preliminary and further analysis is in progress.

Unplated steel gun barrels are characterized by over-all wear or erosion early in the firing sequence. Altered zones are also noted but, in general, are found over the entire bore surface layers as well as surrounding some shallow cracks. The unplated

steel barrels will be retired earlier than chromium-plated barrels for accuracy and projectile velocity considerations because of the greater over-all bore enlargement.

1.4 DISCUSSION:

I. Ahmad: How do you explain the presence of calcium carbonate in the products after firing?

M. E. Levy: $CaCO_3$ is used as an ingredient in preparation of ball propellant (serves to overcome any acidic characteristic in nitrocellulose). Previously, content of $CaCO_3$ was approximately 0.6-0.8%. Recent tests in M16 (5.56mm) showed $CaCO_3$ was depositing in gas tube (along with gilding metal) causing stoppages. This was noted with ball propellant of the higher $CaCO_3$ contents (0.6-0.8). Using reduced levels (0.1-0.4%) drastically reduced this deposit. Specifications for ball propellant are now being altered to allow for maximum of 0.25% $CaCO_3$, I believe.

Mrs. D. Taylor (comment): In the UK we had a serious working problem in the chromium plated 3" 70 gun. This was due to the presence of a tin/lead alloy in the round for decoppering causing intercrystalline cracking. When the decoppering agent was removed, cracking ceased.

1.4 DISCUSSION:

W. T. Ebihara: I certainly appreciate the comments of Mrs. Taylor. Since decoppering agents are not used in the particular ammunition employed, liquid metal interactions may not be important considerations. However, more investigation in this area appears necessary before we can dismiss the phenomenon as an unimportant contribution to the deterioration process.

Bill Thielbahr: What burst rate did the 1500 rounds refer to?

W. T. Ebihara: A singular firing rate was used throughout the tests: 4000 rpm per complement or 667 rpm for each individual barrel. The 1500 round schedule comprised of five (5) - 300 round bursts as described in the paper.

COMMENTS ON INTERIOR BALLISTICS AND HEAT TRANSFER IN GUNS

Herman P. Gay
Interior Ballistics Laboratory
U.S. Army Ballistic Research Laboratories

A brief review of the status of Interior Ballistics is given to illustrate the phenomena that take place in the gun as the projectile passes down the bore. An understanding of the dynamics and the thermodynamics of guns, together with a knowledge of the techniques for studying them, should help in establishing discrinating studies of the erosion in guns.

The science of interior ballistics started in about 1740 with Robins' use of a ballistic pendulum to measure the velocity of the shot. The mathematical formulation of interior ballistics began in 1860 with Resal's introduction of the energy equation. From then until after World War II there was a continuous effort to refine the equations and to devise methods of solving them. Cranz[1] gives a good review of the situation in 1926. The development of the piezoelectric pressure gage and the cathode ray oscillograph in the early 1930's opened new possibilities because the details of the pressure-time history could be measured instead of only the maximum pressure and the muzzle velocity. During World War II additional methods were formulated to aid in solving the equations. A, "Comparison of Interior Ballistic Systems"[2] was made by Laidler in 1947. Corner's book, "Theory of the Interior Ballistics of Guns"[3] of 1950 is the most available and complete text. The Engineering Design Handbook, "Interior Ballistics of Guns"[4] gives more detail (especially of U.S. work) in some areas.

To indicate the kind of information that can be obtained from a typical method of calculating the interior ballistics, the equations from Chapter V of Corner are given below:

$$\phi = (1 - f)(1 + \theta f) \tag{1}$$

$$D\frac{df}{dt} = -\beta P \tag{2}$$

$$P\left(\frac{1 + \frac{C}{3W_1}}{1 + \frac{C}{2W_1}}\right)\left[U + Ax - \frac{C(1 - \phi)}{\delta} - C\phi\eta\right] = C\phi RT \tag{3}$$

$$\frac{\phi CR}{\gamma - 1}(T_o - T) = (1 + X)\left(W_1 + \frac{C}{3}\right)\frac{V^2}{2} \tag{4}$$

$$\left(W_1 + \frac{C}{2}\right)\frac{dV}{dt} = AP \tag{5}$$

The initial conditions are:

$$V(0) = 0 = x(0);\ P(0) = P_o,\ \text{the "shot start pressure"}$$

We will be concerned here with the nature of the equations, rather than the technical details. Thus, equation (1) deals with the "layered" burning of the grain; ϕ is the fraction of propellant burned; f, the fraction of web remaining; and θ, the form function, which depends on the geometry of the grain. Equation (2) is the burning rate equation, linear in this particular case; D being the initial web size; β a constant of proportionality for the particular propellant used; P the pressure at the breech. The third equation is the equation of state; the expression in the left parentheses corrects for the pressure gradient between the breech and the projectile; the bracketed quantity is the "volume". The fourth equation is the energy equation: the thermal energy lost by the gas being equal to the kinetic energy of the projectile plus gas; the additional factor of proportionality X, accounts for heat loss to the bore. The last equation (5) is the conservation of momentum; W_1 is an adjusted mass of the projectile to account for some secondary effects such as friction, spin of the projectile, and recoil of the gun. The proper value of W_1 depends on the interior ballistic system being

used. For example in Serebryakov's, "Interior Ballistics"[5] W_1 is taken to be somewhere between 1.05 and 1.10 times the weight of the projectile, depending upon the particular kind of gun.

Figure 1 illustrates the energy distribution in a typical gun. Note that about two-thirds of the energy is in the gas, a little less than a third is in kinetic energy, and the heat loss to the gun is relatively small.

Although it is a secondary effect in interior ballistics, the heating of guns is important because it limits the length of burst in automatic weapons, it can induce "cook-off" of a round in the chamber, and it is intimately related to erosion. Quantitative investigations of the heat transfer were first carried out by St. Robert in 1870 on rifles and on guns by Noble and Abel in 1875. Most of the early experiments used gross calorimetric methods because instruments having good resolution in both time and space were not yet available. Thus, the early mathematical studies of heat transfer led to controversy because they, like interior ballistics, could not be verified in detail. (see Cranz, p. 213). However, heat transfer had the advantage of industrial applications such as steam plants. When the National Defense Research Council undertook the study of gun erosion in World War II, a vast background of theory and experiment on heat transfer had been accumulated. Of the work reviewed in the NDRC Summary Report[6] the report A-87, "Heat Conduction, Gas Flow, and Heat Transfer in Guns", by Hirschfelder, et al[7] gives a good discussion of the fundamental theory.

To illustrate some of the practical problems in studying heat transfer, consider the equation for one dimensional heat conduction:

$$\frac{\partial T}{\partial t} = \alpha \frac{\partial^2 T}{\partial x^2} \text{ , where}$$

T = temperature

t = time

x = distance

α = thermal diffusivity

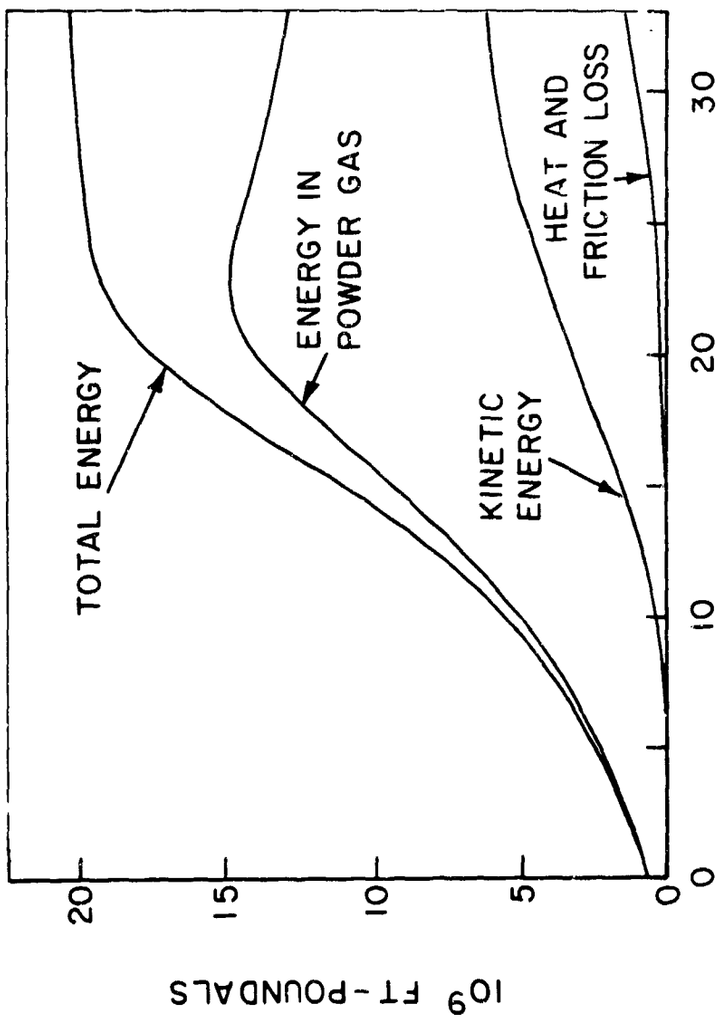

FIGURE 1-DISTRIBUTION OF THE ENERGY IN A GUN
(FROM NDRC RPT. A-201)

The well-known solution when the surface temperature is suddenly changed by T_o is shown in Figure 2. Note that for times pertinent to guns, the temperature gradients near the surface are extremely large; only a few thousandths of an inch make a wide difference in temperature. This must be borne in mind when considering the bore surface temperature. In even the 20mm gun, the grooves are about fifteen thousandths of an inch deep so that there is no ideal mathematical surface. Furthermore, Hobstetter*.points out, "By virtue of its well-established independence of chemical effects, it is to be expected that the thickness of the thermally transformed layer will depend on the severity of thermal conditions along the barrel in which it forms.- - - It was found that the geometry of the projecting lands enhanced the heat transfer so that transformed layers in the lands were thicker and less sensitive to the type of powder than layers in the grooves."

In a gun, the boundary value is:

$$k\frac{dT}{dx} = h(T_g - T_o), \text{ for } x = 0, \text{ and}$$

h = heat transfer coefficient

k = heat conduction coefficient

T_g = temperature of gas

T_o = temperature of wall

From Reynold's analogy for momentum and heat transfer:

$h = \frac{\lambda}{2}\rho C_p V$, where

λ = a friction factor that depends on Reynold's Number and the surface roughness

ρ = density of gas

C_p = specific heat of gas

V = velocity of the gas

*See pages 319 and 320 of reference 6.

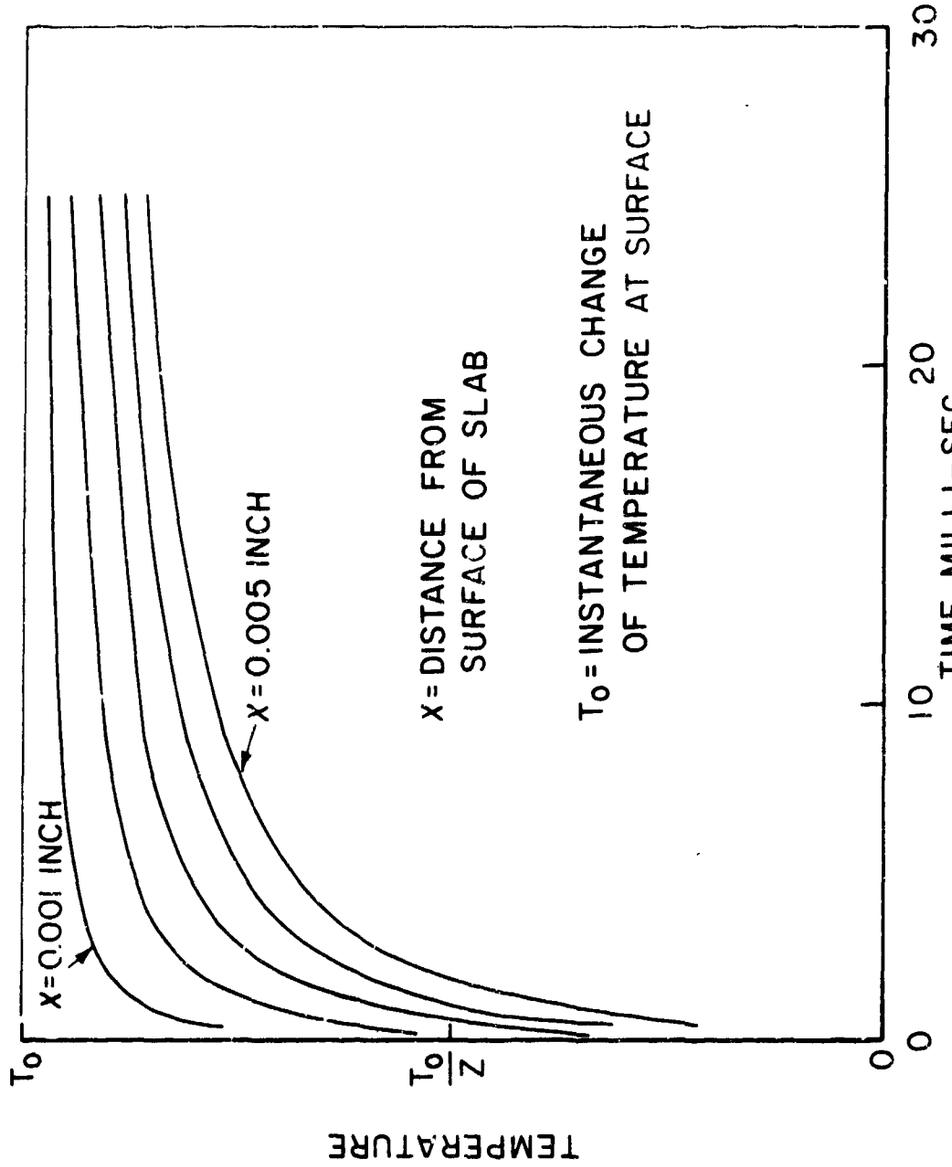

FIGURE 2-TEMPERATURE DISTRIBUTION IN A STEEL SLAB

Now the solution of the heat equation with this boundary value can be done (simply in one direction, with some difficulty in two directions) with present day computers. The problem is to select appropriate values for the parameters such as λ, V and T_g which vary with distance and time. The selection may be made easier by using boundary layer theory such as developed by Hicks and Thornhill*, but - to quote Corner, "It is clear, however, that the heat transfer coefficient as calculated previously has to be increased by a substantial amount to give agreement with measured heat inputs to gun barrels. This increase is about 20 per cent in guns and up to 40 per cent in small arms".

There was little interest or effort to improve the situation of 1950 until the Southeast Asia conflict brought emphasis on conventional weapons. Also, the introduction of high frequency multichannel magnetic tape recorders about five years ago started a revolution in data acquisition. This, together with data processing and display by computers, now makes it possible to carry out extnesive measurements and analysis of quantities that vary with both distance and time. The tools are available; the need for further study of heating was evolved at the Interior Ballistics Laboratory through efforts to calculate the maximum length of burst in guns for helicopters. (Studies by the Weapons Systems Laboratory have shown that the effectiveness of a weapon may be seriously impaired by a limitation on the length of burst). We are now in the preliminary stage of an investigation to establish heat transfer coefficients in terms of the interior ballistic parameters. By a combination and a continuing refinement of theory and experiment the Interior Ballistics Laboratory expects to establish a better

*See pages 410 to 418 of Corner, reference 3.

understanding of the heating of guns. In this work I expect that one of the problems will be to distinguish between the heat supplied by the powder gas and the heat supplied by friction of the rotating band.

There are other aspects of interior ballistics and erosion that require study, as pointed out by Corner and the NDRC Summary Report. A research worker in any of these fields can profit by reading the William R. Murray Lecture of 1967 titled, "Thoughts on the Present and Future Interrelation of Theoretical and Experimental Mechanics", by D. C. Drucker.[8] My interpretation of that lecture may be summarized as: (a) an experiment done without the light of theory is mainly just collecting numbers, (b) the use of computers to solve extensive and complex equations is mainly a numbers game, if done without collateral discerning experiments, and (c) a balance of theory and experiment will increase our understanding of physical phenomena. I hope that you will find the time to read the lecture and a few of the other references too.

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6. National Defense Research Committee, "Hypervelocity Guns and the Control of Gun Erosion," Summary Technical Report of Division 1, NDRC, Vol. 1, (1946).

7. Hirschfelder, J. O., Garten, William, Jr., Hougen, Olaf, "Heat Conduction, Gas Flow and Haat Transfer in Guns," NDRC Report A-87 (Aug 1942).

8. Drucker, Daniel C., "Thoughts on the Present and Future Interrelation of Theoretical and Experimental Mechanics," The William M. Murray Lecture, 1967, Experimental Mechanics, pp 97-106, (Mar 1968).

EROSION OF THE SOVIET 122MM D74 FIELD GUN

Robert J. Thierry
Component Development Section
Watervliet Arsenal
Watervliet, New York 12189

Abstract

A general comparison is presented of the projectile band and rifling design of a Soviet weapon which was captured in Vietnam, with other weapons. This will define a Soviet approach to extend the wear life of this medium velocity weapon (3,000 ft/sec).

The approach will be developed from a discussion of comparative wear factors, band pressure, interference ratio, excess band material, obturator configuration, the general rifling design, and wear data on the weapon.

Introduction

The erosion data and gun projectile design considerations presented were determined from a Soviet 122mm D74 field gun which had been captured in Vietnam. It was presented in response to a suggestion that this data would be of interest to the attendees.

Two prewar Soviet 122mm Howitzers operated at lower velocities and employed more common rifling and band configurations. The 3,000 ft/sec muzzle velocity used by this weapon is in the range of velocities for conventional projectiles wherein the tube wear life is a problem. Wear life for this type of projectile is usually under 1,000 rounds.

General Design Approach

The Soviet design approach was to change projectile band and rifling design from the more usual configuration which was used in previous Soviet 122mm weapons to the design shown in Figure 1.

This design minimized the engraving work done on the band, and the band pressure, and provided for the balance of the required obturation function by the obturator flange. A larger amount of permissible wear was provided by a greater depth of rifling and the proportionately larger obturator diameter which provides for obturation through the life of the gun and allows for a greater diameter for the condemnation limit.

Weapon and Round Erosion Characteristics

It is to be noted that the rifling depth used (Figures 1 & 2) is more than twice that used in the older 122mm weapon. The effective band length has been kept to a minimum consistent with the torque requirements and the band diameter equals the groove diameter. Accordingly, a lesser amount of excess band material will need to be displaced on engraving. The rear obturator is proportionately much larger than conventional design and has no cannelure or groove to accept the deformed flange. Adequate space for the displaced main band material is provided by the spacing of the main double band and the cannelures. They also employed considerable length of forward and rear slopes to minimize fringing. It can also be seen that the forward band runs free for approximately .3 inches before it engages the origin of rifling.

The comparative rifling forms and band characteristics for this weapon and another 122mm Howitzer are illustrated in Figure 2. The principal difference is the factor of 2 increase in rifling depth and the minimum amount of band interference in the D74. The wear factor is moderate for the size and velocity

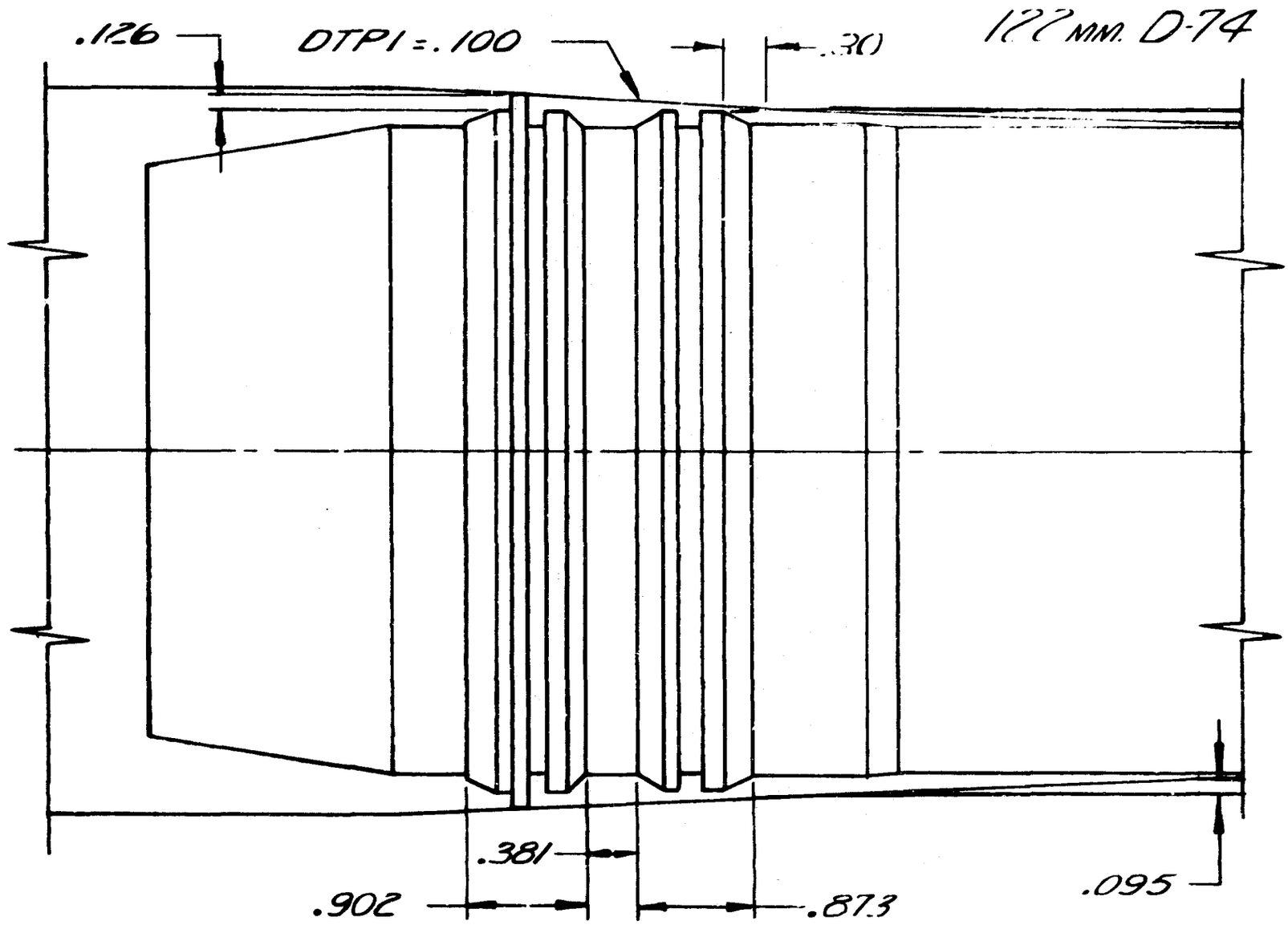
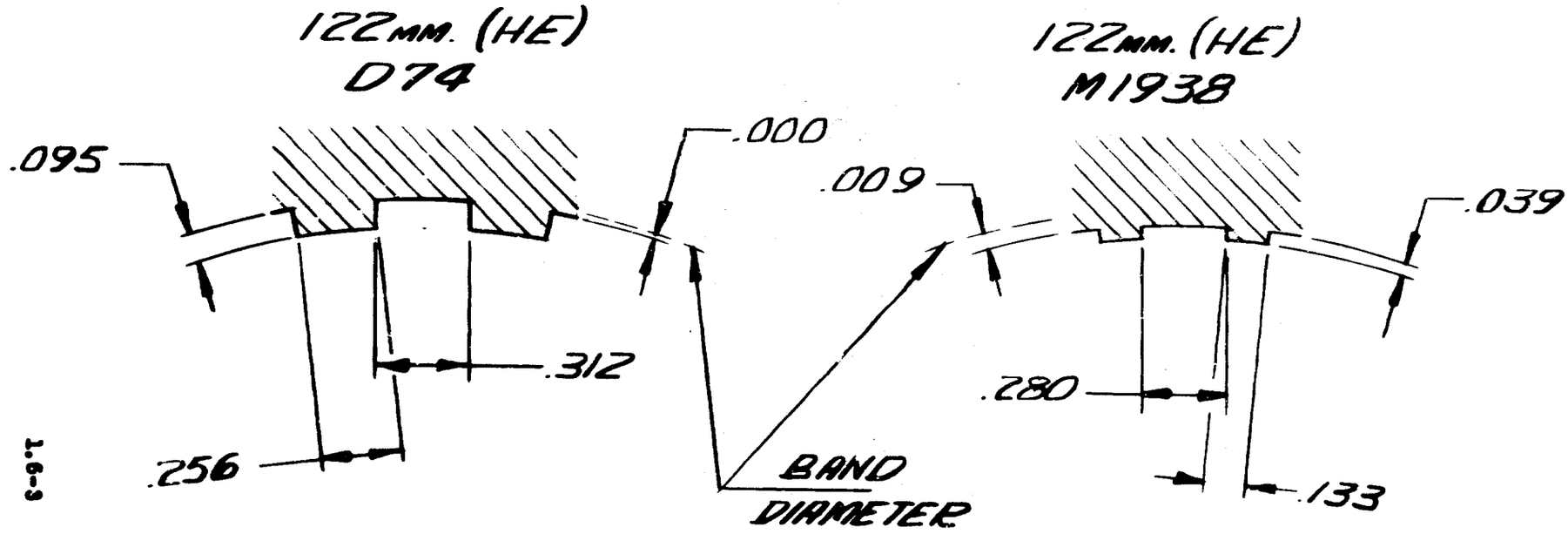


FIGURE 1 - 122 MM. PROJECTILE OF 777



	D74	M1938
FORCING CONE (DTPI)	.100	—
NO. GROOVES	28	36
TWIST $\left(\frac{\text{TURN}}{\text{CALIBER}}\right)$	1:25	1:25
WEAR FACTOR $\left(\frac{\text{FT. LBS}}{\text{IN}^3}\right)$	78,748	84,500
BAND PRESS (P_b/Y)	2.94	2.22
EQUIV BAND LGTH (IN.)	1.07	.568
FINAL BAND LGTH (IN.)	1.94	1.11
INTERFERENCE RATIO	.017	.0098
LAND W. / GROOVE DP.	2.7	3.41

FIGURE 2 - RIFLING FORMS

of the round. Band pressure also is minimized by the band design. The interference ratio is higher because of the considerable groove depth. The small difference in the final and equivalent band lengths illustrates that the design provides a minimum amount of excess band material which must be displaced. These effects contribute toward an optimum wear experience with the gun.

The wear curve (Figure 3) shows the typical wear pattern develcped by this design in comparison with the more usual wear curve encountered in weapons employing standard rifling and bands. The estimated number of rounds used in this tube based upon actual data for comparative weapons is in the vicinity of 90 rounds.

Borescope pictures taken in the vicinity of the origin show moderate heat checking, Figure 4. The tube inspection showed that although wear was evident on the driving face lands throughout the length of the tube, the wear was smooth and does evidence that little gas erosion took place and that the obturator is successful.

Attempts to categorize this weapon for wear characteristics in order that a wear comparison may be made with weapons having known wear is being conducted. The wear capability is estimated thus far as in excess of 1,000 rounds.

Conclusion

The Soviet designers apparently achieved a satisfactory wear life for this weapon without resorting to chrome plating or wear additives. The weapon design emphasizes the need for continual basic research into band and rifling configurations, and materials to insure that progressive updating of the state of the art is realized.

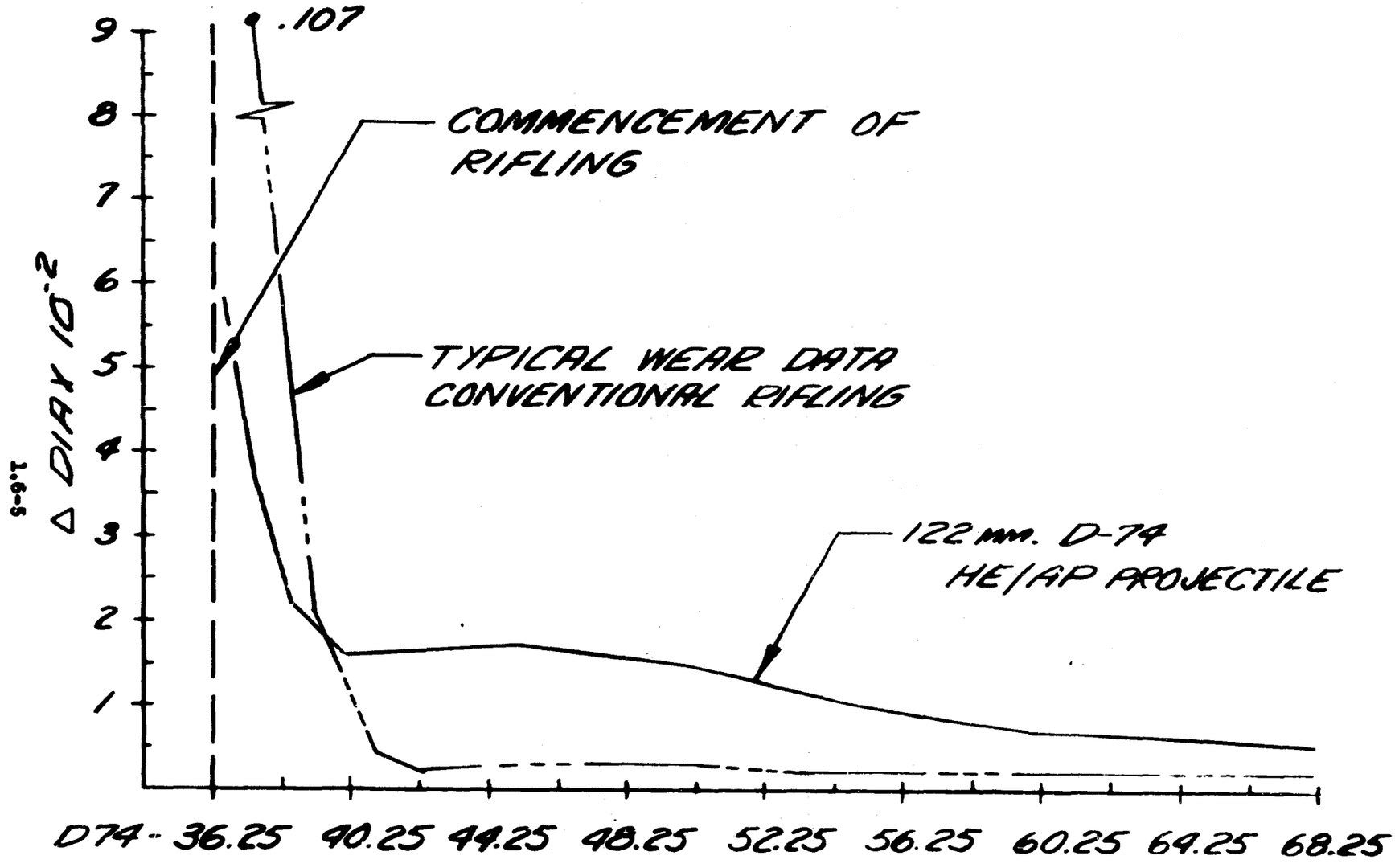


FIGURE 3 - COMPARATIVE WEAR DATA

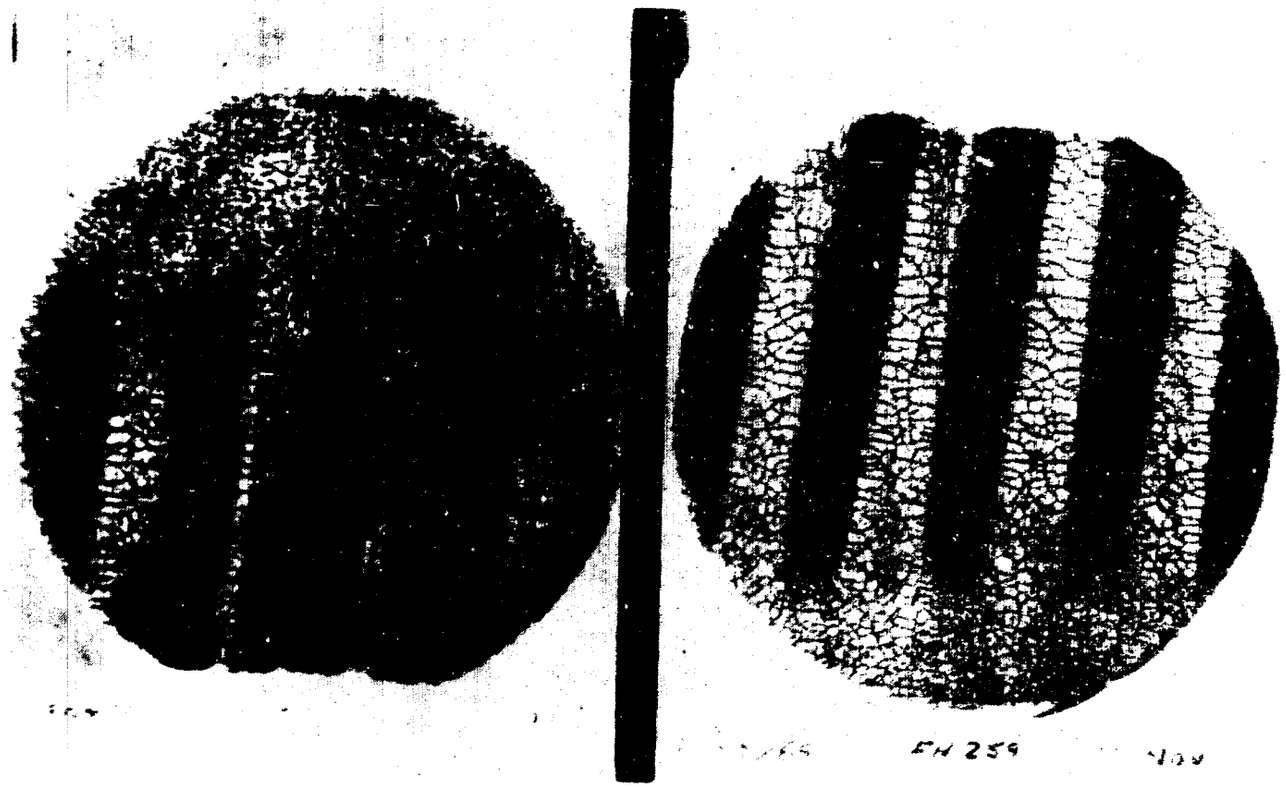


FIGURE 4 - HEAT CHECKS ON 122MM., D14

1.6 DISCUSSION:

H. P. Gay (Comment): It seems that the initial position of the projectile might vary from round to round because of small change in diameter of the obturating ring. This variation in initial volume of the chamber might cause undue variation in muzzle velocity. Are data available on the uniformity of muzzle velocity?

R. Thierry: At this time, it is not available.

SHORT NOTE ON BARREL HEATING REDUCTION BY THE USE OF ABLATIVE AMMUNITION

W. Richard Brown
Cornell Aeronautical Laboratory, Buffalo, New York

Abstract

Recent studies at CAL have shown that silicone fluids and gels placed behind the projectile can be very effective in reducing the heat transferred to barrels from the propellant gases. It is known that a sacrificial coating is formed in the barrel, and the term ablative has been applied to the fluids. Barrel temperature reduction can alleviate problems such as cook-off, stress failure, and binding due to thermal expansion in rapid fire weapons. It is observed that the ablative material is most effective in the origin-of-rifling area, suggesting that erosion may be markedly reduced in guns firing the modified ammunition.

Introduction

A CAL study[1] of heat transfer in the XM140 30mm gun concluded that the barrel would be unable to withstand the heating imposed by a 600 round continuous burst requirement. A review of the literature revealed that silicone fluids, when loaded in capsules and placed behind the projectile, had shown some heat reduction capability. Extensive single-shot testing was done to guide the selection of fluid viscosity and capsule configuration such that the desired "heating profile" could be approached in the XM140 during rapid firing. These experiments and some very recent ones with modified 7.62mm NATO ammunition are outlined very briefly in the following. Details are available in CAL reports [2,3], and it is hoped that a more complete account of the studies can be published in the near future.

Findings - 30mm XM140 Tests

An XM140 barrel was instrumented to measure barrel heating in a single shot. The existing propellant charge was altered such that enough free volume became available in the case to accommodate a sealing diaphragm and up to eight grams of silicone fluid. Initial tests, (Fig. 1), indicated that heat reduction near the breech was greatest with high viscosity fluids. Other tests showed that heat reduction down the barrel was favored by lower viscosity fluids. Tests were done to confirm that the heating reductions measured were due primarily to the fluid and not to the use of a different propellant.

Several thousand rounds containing five grams of fluid in a polymer capsule were tested in rapid firing at Ford Aeronutronic. Temperature comparisons in firing a certain CDC Mission in a CG27 Alloy barrel are shown for ablative and conventional ammunition in Fig. 2. It may be seen that peak temperatures at the six inch barrel stations become critically high near the end of the schedule, but are reduced more than 200°F by the ablative ammunition. In other tests requiring 600 rounds to be fired in a continuous burst, a maximum of 441 round was achieved before stoppage with conventional ammunition, but 597 (the total available at the time) ablative rounds were fired straight out without difficulty.

NATO 7.62mm Tests

Recent preliminary tests of 7.62mm ammunition containing a rubber ablative capsule as shown in Fig. 3 indicate that important

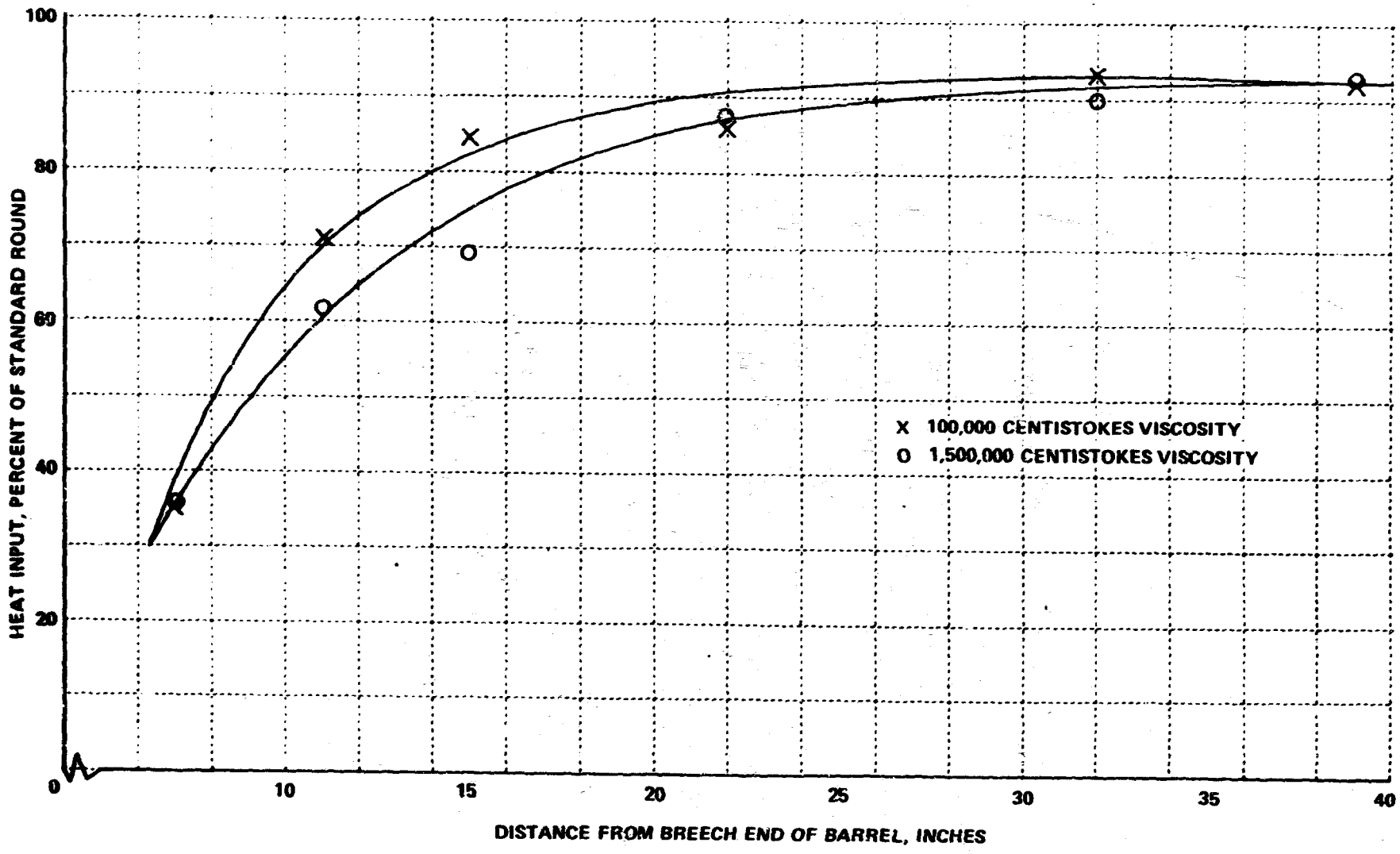


Figure 1 BARREL HEATING REDUCTION WITH ABLATORS

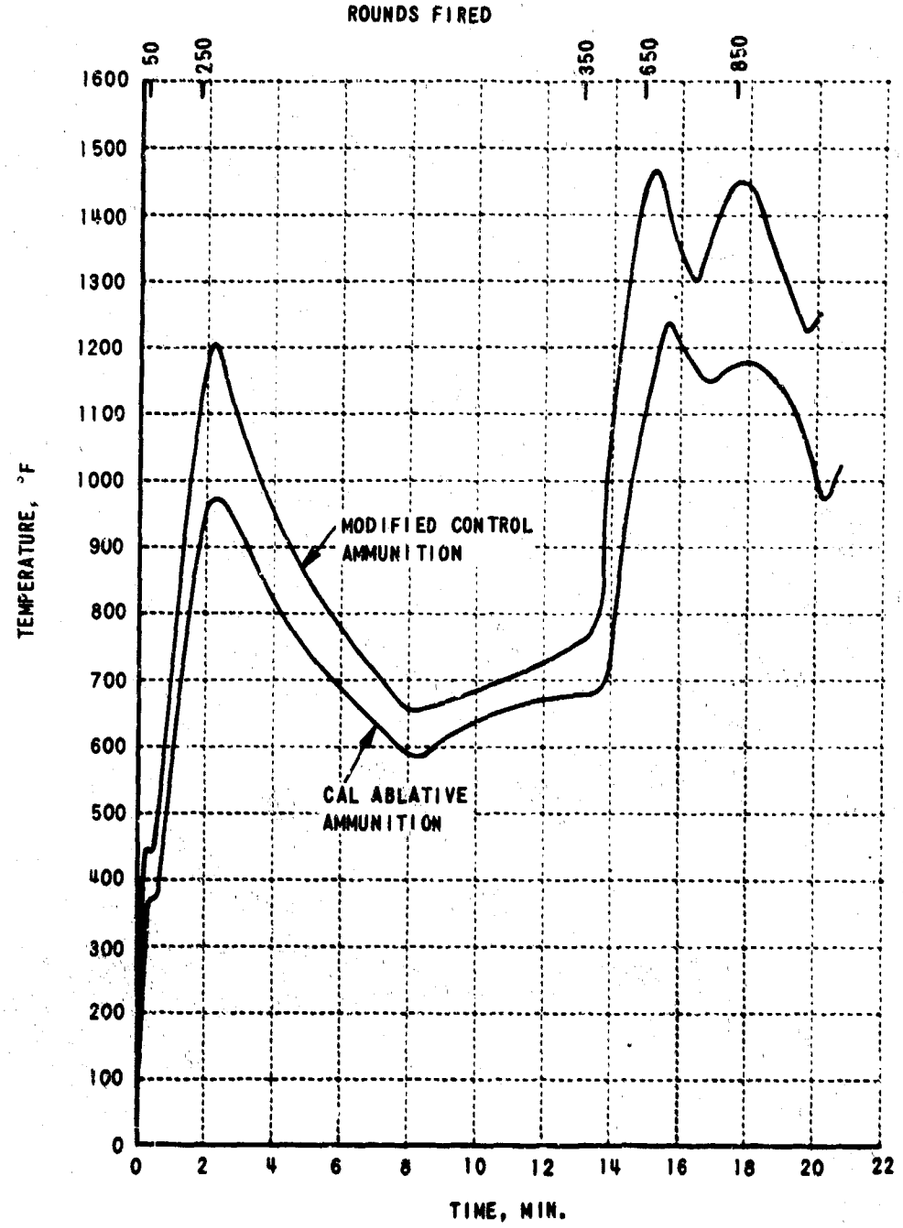


Figure 2 BARREL TEMPERATURE AT 6 IN. FROM BREECH DURING CDC MISSION 1.3.1, CG27 BARREL, O.D. = 1.860 IN.

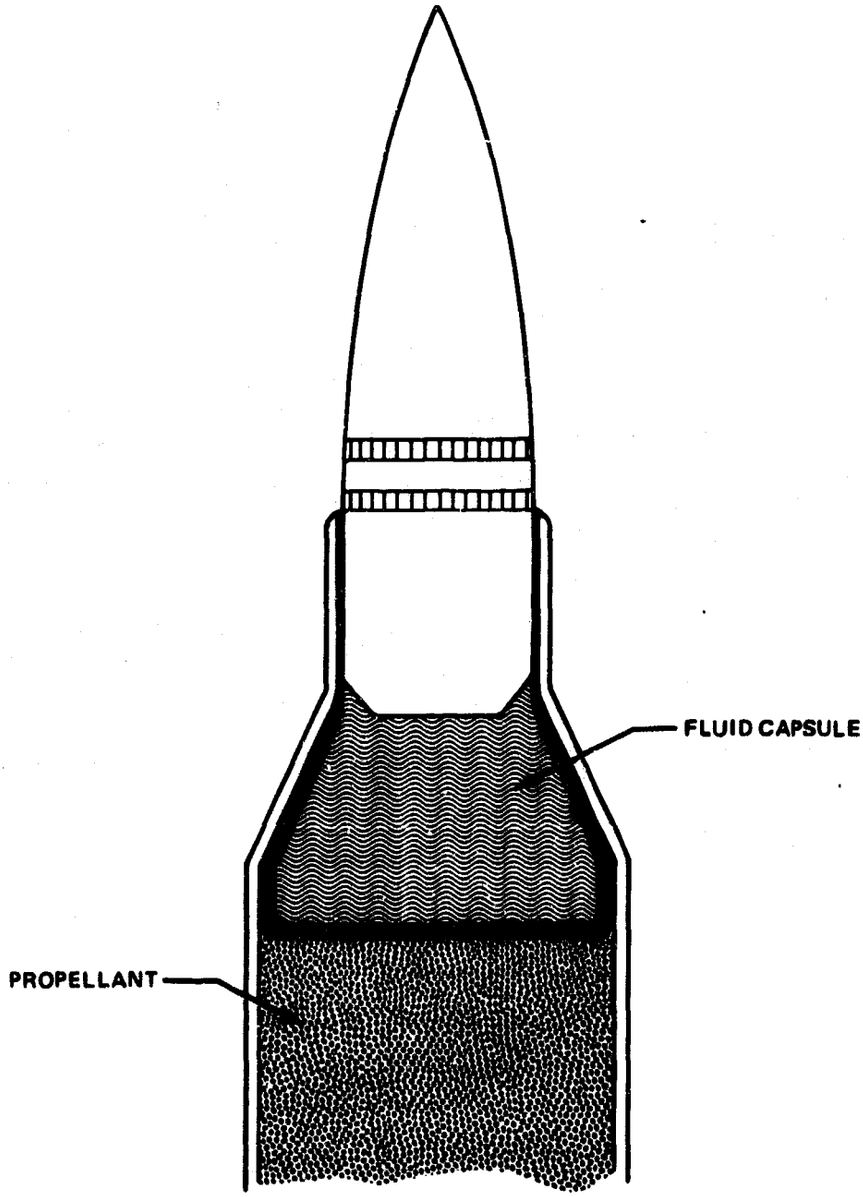


Figure 3 NEOPRENE RUBBER ABLATIVE CAPSULE

heat transfer reductions can be achieved in small calibers. Again it was necessary to alter the propellant charge to accommodate the fluid. A somewhat hotter propellant mixture was employed such that velocity was maintained, with peak pressure increased about 20 percent.

Using 0.5 grams of fluid, temperatures were reduced at all barrel stations, and comparative testing established that the reduction near the breech end was entirely attributable to the ablative fluid. Comparisons were made among the standard NATO ball propellant, the CAL ablative ammunition having a modified propellant charge, and the latter propellant charge with wadding in place of the fluid. Most of the tests were done in instrumented M14 barrels, Fig. 4., which are monolithic and thus are free of heat transfer complications caused by liners and interfaces.

The performance of the experimental ammunition at elevated temperatures was determined by rapidly firing twenty round magazines of conventional ammunition to provide heating, and interspersing three round groups of the type under test. Results are typified by Fig. 5, in which the left-hand ordinate represents measured data in the M14, and the right-hand scales refer to calculations of generalized heat input and predicted heating in the Minigun. The dashed portions of the curves are extrapolated.

There are three important conclusions which can be drawn from Fig. 5. First, the lower heat input per round from ablative ammunition means that many more rounds can be rapid fired before

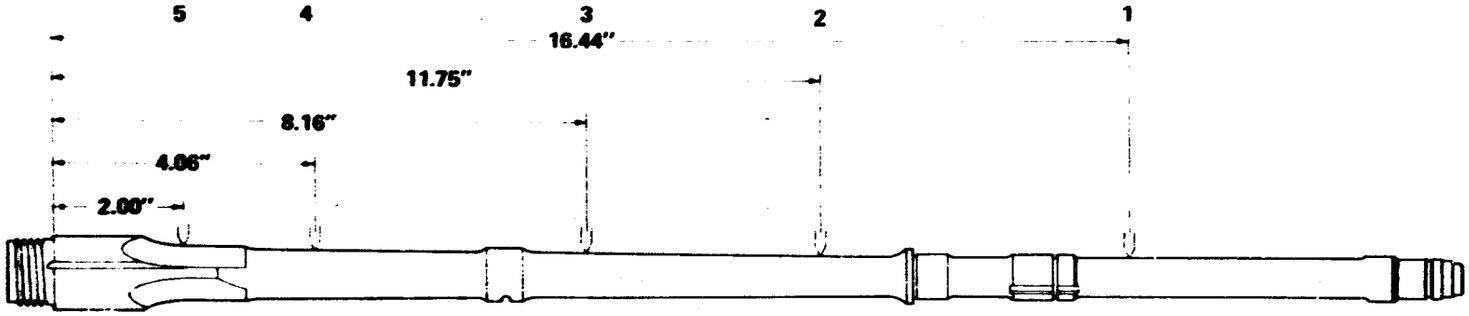


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Figure 4 THERMOCOUPLE - INSTRUMENTED M14 BARREL

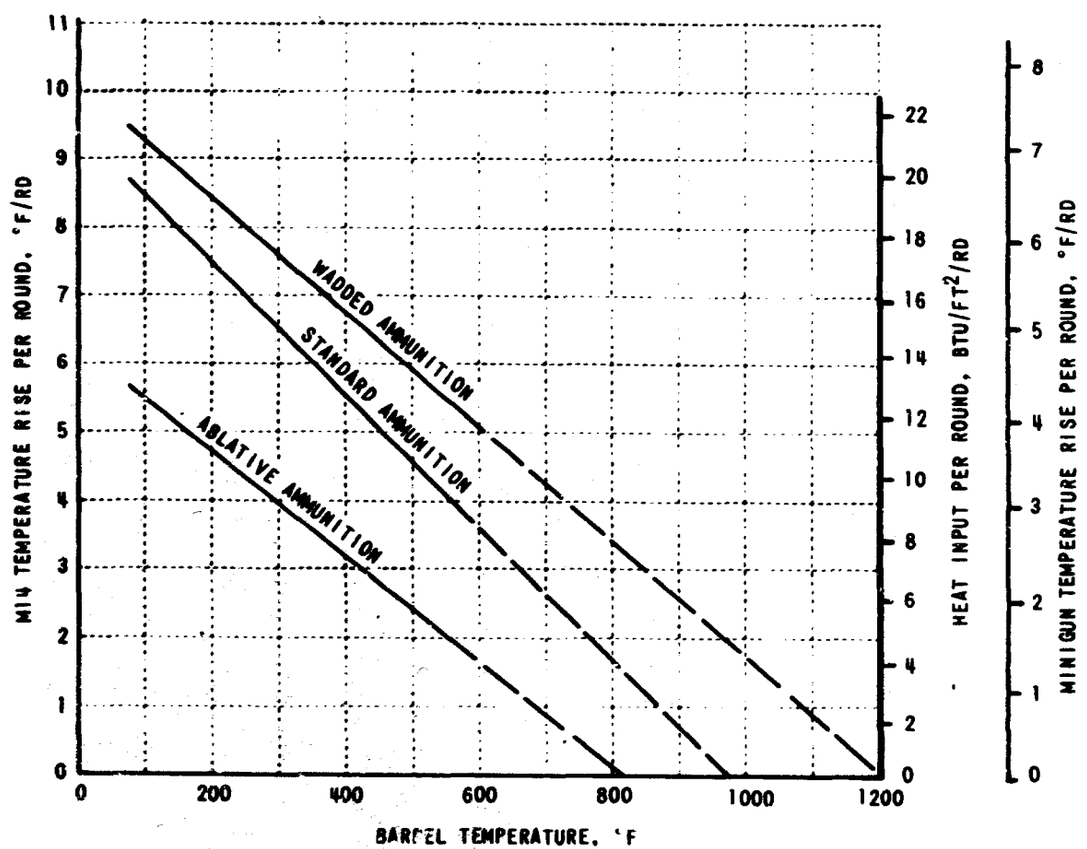

Figure 5 HEATING AT POSITION NO. 5 ON M14 AND MINIGUN BARRELS

reaching a given temperature. Second, the extrapolations to the abscissa represent zero temperature rise, i.e., the equilibrium temperature for each type of ammunition at the barrel station in question. Lowered equilibrium temperatures can have profound effects on barrel life as well as extending effective firing schedules. Third, the curve for wadded ammunition containing the same propellant as the ablative ammunition indicates that the necessity to employ the hotter propellant places the ablative ammunition at a great disadvantage relative to the standard. If space is made available additives can be used with ordinary propellant, the heat reductions secured should be large.

Future Work

Studies of the erosion-reducing effect of ablative additives are planned. Work is underway to replace fluid additives with gelled or thickened materials which would obviate any possibility of leakage.

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2. Adams, D. E.; Brown, W. R.; Sterbutzel, G.A.; and Vassallo, F. A.: "Design Studies of the XM140 Barrel, Volume II," Report No. GA-2446-Z-1, Cornell Aeronautical Laboratory, October 1967.

3. Adams, D. E. and Brown, W. R.: "7.62mm Ablative Ammunition," Report No. GM-2765-Z-1, Cornell Aeronautical Laboratory, January 1970.

1.7 DISCUSSION:

A. Victor Nardi: Did NATO 7.62mm ammunition with additive meet velocity and pressure requirements of system?

W. R. Brown: In the additive modified NATO 7.62mm ammunition, velocity was maintained the same as standard, but to gain volume, quicker propellant was added such that the peak pressure was approximately 61,000 psi instead of 50,000 psi.

"EFFECT OF ROTATING BANDS ON TEMPERATURE OF GUN TUBES"

Reinier Beeuwkes, Jr.

Army Materials and Mechanics Research Center
Watertown, Massachusetts

ABSTRACT

The effect of the rotating band on heating of guns and consequent erosion and failure is briefly discussed, and the measurements on a 37mm gun tube of heating as a function of charge and band diameter are analyzed for gilding metal and wax impregnated powdered iron having a density of five. Although the erosion and wear characteristics associated with these bands are quite different, the total heat input to the barrel does not differ substantially. In each case, there is slightly more heat input on the average with the bands of smaller diameter, although this difference is often exceeded by round-to-round variation.

MANUSCRIPT WAS NOT MADE AVAILABLE

Session II

Chairman: G. L. Warlick
Naval Ordnance Station
Indian Head, Maryland

REVIEW AND TRENDS OF WEAR REDUCING ADDITIVES IN LARGE CALIBER TANK AND ARTILLERY CANNON

Harry Hassmann
Act'g Ch, Propulsion Applications Section
Process Engineering Laboratory
Picatinny Arsenal
Dover, New Jersey 07801

A general review is presented of bore wear reducing additives both in current use and planned for the future. Specific additive applications are described for gun systems ranging from 90mm tank guns through the 175mm artillery cannon. Based on actual experience, particular attention is given to the significant increases in tube life afforded by use of both polyurethane and titanium dioxide - wax additives. Available data is provided showing the promising potential wear reducing capability of the talc-wax additive. Plans to investigate use of talc in lieu of titanium-dioxide in future gun systems are presented.

Background:

1. Gun erosion has long been a problem in many ways. The cost of replacing worn gun tubes is the most obvious factor. Logistic effects include transportation and inventory costs as well as the time to replace tubes, particularly in distant combat areas. Construction, maintenance, and operation of additional gun tube manufacturing facilities is one of the less apparent but very costly results of gun erosion.

2. Ballistic effects can be very serious. With each round fired, erosion increases the gun tube diameter thereby decreasing the muzzle velocity of subsequent firings. This is reflected in reduced range and armor defeating effectiveness of tank ammunition. Accuracy is also impaired.

3. Gun erosion imposes a design handicap in limiting propellant energy levels for high kinetic energy projectiles. For example, in the 105mm round, Armor Piercing Discarding Sabot, M392, the velocity suffers a loss of 50 ft/sec over the tube life. This is the equivalent of a very significant loss in effective range of 500 yards to defeat a given target. The use of the additive has reduced the velocity fall-off to zero. Another example is the current development of the 152mm Kinetic-Energy Round for the Main Battle Tank, which would probably not be feasible without the additive. This is the case in the APFSDS, Projectile, XM578, for the XM150 Gun launcher. Without the additive, successful development of this type of ammunition would not have been possible.

4. The effects of gun erosion can be seen in borescope photographs. As erosion proceeds with successive firings, the pitting and wearing of the rifling lands in the tube are most evident at the commencement of rifling. When this effect interferes with proper engagement of the round's rotating band, accuracy becomes affected.

Case History:

Polyurethane Foam (Laminar Coolant)

1. During the late 1950's, experimental work on the reduction of gun erosion in Canada, the United Kingdom, and the United States was based chiefly on the discovery of a laminar gas layer effect acting along the inside surface of gun tubes during firings. It was found that a cartridge case liner of suitable material could be vaporized at the time of firing, and thereby generate a protective laminar gas layer that would be cooler than the propellant gases. This cooler gas, by remaining close to the tube wall, acts to reduce heat transfer, and thereby erosion from

the hotter propellant gas to the gun tube. Various polymer materials considered and tested as laminar coolants for this liner application included polystyrene, polyvinyl chloride, polyvinyl acetate, polyethylene, and polyurethane. Foamed material was used to obtain high specific surface area. Polyurethane foam was found the most satisfactory laminar coolant.

2. Based upon this concept, the polyurethane foam was initially evaluated in the 105mm Tank Gun M68. (Table I).

3. The system tested consisted of the Armor Piercing, Discarding Sabot, APDS, Projectile M392 using M30 triple base, high-energy propellant. The chamber pressure is 55,000 psi with a muzzle velocity of 4,850 feet per second. As you can see, this is a relatively high pressure, high velocity gun system. The test data from Aberdeen Proving Ground is tabulated as the average bore wear per round (in inches). The chrome plating of the tube gave only limited improvement, while the use of the polyurethane foam coolant provided a significant improvement in the wear rate.

4. The polyurethane foam was applied as an 1/8" thick sheet contoured to the interior surface of the cartridge case immediately behind the projectile. The conclusion of the Aberdeen Proving Ground test was that the polyurethane foam would double the number of the rounds that could be fired from the 105mm M68 Gun before accuracy was lost. Based upon this finding, the liner was incorporated into production ammunition in 1962.

5. Polyurethane foam was evaluated in other tank-ammunition systems. The improvement in wear reduction with the use of a laminar-coolant in other tank rounds is shown in Table II.

TABLE I

POLYURETHANE FOAM - LAMINAR COOLANT

Tube	Additive	Av Bore Wear Per Round (In)
Unplated	None	0.000710
Chrome Plated	None	0.000510
Unplated	Polyurethane	0.000128

Gun - 105mm - M68

Propellant - M30

Chamber Pressure - 55,000 (psi)

Muzzle Velocity - 4,850 (ft/sec)

APDS - M392 Projectile

TABLE II

SUMMARY - ADDITIVE CASF HISTORY - POLYURETHANE FOAM

Caliber	Tank Round	Type	Ballistics		Total Wt Additive (oz)	Wear Life	
			Press (psi)	MV (f/s)		Before (Rds)	After (Rds)
90mm	M318	AP-T	52,000	3000	10	700	1900
120mm	M358	AP-T	54,000	3500	15	300	700

Swedish Additive (Titanium Dioxide/Wax)

1. In 1961, a major breakthrough in gun erosion was achieved with Swedish Additive for U.S. military application. The material is a mixture of titanium dioxide-paraffin wax coated on a rayon cloth. Its nominal composition is shown on Table III. Other materials such as tungsten trioxide-paraffin wax were also evaluated. However, titanium dioxide was chosen on the basis of effectiveness and cost. The use of the additive does not degrade ballistics, storage, or handling characteristics of the rounds tested.

2. The effectiveness of the Swedish Additive in reducing bore erosion in tank ammunition is tabulated in Table IV. A 3-9 fold improvement has been achieved depending on the caliber, type of projectile, and relative ballistics.

3. The weight of additive used and the gun ballistics are also shown. Please note that the improvements shown relate only to bore wear before gun accuracy is lost. It does not consider limitation of gun life because of cannon fatigue considerations. Limitations of life because of cannon fatigue have been discussed in other papers during this conference.

4. In tank ammunition, the location of the additive and how it is inserted into the cartridge case was critical. Again, I use the 105mm M392 APDS round as an example. For maximum effectiveness, the liner is pushed as far forward as possible, and flaps are folded down on the propellant, at the mouth of the cartridge case, before the projectile is assembled. This unique arrangement was required to produce the best results.

TABLE III

SWEDISH ADDITIVE COMPOSITION - NOMINAL

Titanium Dioxide	46.0
Paraffin Wax	53.5
Dacron Staple	0.5
Stearyl Alcohol	(1.0% max)
	100.0

Cloth: Viscose Rayon

TABLE IV

SUMMARY - ADDITIVE CASE HISTORY - TANK AMMUNITION

Caliber	Round	Type	Ballistics		Total Wt Additive (oz)	Wear Life	
			Press (psi)	MV (f/s)		Before (rds)	After (rds)
90mm	M431	HEAT-T	53,000	3950	4.0	240	2100
90mm	M353 M318	TP-T AP-T	52,000	3000	6.0	700	2100
105mm	M456	HEAT-T	58,000	3850	4.5	125	1000
105mm	M392	APDS-T	55,000	4850	8.0	100	10000
120mm	M469	HEAT-T	41,000	3750	17.0	350	1750

Manufacturing of Swedish Additive

1. I would like to give you a brief description of how this wear-reducing additive is produced for the U.S. Army.

2. Additive-coated cloth is manufactured at Indiana Army Ammunition Plant, Charlestown, Indiana. Paraffin wax (melting point 160°F) is melted in a steam-jacketed kettle; the TiO_2 is added and mixed to a putty-like consistency. A recent improvement involves addition of 3/8" dacron fibers (0.5% by weight) to the molten mix, which is then extruded from a hopper onto a moving belt carrying the rayon cloth backing. The cloth passes under a doctor blade which smooths the additive onto the cloth to the desired coating thickness. Temperature control is important to achieve the right additive consistency that will permit ease of coating but without excessive wax penetration of the rather loose-woven cloth. It is desirable to have the coating on only one side of the cloth. The continuous coated cloth is cut to the desired length of liners, which are then individually inspected for adjustment of coated weight.

Use of Wear-Reducing Additives for Artillery Cannon Employing Separate-Loading Ammunition

1. So far I have given you a summary of additive applications in tank ammunition from caliber 90mm to 120mm. The use of Swedish Additive has also proven its effectiveness in large caliber Artillery Systems employing separate-loading, bag-type, propelling charges. Here, the charge is loaded into the gun chamber separately, after the projectile has been rammed by hand or other means. In this ammunition, where there is no cartridge case, the additive cloth must be inserted within the construction of the bag increments or applied as a jacket over an assembled pro-

pelling charge. This was the case for the 175mm Propelling Charge, M86 Series, where the bag charge was already employed in the field, and it was necessary to furnish the wear-reducing jacket as a separate item of issue. The application of the slip-on jacket is shown in Figure 1.

2. The 175mm Gun, which is currently the Army's longest range system, is a high performance system which launches a 148 lb projectile at a muzzle velocity of 3000 ft/sec. To provide the propulsion, a 56 lb charge consisting of single-base propellant (M6) is used. However, even with the low energy, low flame temperature propellant, the wear life of the 175mm System was only 375 maximum charge rounds because of the large quantity of propellant required to achieve the ballistics. With the additive, the wear life of the M113 Series Cannon was increased to 1100 rounds or a 3 fold improvement. Again, I emphasize, this improvement relates only to wear life or loss of projectile accuracy. It does not consider the fatigue aspects of the M113 Series Cannon.

3. The use of wear-reducing additive was evaluated in the 155mm Howitzer System in 1965, where extended range in the M109 SP Howitzer was achieved by using the new propelling charge designated XM119. Here, a high-energy propellant, M30 was required to provide the higher ballistics. Because of the higher charge weight and higher pressure required to launch the standard M107 Projectile to the required range, a wear life of only 700 rounds resulted. Also, the wear condemnation of this cannon, that is, the pullover land diameter, was lowered because of the serious erosiveness of the propellant system. The use of 13.0 oz wear reducing sleeve was inserted within the bag construction and a three-fold improvement in wear was demonstrated, or a cannon life of 2100 rounds.

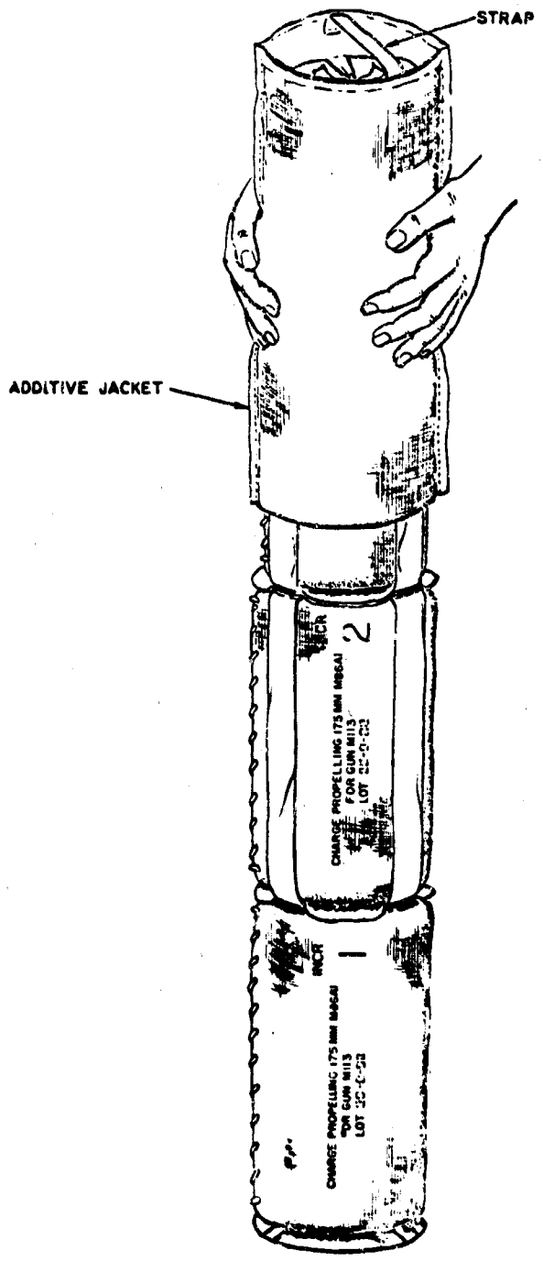


FIGURE 1 - 175mm Propelling Charge with Additive Jacket XM1

4. Not all additive applications have been successful. In 1967, a wear reducing jacket (similar to that used in the 175mm System) was evaluated in the 155mm Gun System, employing the M19 Propelling Charge. This 30 lb propelling charge which uses a low-energy, single base propellant, M6 was being employed in Southeast Asia by the Marine Corps to provide maximum range performance in the M53 Self-Propelled Gun. Because of the long charge length, about 40 inches, the propelling charge has a double wrapping of propellant cloth around the charge increments to provide rigidity during handling and gun loading. Since the M19 Charge was a field item, the jacket application of the additive was the only practical way of applying the wear-additive. The test results showed that no improvement was achieved with titanium-dioxide/wax applied as a jacket. It appeared that the extra layers of cloth prevented the heat-reduction mechanisms to take place, and no reduction in cannon wear was achieved.

Improvement/Changes for Wear-Additives

1. Numerous improvements have been suggested and tested in the composition and manner of application for the additive. The initial additive liner configuration had certain defects. The wax-TiO_2 mixture was brittle and tended to crumble off the cloth with normal handling. The process of coating the cloth and manually inserting it in cartridge cases at first was expected to be quite difficult and costly. Several alternatives were considered.

2. Dry spraying an additive mixture of TiO_2-wax, and polyethylene to the inside wall of the cartridge case was effected by an electrostatic-thermal operation. An adherent coating was obtained, but costs eventually ruled out this method, particularly with regard to production of sprayable

small particles of the homogeneous additive mixture.

3. A wet emulsion application was explored with some success in achieving an adherent coating. Solvent removal would be costly, however, and would weaken the coating's cohesiveness. Moreover, controlling the weight of coating would be difficult.

4. The automatic insertion of cloth liners into cartridge cases was considered to be economically desirable, expecially for smaller caliber systems. A prototype machine was developed for the 105mm rounds, but manual insertion improved sufficiently to render such equipment unnecessary for this relatively large caliber.

5. The wax itself had to be changed over the past years as it became generally recognized that the high temperature limit for design of ammunition systems should be 145°F instead of the 125°F limit that was customary when the additive was first being evaluated. A much higher melting wax resulted in an undesirable rise in ballistic pressure for extreme temperature firings. A ballistically acceptable wax of 160°F melting point was selected but was too soft to withstand propellant abrasion during rough handling at 145°F. As a result propellant grains would become coated with the softened additive, which would interfere with ignition in subsequent firings. A mylar film was sewn over the coating t protect the additive from the bare propellant. In addition, 3/8" dacron fibers have been incorporated in the additive mixture to counteract the tendency of the additive to crumble.

6. Another suggested improvement in the application of additive was to incorporate it directly in the propellant. This has been unsuccessful in both small and large calibers. Either wear reduction was completely

ineffective or ballistic performance was impaired.

Future Trends:

Talc-Wax to Replace Titanium Dioxide-Wax

1. A research program has been underway at Picatinny Arsenal to investigate certain other oxides (or other materials) for effectiveness in the role of wear reducers.

2. The laboratory's research is centered around a group of complex silicates. Evaluations have been made in both a high pressure laboratory device (which simulates the erosive effects encountered in actual gun firing) and also in gun systems. These evaluations will be presented in other papers during this conference.

3. The most promising replacement for TiO_2 is Talc, and in the laboratory it has been shown to be superior. Talc is a complex magnesium silicate hydrate mined in Montana or California. The type used is a mistron-vapor having a particle size of 1/2 micron. Limited gun tests have also demonstrated the superiority of talc over TiO_2 (Table V). As you can see, the superiority varies with the system. For future developments, our intention is to explore the use of talc vs. TiO_2 in early stages of propelling charge development. The use of talc is being considered in two active propelling charge developments. In both the 155mm and 8 Inch Improved Weapon Systems, new separate-loading, bag-type, super charges are being developed to provide extended range performance with Rocket-Assisted Projectiles. For example, the 155mm Propelling Charge, XM123, is being developed for the XM549 RAP to provide the maximum range requirements for the new XM198 Towed Howitzer. Similarly, the 8 Inch Propelling Charge, XM188 will provide maximum range using the XM650 RAP

TABLE V

SUMMARY - GUN FIRING - TITANIUM DIOXIDE VS TALC

System	Wear Rate (in.) TiO_2	Wear Rate (in.) Talc
105mm Gun M68 HEAT M456	0.003/50 Rds	0.001/50 Rds
105mm Gun M68 APDS M392	0.006/50 Rds	0/50 Rds
175mm Gun M113 Prop Charge M86A1	0.050/100 Rds	0.040/100 Rds

in the 8 Inch Self-Propelled Howitzer, M110E2.

4. In both cases, a liner of additive will be inserted within the final charge construction, so that cannon wear life requirements can be met. Both talc-wax and TiO_2-wax liners are being considered.

5. In the development of the 152mm Cartridge, Armor Piercing, Fin-Stabilized, Discarding Sabot, XM579 for the XM150 Gun, talc is being considered to reduce the gun wear characteristics. This effectiveness of this hypervelocity round depends solely on maintaining the high launched velocity and the use of an effective wear-reducer becomes critical to performance and effectiveness.

Summary:

In summary, the wear-reducing additive has shown considerable success for increasing the wear life of tank and artillery cannon, thus reducing the economic and logistic problem of tube replacement. For tank ammunition employing cartridge-cased ammunition, a three to nine fold improvement in the wear characteristics of the cannon has been demonstrated, depending upon the type of ammunition. It also offers a significant advantage to the design of effective Hypervelocity, kinetic energy ammunition for the anti-armor role.

In separate-loading propelling charges for larger caliber artillery cannon, the use of an effective wear reducing additive has been proven and has increased tube life 300 - 400%, based on wear.

SMALL ARMS BARREL EROSION

Marvin E. Levy
James F. Kowalick
Gerald B. Franklin
Frankford Arsenal, Philadelphia, Pa.

ABSTRACT

A review is presented of the results of small arms barrel erosion studies in various calibers. Comparison is made between barrel life obtained with ball propellant and various single and double base extruded types. The effect of the following factors on barrel life are discussed in detail and examples of each are given: chemical nature of the combustion gases, thermochemical properties of the propellant, and barrel-to-barrel variation in a given test.

DISCUSSION

General Review

One of the important performance characteristics required of small arms ammunition is that it yield satisfactory gun barrel life when fired in the automatic weapon for which it was developed. To date, the approach to increase barrel life in small arms has been primarily thermal, i.e., reduction of the propellant flame temperature without adversely affecting ballistic performance. There is, however, a practical limit below which temperature cannot be reduced without encountering problems of ignition or inadequate propellant potential energy in the limited case volume.

The widespread introduction of ball propellant in small arms ammunition, which occurred approximately twenty years ago, was primarily due to the greater barrel life obtained with ammunition assembled with this propellant, rather than the then-current single base extruded propellant counterparts. This improvement was observed in many calibers.

However, improvement was greatest in the larger calibers where increased amounts of endothermic deterrent coating, dibutyl phthalate, were used in the ball propellant formulation to obtain the mass burning rate needed for attainment of velocity/pressure requirements. In these calibers, the isochoric flame temperatures of the ball propellants were substantially less than those of their dinitrotoluene-coated extruded single base counterparts.

Cooler burning extruded propellants were developed through use of more endothermic deterrents; e.g., methyl centralite or ethylene dimethacrylate. These have provided considerably increased barrel life in several small arms calibers, and have made the single base extruded propellant competitive with ball propellant in regard to erosion without sacrifice of other performance characteristics.

Following is a brief synopsis of the main developments in small arms barrel erosion testing over the past fifteen years. Gun barrel erosion tests were conducted in caliber .30, 7.62mm, caliber .50, 20mm, and 30mm. The 7.62mm erosion firings covered several ball propellant types, single base extruded propellants coated with dinitrotoluene, methyl centralite, or ethylene dimethacrylate, as well as double base extruded propellants. Use of tin dioxide, an anti-fouling agent, was shown to offer no increase in erosion life obtained with ball propellant. It had been previously observed that metal fouling in the barrel occurred frequently in firings with ball propellant. This effect masked erosion life by causing a barrel to be disqualified on the basis of inaccuracy before bore wear itself caused the end of service life. It was thought that by reducing fouling, tin dioxide would provide increased gun barrel

life. Caliber .50 erosion tests covered various ball propellants and a wide range of single and double base extruded propellants having different base compositions and deterrents. The powerful effect of propellant flame temperature upon barrel life was demonstrated in these tests. Regardless of composition, propellants having flame temperatures of 2600°K or less yielded substantially longer barrel life than those of 2850°K or greater. Erosion firings in 20mm (mainly the M55-type cartridge for the M39/M61 gun) were conducted with various ball propellants and single base extruded propellants coated with dinitrotoluene or methyl centralite. Similarly, 30mm erosion firings involved the former types as well as double base extruded propellants.

In all the larger caliber firings (caliber .50, 20mm, and 30mm), barrel life obtained with ball propellant exceeded that obtained with the corresponding extruded types. A problem that affects gun barrel erosion firings is non-reproducibility of results. This is due partly, at least, to barrel-to-barrel variation.

As mentioned previously, all the above efforts toward reduced gun barrel erosion were based on reduced propellant flame temperature. It has been demonstrated that gun barrel erosion in artillery could be substantially reduced by the use of wear reducing additives. Studies involving use of the additive talc in small arms ammunition are presently being conducted.

Rather than describe in detail all the results of small arms barrel erosion studies, this paper will attempt to discuss selected studies which shed light on the problem of barrel erosion. These studies have

served to indicate the effect of specific propellant and/or ammunition characteristics, as well as barrel properties, on gun barrel life.

Effect of Chemical Nature of Combustion Gases

In the early stages of the development of combustible cased ammunition for artillery (ca. 1948-1958), considerable work was done on ammonium perchlorate-based compositions. These materials consisted of cotton gauze impregnated with finely divided ammonium perchlorate, a resin binder additive, and a plasticizer. The sheets were then laminated in cylindrical form to yield combustible cases of desired thickness.

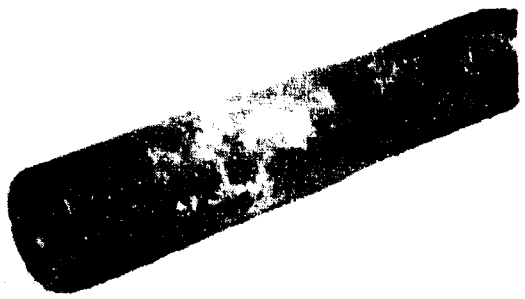
No serious problem was reported in regard to corrosive effect of these cases when tested in the artillery development studies. However, it was believed that the magnitude of the problem would be considerably greater in small arms automatic weapons where the heat developed in the gun is maintained at a very high level for sustained periods. Standard gun propellants are based on the carbon-hydrogen-oxygen-nitrogen system, the product gases of which are non-corrosive. However, combustion of ammonium perchlorate yields substantial quantities of hydrogen chloride which, in the presence of water vapor and sustained high temperature, can cause considerable oxidation (corrosion) of metal surfaces.

Tests were therefore conducted using simulated combustible caliber .50 ammunition. These rounds consisted of sections of the ammonium perchlorate impregnated gauze scrolled about a granular ball propellant charge in a brass case. The ratio of the ball propellant/combustible case charge used in these rounds was 5/1. Ballistic tests, including

automatic firing, were conducted in a caliber .50 M3 machine gun having a stellite lined, chromium plated barrel. A total of 800 rounds were fired automatically with complete cooling after 400 rounds.

The product gases of the simulated combustible cased ammunition caused severe corrosion of the functioning parts (gun steel) of the gun. Photographs illustrating the severity of corrosion are shown in Figure 1. These were taken three days after the test firings during which time the gun was kept in an air-conditioned area. (The color prints presented in the original report describing this study illustrate to a much greater degree the severity of corrosion than do the black and white photographs presented herein.) The appearance is essentially similar to that noted immediately after firing. The degree of rust formation of the gun parts was a function of the proximity of the given part to the combustion gases. Considerable quantities of metallic deposits were also noted in the bore. These were found to contain a large percentage of chromium, indicating removal of the chromium plating in the barrel. The fired gun was cleaned and oiled in the standard manner. However, re-examination of the gun two weeks later revealed signs of rust reappearing through the preservative lubricating oil.

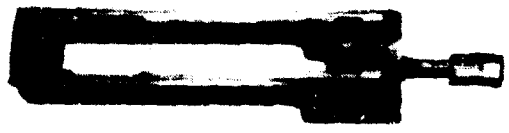
The conclusions to be drawn from this study are obvious; viz, that use of materials yielding corrosive combustion products cannot be tolerated under the severe operating conditions of automatic weapons.



Muzzle Bearing Surface

Side Plate Showing Extractor Switch

Bolt Group - Rear View



Barrel Extension Group

Bolt Group and Driving Spring Rod

Figure 1. Corrosion of Caliber .50 Machine Gun

Effect of Propellant Flame Temperature

An extensive barrel erosion test, conducted in 1956, encompassed caliber .50 M33 ammunition assembled with many different propellant types; viz. ball propellant and a wide range of extruded propellant formulations, including single and double base types as well as novel formulations. The results served to demonstrate the powerful effect of average propellant flame temperature on barrel erosion. The various propellants evaluated are described in Table I. Average flame temperatures were calculated, based on overall propellant formulations. Initial flame temperature represents the calculated isochoric temperature of the deterred layer (i.e., the initial burning portion) of the propellant. Microscopic examination of the propellants permitted determination of the depth of deterrent penetration in the grain. Knowing this, it was possible to calculate the composition and thus the flame temperature of this deterred region.

A firing schedule of 400 round bursts, with complete cooling between bursts was employed. Firings were conducted in lined and chromium plated M3 machine gun barrels. A summary of the results is presented in Table II, including unit throat and muzzle erosion values. These were determined by dividing the total erosion by the number of rounds fired. (It is realized that the assumption of linear erosion rates is inherent in this treatment. However, the fact that the barrels were only stargauged after the end of barrel life necessitated this assumption.)

Table I. Description of Propellants Tested in Caliber .50 Erosion Program

Propellant	Source	% Nitro-glycerin	Additional Matrix Constitutents	Anti-fouling Agent	Deterrent	Flame Temperature (°K) Average	Initial
HES 5333.13	Hercules	20	-	Sn	DBP	2530	1280
HES 5332.21	Hercules	10	-	Sn	DBP	2510	1530
HES 5333.19	Hercules	20	-	Sn	DEP + Vin	2840	1830
HES 5337.3	Hercules	20	-	MoS_2*	DEP + Vin	2840	1870
HES 5343.29	Hercules	20	-	Sn	DBP**	2450	1460
EX 7365	DuPont	-	-	Sn	MC	2520	1950
PAE 15884	Picatinny	10	-	SnO_2	DBP	2590	ND***
PAE 13979	Picatinny	-	CA + DNEB	-	DNT	2340	ND***
IMR 5010	DuPont	-	-	-	DNT	2890	2580
MC 860	Olin	10	-	-	DBP	2560	2180

Code: MoS_2 - Molybdenum disulfide
CA - Cellulose acetate
DNEB - Dinitroethyl benzene
Sn - Tin
SnO_2 - Tin dioxide

DBP - Dibutyl phthalate
DEB - Diethyl phthalate
Vin - Vinsol (trade name)
MC - Methyl centralite
DNT - Dinitrotoluene

* Antifriction agent
** Incorporated and coated
*** Not determined

Table II. Summary of Barrel Erosion Tests

	HES 5333.19			HES 5337.3			IMR 5010	
T, average (°K)	2840			2840			2890	
T, initial (°K)	1830			1870			2580	
No. of rounds	790	790	800	765	678	750	400	400
Throat erosion (in.)	0.006	0.005	0.005	0.004	0.003	0.004	0.011	NM*
Unit throat erosion x 10^4	0.076	0.038	0.038	0.052	0.044	0.053	0.275	-
Muzzle erosion (in.)	0.025+	0.025+	0.025+	0.025+	0.025+	0.023	0.017	NM
Unit muzzle erosion x 10^4	0.316+	0.316+	0.313+	0.327+	0.369+	0.307	0.425	-
Reason for termination	Yaws	Yaws	Yaws	Yaws	Yaws	Yaws	Yaws	Yaws

	HES 5333.13	HES 5343.29		HES 5332.21		WC 860
T, average (°K)	2530	2450		2510		2560
T, initial (°K)	1280	1460		1530		2180
No. of rounds	9200	5500	3600	6000	1600	9970
Throat erosion (in.)	0.009	0.008	0.006	0.007	0.004	NM
Unit throat erosion x 10^4	0.010	0.015	0.017	0.012	0.025	-
Muzzle erosion (in.)	0	0	0	0.004	0	NM
Unit muzzle erosion x 10^4	0	0	0	0.007	0	-
Reason for termination	Ammunition expended	Dispersion	Ammunition expended	Yaws	Yaws (defective barrel)	Bullet through chamber wall

	EX 7365		PAE 15884		PAE 13979	
T, average (°K)	2520		2590		2340	
T, initial (°K)	1950		-		-	
No. of rounds	3950	5200	6300	2800	4000	5200
Throat erosion (in.)	0.011	0.005	NM	0.004	0.007	0.007
Unit throat erosion x 10^4	0.028	0.010		0.014	0.018	0.013
Muzzle erosion (in.)	0	0	NM	0	0	0
Unit muzzle erosion x 10^4	0	0	-	0	0	0
Reason for termination	Yaws	Ammunition expended	Velocity; bullet through barrel wall	Ammunition expended	Yaws	Ammunition expended

*Not measured

It is seen that the barrel life obtained with the different propellants may be divided into two groups regardless of whether single or double base compositions are considered. Thus, propellants having flame temperatures in the range of 2600°K or less yielded relatively long barrel life, and those having average temperatures in the range of 2850°K or greater yielded relatively short barrel life. On the other hand, the initial flame temperature of the different propellant types exhibited no correlation with barrel life. Similarly, unit throat and muzzle erosion values may be divided into two categories by average flame temperatures, but not by initial flame temperatures. This is most pronounced at the muzzle, where no erosion was produced by the cool propellants in almost every case. The presence of antifouling agents in several propellants had no significant effect upon barrel life.

The poor reproducibility in barrel life with some of the cooler propellants points to barrel variations as being significant in these tests. Differences in properties of the barrel would manifest themselves in differences in resistance to wear. As a result, there may have been two effects which determined barrel life in these tests: thermal and barrel material characteristics.

Effect of Barrel Variation

20mm

The problem of barrel-to-barrel variation has also plagued erosion testing of propellants/ammunition in other calibers, e.g., the 20mm M39 gun. In this system, the variation in a given test is generally relatively small with extreme barrel life spreads of approximately 20% with a given

ammunition lot fired in different barrels. Barrel variability has necessitated use of several barrels in a given propellant evaluation test in an attempt to obtain a reliable mean erosion life. However, there have been instances where extremely anomalous results have nevertheless been obtained in barrel erosion testing. An example is seen in Table III.

Table III 20mm Barrel Erosion Tests

Test: M55 Ammunition fired in M39 machine gun

Schedule: 125 Round burst with 30-second cooling between bursts; complete cooling after 250 rounds.

Failure Criteria: Average velocity drop of any 20 consecutive rounds in a burst 6% or greater than velocity of first 20 round burst.

or

Yaw of 15° or more with at least 20% of any consecutive 40 rounds in a burst.

Propellant	Barrel Life Rounds	Failure	Barrel Life Range
Standard WC 870 Ball Propellant	2835	Velocity	2740 to 3625
	3625	Velocity	
	3480	Velocity	
	2740	Velocity	
Experimental Single Base Extruded Propellant	2585	Velocity	2250 to 2750
	2645	Velocity	
	2250	Velocity	
	2750	Velocity	
Experimental Ball Propellant	6250+*	—	1950 to 6250+
	1950	Yaw	
	5000+*	—	

*Test discontinued, barrel still serviceable.

While the first two propellant types gave fairly good uniformity of erosion end points, the results with the experimental ball propellant were quite the opposite. Two barrels (6250+ and 5000+ rounds) were still serviceable when firings were discontinued due to lack of ammunition. These represented the longest barrel life attained in any known M39 erosion testing program. On the other hand, the third barrel was disqualified relatively early due to excessive yaw. Examination of this barrel after firing did not reveal any cause for the early failure. Extremely light erosion of the barrel surface was noted, and was not considered to be a factor in determining the end of barrel life. Neither did there appear to be any significant differences in dimensions of the three barrels, all being regarded as acceptable for the erosion test. Thus the question as to why failure occurred remained unresolved, being attributable only to unknown ammunition/barrel variability.

7.62mm

The effect of barrel variation has also caused considerable problems in barrel erosion testing of 7.62mm ammunition. Variations in barrel life with similar ammunition components have been noted both within a given test as well as over a period of time.

Propellant and cartridge specifications for 7.62mm NATO ammunition include, among others, the following barrel life requirements. "The test cartridges shall not cause the average life per barrel of three barrels to be less than 5000 rounds. The barrel life shall be considered as having ended when the average velocity of an individual burst in the test drops 200 (fps) or more with respect to that of the initial burst

or when the bullets from 20 percent or more of the cartridges in any burst show key-holing which is defined as yaw exceeding 15 degrees at 1000 inch range, whichever occurs first."

During the course of development and engineering tests with a new, single base extruded propellant candidate (IMR 8138M) for 7.62mm, erosion tests were conducted in accordance with the above requirement. Similar tests with this propellant type were also conducted for NATO pre-qualification and qualification evaluations and, later, when a change was made from gilding metal jacketed bullets to gilding metal clad steel jacketed bullets for 7.62mm ball and tracer ammunition.

Tests conducted during the development stage showed that M80 ball ammunition assembled with this propellant easily passed the erosion requirement. However, subsequent tests with production lots indicated a marginal ability to pass, and, on several occasions, the ammunition failed this test. This trend was, at first, ascribed to deterioration in the quality of the propellant produced; i.e., the initial lots were thought to be superior to the production lots that followed.

However, review of the barrel erosion data revealed some very interesting facts. The data from these tests are presented in Figure 2. All firings were conducted in the same type of gun. The same erosion schedule was also used; viz, a 25 round burst every 12 seconds, with a 4 minute cooling period after every 500 rounds; after 5000 rounds (if it has not been disqualified), the barrel is completely cooled and cleaned, and firings are then resumed. Termination of barrel life was based either on velocity loss or excess keyholing. In Figure 2, bullet type is indicated as GM for gilding metal jacket and GMCS for gilding metal clad steel jacket. IMR 8138M propellant lots 1 and 2 are those produced during the development stage.

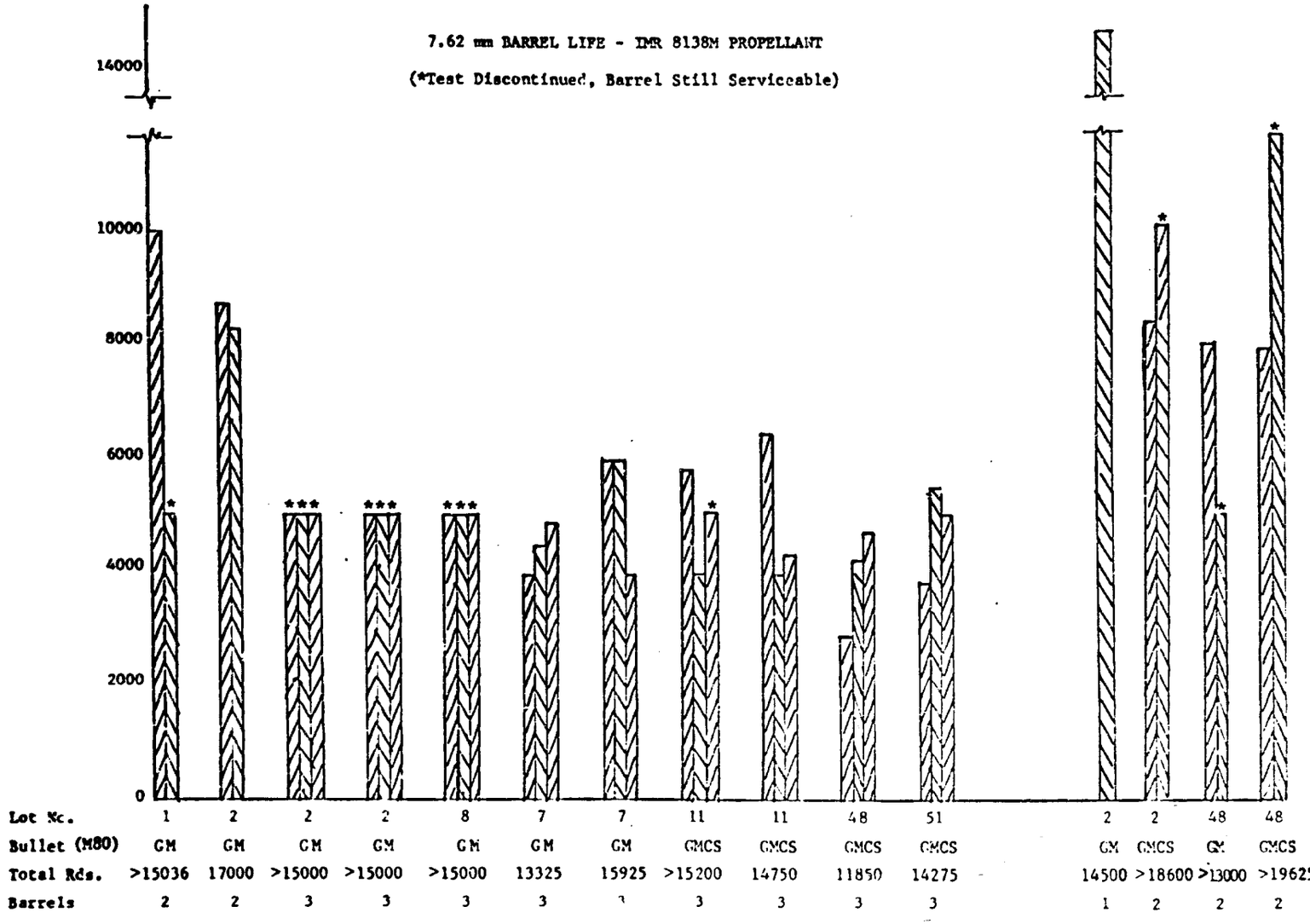


Figure 2. Barrel Erosion Data - First Series of Tests Considered

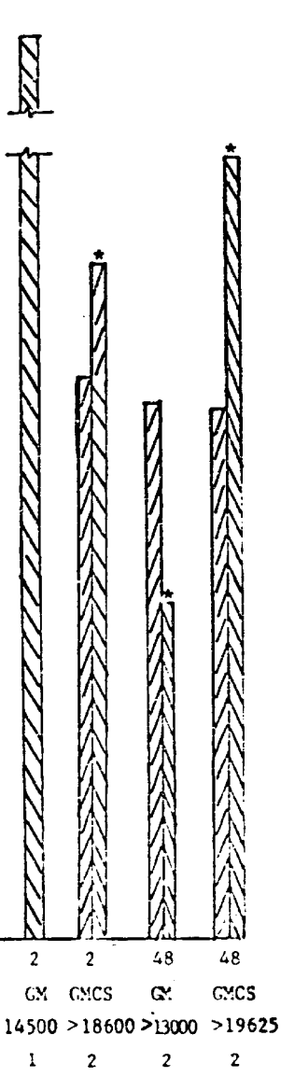


Figure 3. Barrel Erosion Data - Repeat Tests

Higher lot numbers, which generally reflect the order of manufacture, are those made during standard production runs.

Examination of the data reveals the following:

(1) In those tests where barrel disqualification occurred, there was considerable variation in barrel life in any given test. For example, in one test with Lot 11 (GMCS), one barrel yielded erosion life approximately half again as great as that obtained with the other two. Similarly, in one of the tests with Lot 7 (GM), two barrels yielded life half again as great as that obtained with the third barrel.

(2) The fact that duplicate tests with Lot 11 (GMCS) and with Lot 7 (GM) resulted in "pass" in one test and "fail" in the other test is disconcerting. Such occurrences suggest that the determining factor was probably the barrel and not the ammunition.

(3) In most tests where failure occurred, the margin of failure was quite small. Selection of other barrels (which might have yielded longer life) could well have resulted in those ammunition lots passing the erosion test. Barrels are chosen on the basis of conformance to dimensional specifications and thickness of plating. However, the considerable variation in barrel life with a given ammunition lot suggests that there are probably other properties of the barrel which have a significant effect on barrel life.

(4) There was no conclusive information to indicate what effect substitution of a gilding metal clad steel bullet jacket for the gilding metal jacket has on barrel life. However, indications are that the effect, if any, was small.

While chamber pressures are not indicated in Figure 2, there was no discernible effect of this factor on barrel life. This would be expected, in view of the narrow pressure spread among the different ammunition lots.

In view of the anomalies in the data, wherein some propellant lots gave much better life than others (when assembled into ammunition), the properties of the various propellant lots used in the barrel erosion tests were compared. These data are shown in Table IV.

Table IV. Coolant Content of Various IMR 8138M Propellant Lots

	IMR 8138M Lot No.							
	1	2		7	8	11	48	51	Source
EDM	3.60	3.36*	3.36*	3.13		3.35	2.95		Frankford
Total Volatiles	1.46	1.60	1.50	1.56		1.15	1.51		Arsenal Lab
Adiabatic Flame Temp °K		2933	2894	2925		2907	2925		Reports
EDM**				3.33	3.04	3.00	2.91	3.07	Mfrs.
Total Volatiles				1.47	1.46	1.39	1.50	1.57	Description Sheet

*Duplicate tests
**On volatile-free basis

No difference of consequence among the various lots was noted. The concentrations of the coolants, the ethylene dimethacrylate deterrent and the total volatiles, in the various propellant lots (which would affect the flame temperature of the propellant and thus the erosion characteristics) showed no relation to the barrel life values obtained with the different lots.

Thus, it appeared that the main cause of the substantially greater barrel life obtained in the test with IMR 8138M Lots 1 and 2 (and, to a degree, Lot 8) lay with the barrels and not the propellant. It was also

tentatively concluded that what was initially regarded as a change in the "quality" of the propellant (from initial through production lots) resulting, in reduced barrel life with time, may well have been due to a different "quality" of barrels used in the early development tests as compared with those used in subsequent qualification tests of production lots.

This observation was confirmed in subsequent repeat erosion tests with IMR 4138M Lots 2 and 48. The results of these tests are shown in Figure 3. The disparity between these and the earlier tests with identical propellant lots is obvious. Barrel life with Lot 2 (GM) in the repeat test was almost double that previously obtained. The difference was even greater with Lot 48 (GMCS), where more than twice the average barrel life was obtained in the repeat tests. Since similar ammunition components were used in both the initial and repeat tests, the conclusion was obvious; viz, the differences were due to barrel variation. It should also be pointed out that Lot 48 easily passed the erosion requirement in the repeat tests with both the GM and GMCS bullets, after having failed the first test with GMCS bullets. In agreement with the earlier tests, the presence of GM or GMCS jacketed bullets had no discernible effect on barrel life.

It therefore appears that the erosion requirements for 7.62mm propellant acceptance is at best, highly questionable, in that it does not entail a test of the propellant (or ammunition) alone but also includes unknown variations in gun barrel characteristics. Furthermore, the criteria for selection of gun barrels appears inadequate in that it does not

differentiate between "good" barrels which will give long barrel life and "bad" ones which give reduced life.

Thus, while barrel erosion testing of small arms ammunition can indicate gross differences in erosion producing characteristics, the problem of barrel variation serves to mask ammunition differences of a smaller nature.

TALC, A NEW ADDITIVE FOR REDUCING GUN BARREL EROSION

By

JEAN-PAUL PICARD
and
RUSSELL L. TRASK

Propellants Laboratory
Feltman Research Laboratories
Picatinny Arsenal, Dover, N. J.

ABSTRACT

It is entirely feasible to obtain high force, low flame temperature artillery propellants by substituting energetic nitrated plasticizers for nitroglycerin and nitroguanidine. This approach results in homogeneous compositions with excellent mechanical properties, therefore making them readily adaptable to high pressure firings.

High density crystalline materials of the nitramine type are shown to produce small arms propellants with force values upward to 400,000 ft-lbs/lb.

The erosion of gun tubes by the hot propellant gases resulting from the utilization of the high energy ingredients is recognized as a major problem. However, a significant reduction in gun tube erosion was achieved when a titanium dioxide/wax mixture (a Swedish development) was coated on a cloth and lined inside the top portion of the cartridge case around the periphery of the propellant charge.

A laboratory investigation undertaken by Picatinny Arsenal has shown that talc, a complex magnesium silicate, in a wax carrier is significantly more effective than the titanium dioxide/wax mixture for reducing gun barrel erosion.

The successful utilization of talc, in lieu of titanium dioxide in selected rounds of artillery ammunition, is reviewed. The actual gun firings corroborate the laboratory findings that talc would provide increased protection at greatly reduced cost.

The addition of one percent talc in the propellant base grain is effective for reducing the erosion in small arms ammunition where it is impracticable to incorporate talc/wax mixtures.

INTRODUCTION

The propellant engineer has the responsibility to develop new propellants with superior force-flame temperature relationships to standard compositions or formulations with comparable force-flame temperature relationships having superior mechanical properties. An example of this development is in the field of triple-base (nitroguanidine) artillery propellants which are attractive for numerous applications. Their major attributes are: high force values at low temperature, reduced gun barrel erosion and, because of the low percentage of combustibles in the muzzle gases, less tendency to flash.

The standard M17 propellant which belongs to this class has some marked drawbacks such as poor mechanical properties, difficulties of ignition, and questionable ballistic performance. These characteristics were particularly evident during firings conducted in the 90mm and 120mm guns where both rounds were noted to have a velocity dispersion well above two percent. Although these rounds were rated to operate at a maximum pressure of 57,000 psi, higher pressures were observed during low temperature firings (Ref. 1).

These deficiencies were somewhat overcome by the development of the M30 propellant, whose compositions differ from the M17 propellant primarily in the substitution of pyrocellulose (12.6%N) for guncotton (13.15%N) and a slight reduction in nitroguanidine content. The composition and thermochemical properties of these propellants are shown in Table I.

In the U. S. today, the M30 propellant has replaced the M17 propellant in the following rounds of artillery ammunition:

TABLE I

M17 AND M30 PROPELLANTS

Propellant	M17	M30
Composition		
Nitrocellulose	22.0	28.0
(%N in NC)	(13.15)	(12.6)
Nitroglycerin	21.5	22.5
Nitroguanidine	54.7	47.7
Ethyl Centralite	1.5	1.5
Cryolite	0.3	0.3
Graphite (glaze)	0.1	0.1
Total Volatiles	0.3	0.3
Thermochemical Properties		
Isochoric Flame Temp., °K	3017	3040
Force, ft-lbs/lb	364,000	364,500
Relative Force to M17, %	100.0	100.1
Gas Volume, moles/gm	0.04336	0.04308
Unoxidized Carbon, %	3.9	3.2
Combustibles ($CO + H_2$), %	38.7	41.0
Heat of Explosion, cal/gm	962	974
Physical Strength @ 70°F as measured by duPont's Side Impact Test, in-ozs	147	323

Weapon	Round
76mm Gun M32, M48	M340A1E1
90mm Gun M36, M41	M353E1
	M318A1
	M431
105mm Gun M68	M392A1
	M456
105mm Howitzer M103, M137	XM606
120mm Gun M58	M358E2
155mm Howitzer M1, M1A1, M45, M114	M454
155mm Howitzer M126	M107 (Zone 8)

In the early proof firings of the 120mm Delta Gun designed to operate at pressures in excess of 80,000 psi, using the M30 propellant, the gun tube was permanently damaged when a slight increase in charge weight was used to reach a pressure around 70,000 psi (Ref. 2). Because of the constant interest in high pressure weapons and the inherent physical weakness of the compositions containing nitroguanidine, Picatinny Arsenal believed that the approach for continuing the development of cool, high force, high strength propellants was through the formulation of homogeneous rather than filled compositions. Prior studies had shown that the replacement of nitroglycerin with other energetic plasticizers would improve not only the mechanical properties but also the force-flame temperature relationship.

DISCUSSION

Artillery:

The initial study was aimed at the development of a 3000°K flame temperature propellant composition to replace the standard, cool M30 (47.7% nitroguanidine) composition. Since the M30 propellant has a high gas volume due to the presence of the nitroguanidine, it was thought to replace the nitroglycerin by other nitrate esters, which in addition to being energetic would also provide a comparable gas volume.

An examination of Table II and Figure 1 shows that the combination of trimethylolethane trinitrate (TMETN)- triethylene glycol dinitrate (TEGDN) using 13.15% nitrocellulose gave a composition designated as XM35 having a gas volume equivalent to the M30 propellant. It is the capitalization of this gas volume, produced by these various alkyl nitrates, that makes it possible to produce a homogeneous formulation having the same force-flame temperature relationship as the filled M30 propellant. The calculated force of the XM35 was corroborated by the closed bomb relative force value of 102.1%. Furthermore, the new composition has vastly improved mechanical properties when compared to those of M30 formulations. As shown in Table II, a five-fold increase in compression strength can be realized at -40°F.

The importance of the gas volume cannot be overemphasized. For example, referring to Figure 1 it is noted that although the standard propellant M26E1 is 100°K hotter than either the M30 or XM35, it has a lower force. This can be attributed to the lower gas volume.

Knowing that a combination of mixed nitrate esters would give us the desired increase in gas volume, the next program of study was to explore the possibility of formulating propellant compositions with increased impetus to produce increased velocity, in the 3300°K - 3400°K isochoric flame temperature range. This idea was by no means new as in the mid-1950s the same attempt was made with RDX propellants. At that time, the RDX propellants eroded the chromium plated gun so rapidly that the ballistic level of these propellants dropped considerably faster than with the standard M17 propellant. In view of these results, the study with RDX propellants was discontinued (Ref. 3).

This new investigation lead to the development of two propellant compositions in the 3300°K - 3400°K isochoric flame temperature range with force values either comparable or superior to that for any standard propellant known today.

TABLE II

SUGGESTED REPLACEMENT FOR M30

Propellant	M30	XM35
Composition		
Nitrocellulose	28.0	58.5
(%N in NC)	(12.6)	(13.15)
Nitroglycerin	22.5	
Trimethylolethane Trinitrate		25.0
Triethyleneglycol dinitrate		10.0
Diethyleneglycol dinitrate		5.0
Nitroguanidine	47.7	
Ethyl Centralite	1.5	1.5
Cryolite	0.3	0.3 (added)
Graphite (glaze)	0.1	0.1
Total Volatiles	0.3	1.0
Thermochemical Properties		
Isochoric Flame Temperature, °K	3040	3030
Gas Volume, moles/gm	0.04308	0.04339
Force, ft-lbs/lb	364,500	365,700
Relative Force to M30		
Calculated, %	100.0	100.3
*Experimental, %	100.0	102.1
Unoxidized Carbon, %	3.2	3.7
Combustibles ($CO + H_2$),%	41.0	57.6
Heat of Explosion		
Calculated, cal/gm	974	955
Experimental cal/gm	968	976
Experimentally Determined Mechanical Properties		
Maximum Stress @ 145°F, psi	2733	2850
Compression at Max. load @ -40°F,%	8.2	42.3

*Closed Bomb at 0.2 g/cc loading density

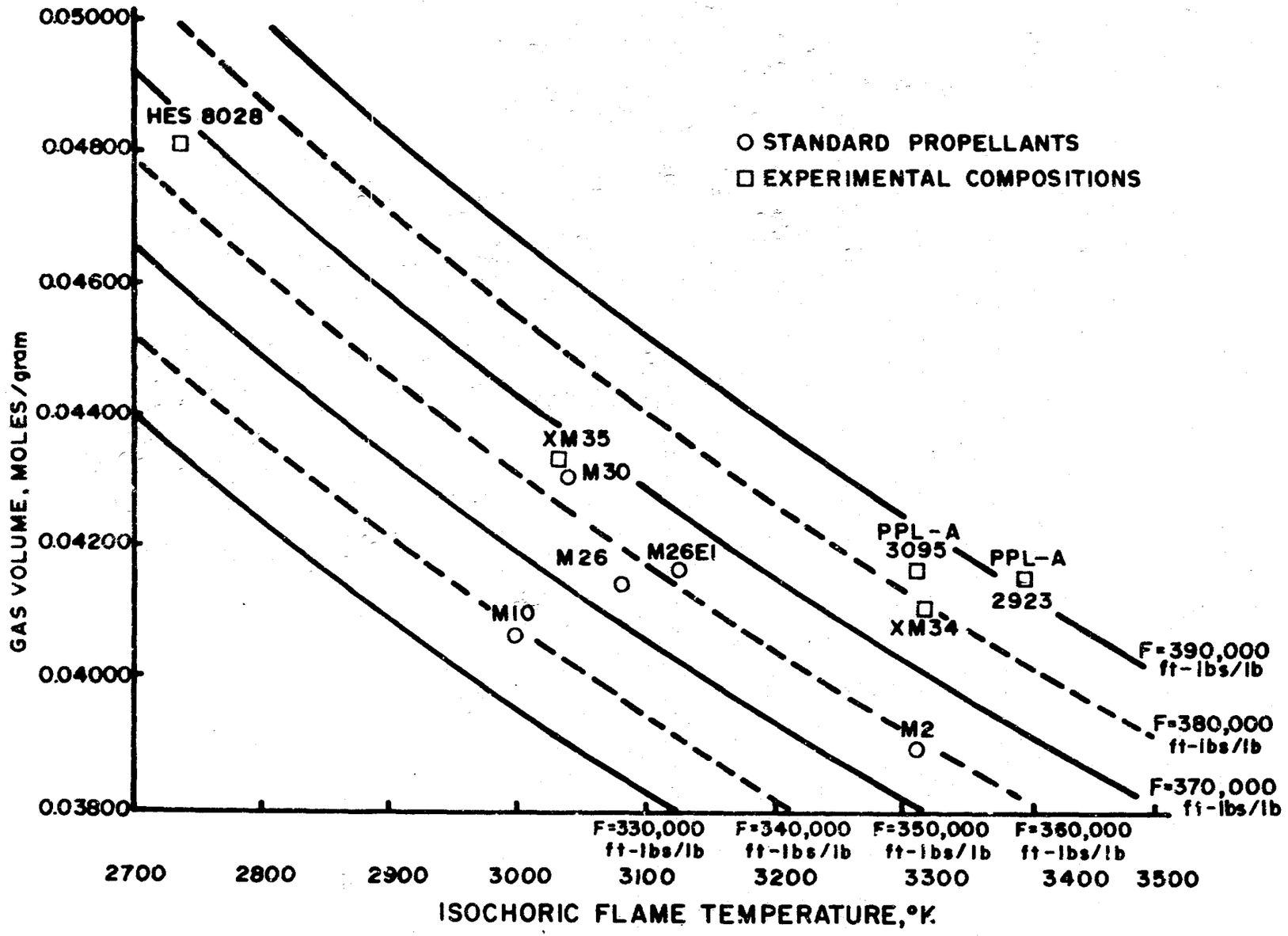


FIGURE 1-GAS VOLUME – FORCE – FLAME TEMPERATURE RELATIONSHIP FOR ARTILLERY PROPELLANTS

Both compositions use a combination of butanetriol trinitrate (BTTN) trimethylolethane trinitrate (TMETN) and triethylene glycol dinitrate (TEGDN) in lieu of nitroglycerin. These are shown in Tables III and IV and graphically in Figure 1. As indicated here, the XM34 can be used as a replacement for M26E1 propellant; its force being 17,400 ft-lb/lb or five percent greater with an increase of only 190°K in flame temperature, while the experimental composition PPL-A-2923 might be suggested as a replacement for either the M8 or M9 propellants in mortar applications. For both formulations, closed bomb and oxygen bomb calorimeter have been utilized to confirm their force and heat of explosion values.

A review of the mechanical properties data, shown in Tables II and IV, indicates that the desired goal of improved physical properties was achieved. In passing, it should be noted that with propellants XM34 and PPL-A-2923, it was found that the optimum TMETN/TEGDN ratio was 5:1 to impart good low temperature ballistic and respectable mechanical properties.

Small Arms:

Very few ingredients have been considered in the area of small arms propellant composition studies. However, the development of new formulations that can be used in small arms applications is within the realm of reality. Several new ingredients, either already available or being synthesized, can be expected to present the propellant engineer with the challenging potential of realizing a greatly improved force-flame temperature relationship. Ingredients to be kept in mind are the high density crystalline materials of the nitramine type which have the additional advantage of a high energy potential. It is anticipated that in the near future such high energy materials as HMX and RDX can be used to produce propellants with force values ranging from 350,000 ft-lbs/lb to nearly 400,000 ft-lbs/lb. The effects of these materials are summarized in Tables V and VI and shown graphically in Figure 2.

TABLE III

SUGGESTED REPLACEMENT FOR M26E1

Propellant	M26E1	XM34
Composition		
Nitrocellulose (13.15%N)	68.7	56.5
Nitroglycerin	25.0	
Butanetriol trinitrate (BTTN)		24.0
Trimethylolethane trinitrate (TMETN)		15.0
Triethyleneglycol dinitrate (TEGDN)		3.0
Ethyl Centralite	6.0	1.5
Graphite	0.3	
Graphite (glaze)	0.1	0.1
Total Volatiles	0.9	0.8
Thermochemical Properties		
Isochoric Flame Temperature, °K	3132	3320
Gas Volume, moles/gm	0.04164	0.04116
Force, ft-lbs/lb	362,800	380,200
Calculated Relative force to M26E1, %	100.0	105.1
Unoxidized Carbon, %	1.6	Zero
Combustibles ($CO + H_2$), %	56.2	50.5
Heat of Explosion		
Calculated, cal/gm	977	1072
Experimental, cal/gm	949	1075
Ballistic Properties		
Closed Bomb at 0.2 g/cc loading density		
Max. Pressure @ 70°F, psi	34,800	36,800
Relative Max. Pressure to M26E1, %	100.0	105.7
Closed Bomb at 0.447 g/cc loading density		
Max. Pressure @ 70°F, psi	109,500	116,200
Relative Max. Pressure to M26E1, %	100.0	106.1
Experimentally determined Mechanical Properties		
Maximum Stress @ 160°F, psi	4390	4595
Compression at Max. Load @ -40°F, %	9.2	43.4

TABLE IV

SUGGESTED REPLACEMENT FOR M8

Propellant	M8	PPL-A-2923
Composition		
Nitrocellulose (13.15%N)	52.15	44.50
Nitroglycerin	43.00	
Butanetriol Trinitrate (BTTN)		24.00
Trimethylolethane trinitrate (TMETN)		25.00
Triethyleneglycol dinitrate (TEGDN)		5.00
Potassium Nitrate	1.25	
Diethyl phthalate	3.00	
Ethyl centralite	0.60	1.50
Graphite (glaze)	0.10	0.10
Total Volatiles	0.40	0.01
Thermochemical Properties		
Isochoric Flame Temperature, °K	3695	3386
Gas Volume, moles/gm	0.03711	0.04149
Force, ft-lbs/lb	381,500	390, 800
Calculated Relative Force to M8, %	100.0	102.3
Unoxidized Carbon, %	Zero	0.50
Combustibles ($CO + H_2$), %	37.2	50.8
Heat of Explosion		
Calculated, cal/gm	1237	1096
Experimental, cal/gm	1234	1092
Ballistic Properties		
Closed Bomb at 0.2 g/cc loading density		
Max. Pressure @ 70°F, psi	36,700	37,500
Relative Max. Pressure to M8, %	100.0	102.2
Experimentally Determined Mechanical Properties		
Maximum Stress @ 160°F, psi	609	3669
Compression at Max. Load @ -40°F, %	40.6	48.9

TABLE V

ADDITION OF HMX TO SMALL ARMS PROPELLANTS

Type Propellant	Extruded (%)		Ball (%)	
	IMR	Mod. IMR	M18	Mod. M18
Composition				
Nitrocellulose (13.15%N)	100.0	85.0	80.0	65.0
Nitroglycerin			10.0	10.0
HMX		15.0		15.0
Dinitrotoluene	8.0(2)	8.0(2)		
Dibutylphthalate			9.0	9.0
Potassium Sulfate	1.0(1)	1.0(1)		
Diphenylamine	0.7(1)	0.7(1)	1.0	1.0
Thermochemical Properties				
Isochoric Flame Temp.,°K	2912	3039	2577	2819
Force,ft-lbs/lb	334,600	350,700	319,000	350,900
Gas Volume, moles/gm	0.04130	0.04148	0.04457	0.04475
Heat of Explosion, cal/gm	891	934	772	820

(1) Added Basis

(2) Coatings

TABLE VI

ADDITION OF HMX AND RDX TO EXTRUDED-TYPE

SMALL ARMS PROPELLANTS

Propellant	IMR 8138M	20% HMX	20% RDX	47% RDX
Composition				
Nitrocellulose (13.15%N)	100.0	49.0	49.0	28.0
Trimethylolethane Trinitrate		25.0	25.0	19.5
Triethyleneglycol Dinitrate		5.0	5.0	3.9
HMX		20.0		
RDX			20.0	47.0
Diphenylamine (Added)	0.7			
Ethyl Centralite		1.0	1.0	0.6
Potassium Sulfate (Added)	1.0			1.0
Ethylenedimethacrylate (coating)	4.0	4.0	4.0	4.0
Thermochemical Properties				
Isochoric Flame Temp., °K	2808	3038	3055	3286
Force, ft-lbs/lb	325,000	371,600	373,700	396,500
Gas Volume, moles/gm	0.04160	0.04397	0.04397	0.04337
Heat of Explosion, cal/gm	890	949	956	1047

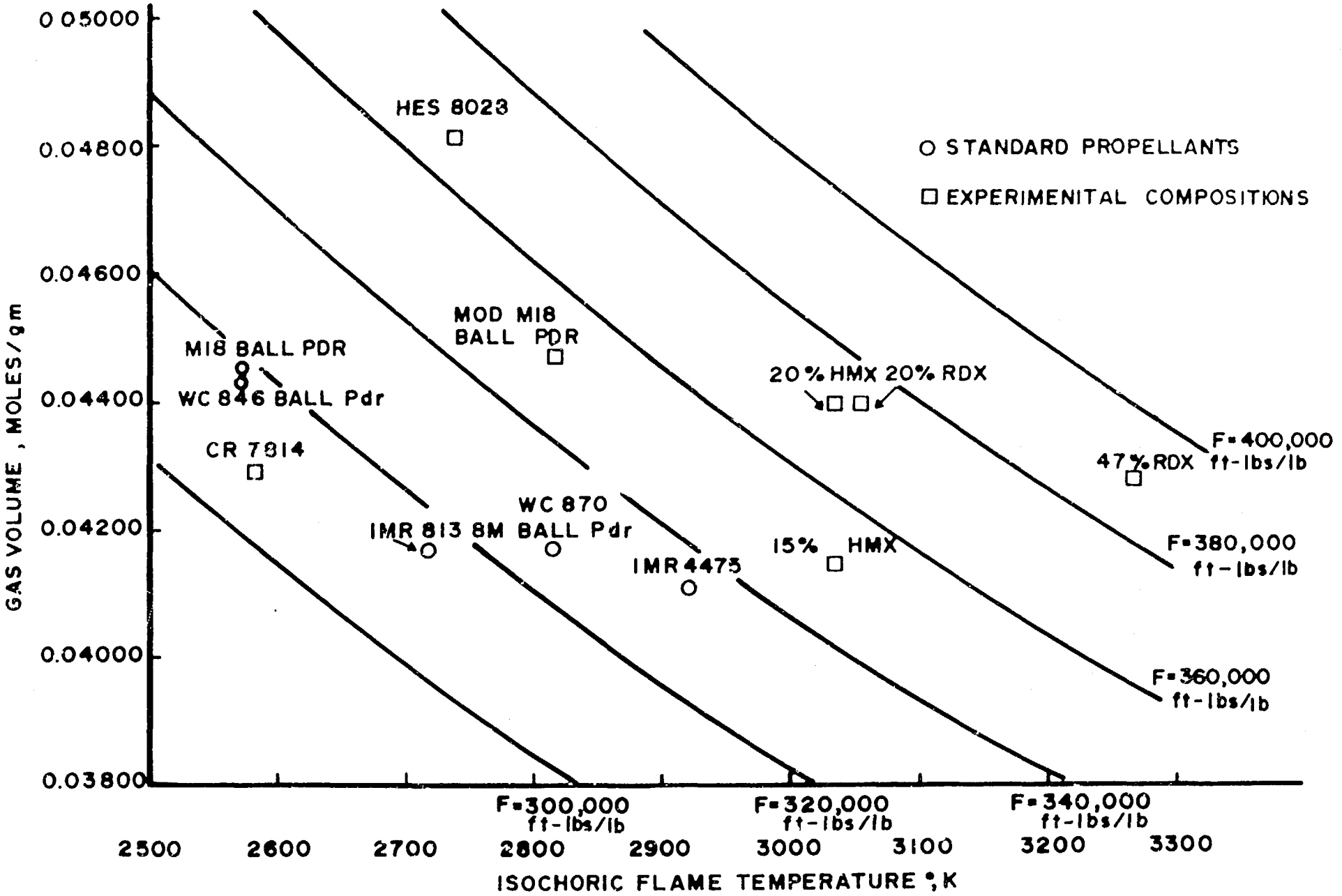


FIGURE 2 — GAS VOLUME-FORCE-FLAME TEMPERATURE RELATIONSHIP FOR SMALL ARMS PROPELLANTS

The search for new binders in small arms propellant technology should not rest on the modification of nitrocellulose. It should be fully understood that the physical limitations imposed by nitrocellulose with respect to cook-off make it desirable, or even mandatory, that other binder materials be considered. At present a study is underway to examine the combination of Hycar rubber-HMX (Propellant HES-8028 in Figure 2) in lieu of the conventional nitrocellulose-nitroglycerin combination. Some of these propellants have been known to withstand 350°F. for a minimum of four hours.

Erosion:

It is realized that the erosion of gun tubes by the hot propellant gases resulting from the utilization of the high energy ingredients reviewed above might be a major problem. However, a significant reduction in erosion was achieved when titanium dioxide (TiO_2) in a wax carrier was coated on a cloth and lined inside the top section of the cartridge case around the periphery of the propellant charge. This wear reducing additive method is basically a Swedish development and was patented in this country by Messrs. Ek and Jacobson (Ref. 4 and 5).

Laboratory Studies:

An extensive development is nearing completion in the Propellants Laboratory relative to gun barrel erosion reducers. A standard 200cc closed bomb was modified for this study by placing an erosion sleeve of gun metal in a barrel segment attached to the bomb's gauge housing (Fig. 3) (Ref. 6). Propellants with or without additives are burned in the bomb. A rubber stopper in lieu of a projectile is accelerated through the erosion sleeve and the barrel as the propellant burns. The propellants, with a single-perforated geometry, are fired at approximately 16,000 psi (the maximum pressure obtainable with this geometry

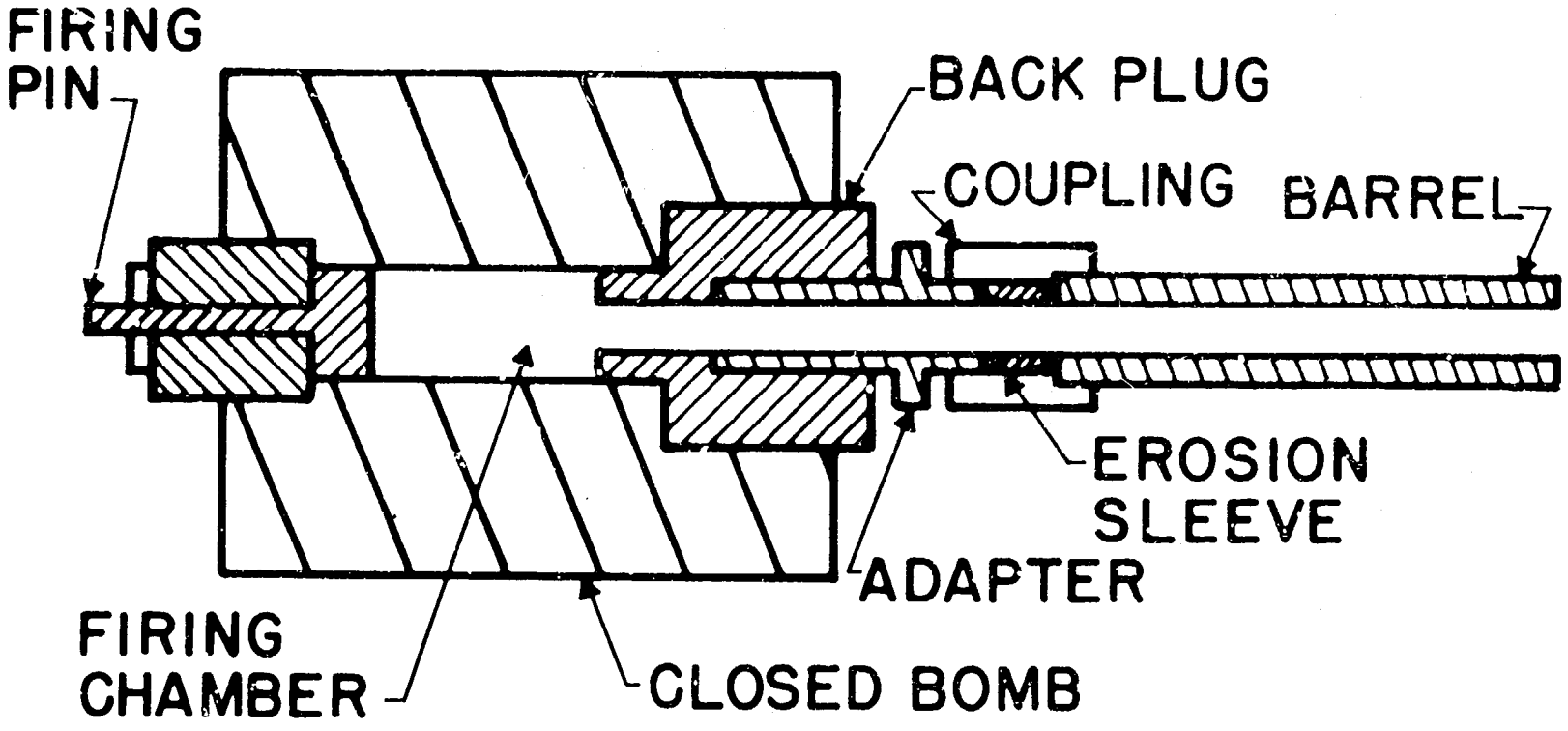


FIGURE 3 - SKETCH OF EROSION APPARATUS

to achieve burnout). The weight loss of the erosion sleeve for each series of firings is a measure of the extent of erosion. All pressures are measured with a strain gauge (not shown in Fig. 3) and recorded with an oscillograph.

This investigation uncovered that a silica-wax system was as good an erosion reducer as the titanium dioxide-wax combination (Ref. 7). Its effectiveness was attributed to the large surface area of the silica particles and its high heat content (Fig. 4). Silica has a heat content of 257 cal/gram as compared to titanium dioxide's value of 210 cal/gram. This finding led to the evaluation of the commercially available metallic silicates kaolin, kaolinite, muscovite mica, feldspar, and talc. The latter is a magnesium silicate whereas the others are all aluminum silicates. Only the talc was significantly more effective than titanium dioxide for reducing gun barrel erosion. It is of interest to note that talc has a heat content value of 282 cal/gram (Fig. 4).

A factorial experiment was designed to study the effectiveness of talc vs. TiO_2. Talcs that differed in particle size were obtained for this study. The TiO_2 had already been standardized as a wear reducing agent. These additives were blended with four commercially available waxes ranging in melting point from 120°F to 180°F. The additive/wax ratios, in turn, were 45/55, 22/78, and 11/89. Five successive firings were made with each sample utilizing M2 propellant (Isochoric Flame Temperature 3320°K) along with the waxes as controls. The results of this experiment are presented in Table VII. It was found that there was a highly significant difference among the waxes as well as between the talcs and the TiO_2. Moreover, the 0.6μ average particle size talc was significantly superior to the 2.6μ talc. The more additive, less wax used in the sample likewise resulted in a significant reduction in the wear of the erosion sleeve.

The insertion of a wear reducing liner in the cartridge case for small arms ammunition would be impracticable because of the high leading density of these

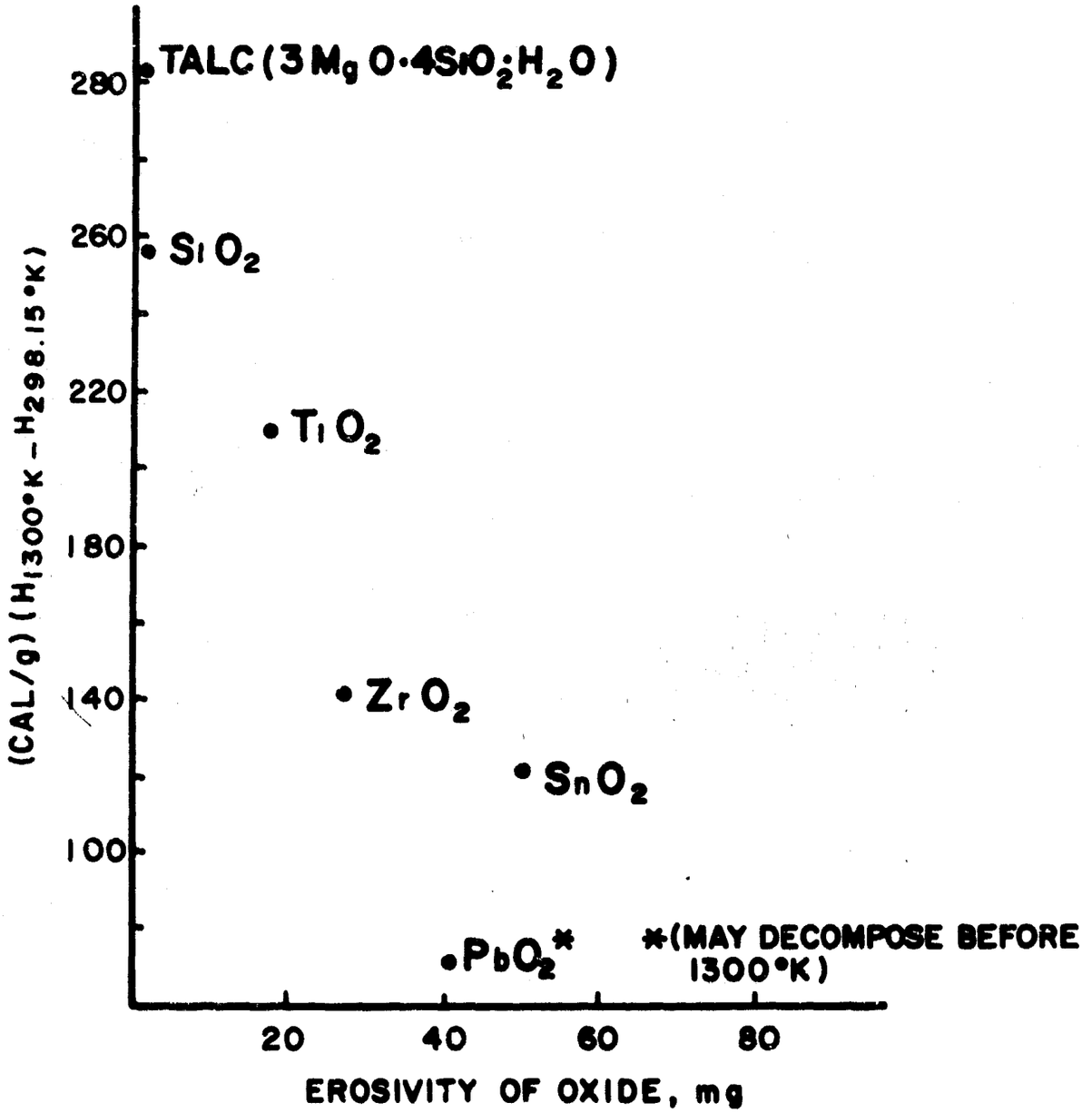


FIGURE 4 HEAT CONTENT vs EROSIVITY

TABLE VII

EROSION STUDY OF TALC VS TITANIUM DIOXIDE IN WAX CARRIER[a]

Additive	0%	Titanium Dioxide 0.6 μ 45%	Titanium Dioxide 0.6 μ 22%	Titanium Dioxide 0.6 μ 11%	Talcs 2.3 μ 45%	Talcs 2.3 μ 22%	Talcs 2.3 μ 11%	Talcs 0.6 μ 75%	Talcs 0.6 μ 22%	Talcs 0.6 μ 11%
Wax Carrier										
120[b]	10.2	5.3	8.6	12.1	1.5	6.7	9.0	3.4	4.9	6.0
140	5.7	4.5	7.6	9.4	5.3	7.2	9.0	4.0	4.8	6.7
160	9.3	4.8	7.5	10.3	5.1	6.5	8.7	3.5	4.7	5.7
180	8.4	5.0	7.6	11.0	3.3	5.3	6.9	1.5	3.2	4.0

NOTES:

a. 30 gm of Propellant, M2 (T_v=3320°K) fired with 4 gm blend of additive/wax carrier consisting of 45 parts additive/55 parts wax, 22 parts additive/78 parts wax and 11 parts additive/89 parts wax, respectively. The erosion is expressed as milligrams wear for five successive shots.

b. Melting point at 1 atmosphere.

rounds and the smallness of the cartridge cases. Consequently, the wear reducing additive, talc, was incorporated in the propellant itself. The data presented in Table VIII shows that the incorporation of two percent talc in the propellant base grain was an effective wear reducing agent for both 7.62mm and 20mm small arms ammunition.

Artillery Weapon Firings:

In order to corroborate the favorable laboratory data for talc, this complex magnesium silicate has been evaluated in three artillery systems to date. The 40mm M385 rapid fire, anti-personnel round is fired from a 14 inch length rifle launcher tube mounted in a helicopter. The ballistics of this round are obtained by firing M2 propellant (Isochoric Flame Temperature 3320°K) in the M169 cartridge case containing a plate pierced by six holes designed to give a peak pressure of 30,000 psi in the cartridge case and only 12,000 psi in the launcher tube (high-low pressure gun). The life of the launcher was approximately 1500 rounds before the hot M2 propellant muzzle gases eroded away the forcing cone and the commencement of rifling. The 40mm M385 round was ballistically tested with 100 mg 2.3μ average particle size talc added in a polyethylene bag to the propelling charge at the base of perforated plate. One launcher tube had over 5,300 40mm M385 rounds fired through it and still had not reached its condemnation limit (Ref. 8).

In the 105mm gun, M68, the 2.3μ average particle size talc/wax mixture (2.3 $\pm$ 0.5% of the propellant charge weight) was coated on a rayon cloth and lined inside the top portion of the cartridge case around the periphery of the propellant charge. No wear occurred in the gun tube from firing 50 rounds each of the HEAT, M456 and APDS M392 projectiles with M30 propellant (Isochoric Flame Temperature 3040°K). Fifty each of these same two rounds with the standardized titanium dioxide/wax liner gave wear values of 3 mils and 4 mils respectively (Table IX) (Ref. 9)

TABLE VIII

EROSION FROM SMALL ARMS PROPELLANTS WITH AND WITHOUT TALC ADDED

	7.62mm Propellant IMR8138M[a]		20mm Propellant CR7814[b]	
	Control	2.1% Talc (0.6μ)	Control	2.1% Talc (0.6μ)
Web, in, SP	0.0139	0.0133	0.0208	0.0227
Measured heat of Expl., cal/gm	896	898	879	808
Relative force at max. pressure, %				
at 70°F	100.0	97.5	100.0	94.4
at -65°F	100.0	97.9	100.0	94.2
Erosion, mg[c]	4.8	0.5	5.0	1.2

NOTES:

a. The calculated thermochemical properties of IMR8138M are:

Isochoric flame temperature, 2810°K.

Force, 324,800 ft-lbs/lb.

b. The calculated thermochemical properties of CR7814 are:

Isochoric flame temperature, 2590°K

Force, 308,800 ft-lbs/lb.

c. 30 grams of propellant fired to give maximum pressure of 16,000 psi.

One hundred rounds were fired in the 175mm Gun M113, with the XM1 additive jacket slipped over the zone 3 bag of the M861E1 propelling charge. This jacket weighed 2.9% ± 0.2% of the M6 propellant charge weight. The rate of wear was 40 mils/100 rounds using an additive jacket containing a 0.6μ average particle size talc/wax mixture. Previous data showed that the average rate of wear was 49 mils/100 rounds when the additive jacket contained a titanium dioxide/wax blend (Table IX) (Ref. 10).

Small Arms Program:

A preliminary evaluation has been completed with both particle size talcs in small arms ammunition. The E. I. duPont de Nemours & Co. manufactured four lots of CR7814 single-base extruded propellant with talc incorporated in the base grain prior to methyl centralite coating. In two of the experimental lots of propellant 0.6μ average particle size talc was incorporated, and in the other two lots 2.3μ average particle size talc was incorporated. It was planned that the experimental propellant would contain 1% and 2% respectively of each type of talc. After manufacture was completed it was found that the two 1% talc lots contained 1.00 ± 0.01% talc; however, the lots that were to contain 2% talc did not contain the requested amount. One lot contained 1.77% 0.6μ average particle size talc and the other lot contained only 1.39% 2.3μ average particle size talc. There was no explanation why the two lots of propellant with high concentrations of talc did not contain the correct amount of talc. These four special propellant lots were loaded at Lake City Army Ammunition Plant into cartridges, 20mm,T.P., M55A2 as well as a control lot of standard WC870 Ball Propellant. The cartridges were loaded to the velocity and pressure requirements of the M55A2 cartridge specification. The Lake City Army Ammunition Plant conducted both the standard Air Force Erosion Test Schedule of a two hundred round burst followed by complete cooling and the continuous

TABLE IX

SUMMARY OF ARTILLERY WEAPON FIRINGS

TITANIUM DIOXIDE VS TALC

Weapon System	Wear Rate	
	Titanium Dioxide	Talc
105mm Gun, M68 HEAT, M456[a]	3 mils/50 rds.	No Wear in 50 rds.
105mm Gun, M68 APDS, M392[a]	4 mils/50 rds.	No wear in 50 rds.
175mm Gun, M113 XM1 Additive Jacket over Zone 3 of Propelling Charge, M86E1[b]	49 mils/100 rds.	40 mils/100 rds.

NOTES:

a. Propellant, M30 (Isochoric Flame Temperature 3040°K)

b. Propellant, M6 (Isochoric Flame Temperature 2570°K)

burst erosion test.

The results of the standard 200 round burst-complete cooling erosion test are presented in Table X. Also reported in this table are the results of the erosion tests fired at Lake City AAP in 1966 with a lot loaded with regular CR7814 propellant and a control lot loaded with the standard WC870 Ball Propellant. The addition of 1.00 $\pm$ 0.01% talc to the base grain of the propellant causes an increase in barrel life, with the 2.3μ average particle size talc giving the larger increase (approximately 29%) in barrel life. The addition of more than 1% talc to the base grain of the propellant causes not only a decrease in the barrel life, but also causes a large increase in the extreme variation of the disqualification points of the barrels in the standard erosion test.

The results of the continuous burst erosion test are tabulated in Table XI. The propellant lot containing the 1.01% 2.3μ average particle size talc again gave the longest barrel life of all lots evaluated, as in the standard erosion test, but in the case of the continuous-burst test, the barrel life was much longer than all others tested. The average barrel life of three barrels tested with the ammunition loaded with the standard WC870 Ball Propellant was 324 rounds, while the average barrel life for two barrels of the ammunitions loaded with CR7814 plus 1.01% 2.3μ average particle size talc was 721 rounds. In the continuous burst erosion test the CR7814 propellant containing 1.39% 2.3μ average particle size talc gave about the same barrel life as the standard WC870 Ball Propellant and the CR7814 propellant itself (no talc added).

From the foregoing small arms discussion, it can be concluded that the possibility exists that the incorporation of less than one percent talc in the propellant base grain may give a greater increase in gun barrel life than the incorporation of one percent talc. Therefore, it is planned to manufacture two

TABLE X

STANDARD AIR FORCE EROSION TEST RESULTS FOR CARTRIDGE, T. P., 20MM M55A2

(200 round burst then complete cooling)

Propellant	Individual Barrel Disqualification Point (Rds Fired)	Reason for Disqualification	Average Disqualification Point (Rds Fired)
Standard	2200	Velocity Drop	
WC870 Ball	2143 Ex. Var. 400	Velocity Drop	2048
(Fired in '66)	1800	Velocity Drop	
CR7814	2600	Velocity Drop	
(Fired in '66)	1737 Ex. Var. 863	Excessive Yaw	2112
	2000	Velocity Drop	
Standard	2020	Velocity Drop	
WC870 Ball	2620 Ex. Var. 600	Velocity Drop	2287
	2220	Velocity Drop	
CR7814 +	2962	Excessive Yaw	
0.99% 0.6μ	2347 Ex. Var. 615	Excessive Yaw	2569
APS Talc	2399	Excessive Yaw	
CR7814 +	2983	Excessive Yaw	
1.77% 0.6 μ	1192 Ex. Var. 1807	Excessive Yaw	1784
APS Talc	1176		
CR7814 +	2792	Excessive Yaw	
1.01% 2.3 μ	2987 Ex. Var. 587	Excessive Yaw	2726
APS Talc	2400	Excessive Yaw	
CR7814 +	1980	Excessive Yaw	
1.39% 2.3 μ	775	Excessive Yaw	
APS Talc	2400 Ex. Var. 1625	Excessive Yaw	1710
	2000	Excessive Yaw	
	1303	Excessive Yaw	
	1801	Excessive Yaw	

TABLE XI

SPECIAL CONTINUOUS BURST EROSION TEST RESULTS

WITH CARTRIDGE, T. P., 20MM M55A2

(Excessive Yaw the Reason for Disqualification)

Propellant	Individual Barrel Disqualification Point		Average Disqualification Point
	Rounds Fired	Extreme Variation	Rounds Fired
Standard WC870 Ball	358 327 287	71	324
CR7814	312 328 368	56	336
CR7814 + 0.99% 0.6μ APS Talc	649 362 400	287	470
CR7814 + 1.77% 0.6μ APS Talc	343 346 349	6	346
CR7814 + 1.01% 2.3μ APS Talc	741 700	41	721
CR7814 + 1.39% 2.3μ APS Talc	355	-	355

additional lots of CR7814 propellant containing talc. These propellant lots are to contain 0.5% and 0.75% 2.3μ average particle size talc, respectively. Also, a regular lot of CR7814 propellant will be manufactured at the same time for control purposes. These three lots of CR7814 type propellant, together with a standard WC870 Ball Propellant control lot, will be tested in Calendar Year 1970, in Cartridge, T. P., 20mm M55A2.

CONCLUSIONS ON EROSION

Talc should be considered as a replacement for titanium dioxide in all standardized artillery weapon systems and evaluated exclusively in newer ammunition systems now under development.

The incorporation of approximately 1.0% talc in the propellant base grain improves the barrel life for 20mm ammunition.

The possibility exists that the incorporation of less than 1% talc may give a greater increase in gun barrel life than the incorporation of 1% talc.

The incorporation of approximately 1% talc causes a greater increase in barrel life in the continuous burst erosion test than the standard erosion tests. Therefore, the incorporation of talc may have more advantages in gun systems that use long continuous burst.

U. S. Patents Serial Nos: 3,392,669 and 3,392,670 covering the foregoing presentation were issued on 16 July 1968 (Refs. 11 and 12).

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2.3 DISCUSSION:

Douglas E. Ayer: How do you explain the real significance of the small arms wear reducing data as being a function of talc content in the base grain when in fact the deterrent level also varied?

Russell L.Trask: It was not always possible to maintain a constant deterrent level on the small arms propellant lots made on a small scale in the laboratory and evaluated in the closed bomb. However, the addition of 1% to 2% talc to the propellant base grain always showed an improvement in reducing gun barrel erosion. The deterrent levels on the CR 7814 propellants evaluated at the Lake City Army Ammunition Plant were adjusted to maintain a constant calorific level. The experimental heat of explosion values for these propellants are tabulated below:

Propellant Lot	Heat of Explosion cal/gram
CR 7814	810
CR 7814 plus 0.99% 0.6 μ APS talc	813
CR 7814 plus 1.77% 0.6 μ APS talc	797
CR 7814 plus 1.01% 2.3 μ APS talc	806
CR 7814 plus 1.39% 2.3 μ APS talc	798

2.3 DISCUSSION:

W. T. Ebihara: In evaluating the effect of talc addition in small arms ammunition, was the amount or weight of original propellant kept constant?

R. L. Trask: In the laboratory phase of this investigation, the weight of small arms propellant, with or without additives, was kept constant.

In the small arms firings conducted at the Lake City Army Ammunition Plant, the charge weight was established for each lot of propellant to meet the ballistic requirements of the 20mm T.P., M55A2 Cartridge Specification. The charge weights for the propellants listed in Tables X and XI were as follows:

Propellant Lot	Charge Weight Grains
Std WC 870 Ball	618
CR 7814 plus 0.99% 0.6μ APS talc	575
CR 7814 plus 1.77% 0.6μ APS talc	600
CR 7814 plus 1.01% 2.3μ APS talc	590
CR 7814 plus 1.39% 2.3μ APS talc	605

2.3 DISCUSSION:

A. K. Roberts: At times during your paper you said the finer the talc the better, but later you said the coarser the talc the better.

R. L. Trask: In the laboratory apparatus, we worked at 16,000 psi. Under those conditions the finer talc worked better. The pressure in actual pressure tests was between 50 - 60,000 psi, when the coarser talc gave better results. The difference in pressure may be one of the reasons. But since we do not yet understand the mechanism of the wear reduction action of talc fully, at this time no definite explanation is available.

THE CONTROL OF EROSION IN NAVAL GUN TUBES

ADVANCED DEVELOPMENT PLANS

L. A. Dickinson & G. L. Warlick
Naval Ordnance Station
Indian Head, Maryland

The increased significance of the problem of down-bore wear in existing Navy gun systems is discussed with appropriate complementary historical background. Solutions to the problem being pursued by the Navy are presented.

INTRODUCTION

The Navy has long recognized the logistic operational advantages of improving the life of large caliber guns on Navy ships. To this end, many approaches have been used such as the Navy Cool propellant, NACO, the improved Canadian polyurethane foam coolant, and titanium dioxide-wax. In addition, it will be recalled that the 3"/70 caliber gun utilized a water-cooled barrel in order to improve life.

Depending on the design and operational rate of fire of the gun, improvements as high as 60-1 have been obtained. For example, with the 6"/47 caliber, and for most guns, proving ground life was extended by 4-1.

The life improvement obtained has been determined by reduction in wear at commencement of rifling; however, with increased effective life, down-bore wear also becomes a life determining factor. Materials which are solid phase lubricants are therefore being added to the wear-reducing

liners so that "plating" of lubricant down-bore may occur. Similarly, addition of metal, etc., to the propellant which then burns to form lubricants is feasible; talc, when added to a propellant, presumably serves to lubricate the barrel.

The goals of our program are to increase life ten-fold, and to minimize velocity variations during the life of the gun tube.

TRENDS IN WEAR REDUCTION ADDITIVE DEVELOPMENT

The wear problem associated with high performance, double-base propellants has attracted attention since the days of Nobel and Abel, who worked on these propellants in the mid 19th century. Abel[1,1/] proposed the use of petroleum

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1/ F. L. Nathan (discourse delivered at Roy Institute, January 29, 1909; reprinted C. N. 1909, p.p. 99, 136, 152, 159) says: "Cordite in the advanced experimental stage consisted of nitroglycerin and guncotton alone, and as their combustion produced no solid residue of any kind, the surface of the bore of the magazine rifle in which the early experiments took place was not fouled in any way. The result was that the cupro-nickel coated bullets, propelled in succession at high velocity through a clean barrel, deposited some of the cupro-nickel in the bore. In order to prevent this, a number of substances were incorporated with the nitroglycerin and guncotton, with the object of producing a deposit of the bore, which it was hoped would get rid of the difficulty of metallic fouling. Of all these various substances the one which appeared to answer the purpose most satisfactorily was refined vaseline, and this material became the third ingredient of cordite as eventually introduced into the British service. When the manufacture was commenced on a large scale, vaseline, which is the proprietary name of one of the refined products of the distillation of petroleum, was replaced by mineral jelly, the same material, but in a cruder form.

grease in the cordite propellants developed at Woolich Arsenal since he considered the grease would lubricate the barrel! Later work showed that while the grease was totally consumed, it nevertheless served a useful purpose since it functioned as an adequate stabilizer from the standpoint of storage life.

In recent years the success of boundary layer cooling using foamed plastic jackets[2,3] and particle-loaded wax liners, has stimulated further study of wear-reduction and barrel lubrication. Recently, it has been shown that the characteristics of the particulate matter are important in determining the degree of wear improvement observed. Specifically, beside particle size the lubricity of the particle appears important since talc appears more effective than titanium dioxide. Talc is well known as a solid lubricant.

It has been found, for most guns, that the most serious wear problems occur close to the commencement of rifling

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1/ (cont'd) The original object with which mineral jelly was introduced was of no importance when cordite was substituted for the black and brown powders used in large guns, but in order to have but one nature of smokeless powder in the service, mineral jelly was added to all cordite whether for use in small arms or artillery. Subsequent experience has demonstrated how very fortunate was the selection of this material for rifle cordite and the extension of its use to all sizes of cordite."

(C of R); in this region the high flame temperature and high pressure environment associated with turbulence results in high heat transfer to the bore of the barrel. Under high rates of fire, or when very energetic propellants are used, the steel is raised above the AC1 transition point; thermo-physical degradation of the surface consequently occurs, this is aggravated, of course, by the engraving process.

Plastic liners (and presumably the talc wax or TiO_2-wax systems) primarily reduce wear at the C of R by producing a cool boundary layer which reduces the heat transfer film coefficient. (Deposition of white particulate matter may also minimize the radiative heat transfer process.) The particulate matter such as the aerosol formed by the degraded polymer matrix or any particles deliberately included may also reduce convective heat transfer by minimizing turbulence adjacent to or in the boundary layer.[4]

The use of polyurethane jackets and particle loaded wax liners have been shown to dramatically increase barrel life using wear at C of R as the criterion (a 4-60 fold improvement is not uncommon[5]). However, down barrel wear becomes a significant problem because the continuing frictional wear from the high velocity shells is more noticeable when barrel life is extended.

Recognizing that down barrel wear is a problem, a program is underway to establish the gas dynamic limitations of the boundary layer cooling phenomenon and develop criteria for selection of down barrel solid phase lubricants which will be superior to talc. These, of course, may be incorporated either into the powder or into the now classical "wear-reducing" jacket.

The additives selected must meet compatibility criteria for the base powder and, of course, they must be readily incorporated into the powder or jackets. Solid phase lubricants of greatest interest are graphite, molybdenum disulphide, and molybdic oxide. They may be incorporated in the glazing of small arms powders, or dispersed in the matrix of the wear-reducing jacket.

Work is now needed to optimize the quantity and location of the solid phase lubricants within the total propulsion package so as to maximize overall wear-reduction without sacrificing ballistic parameters.

CONCLUDING REMARKS

In one hundred years of endeavor in the development of double-base powders, it now seems that Abel's dream of incorporating a bore lubricant to minimize wear is about to be achieved.

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2.4 DISCUSSION:

Jean-Paul Picard:

1. Polyurethane foam has been found to be incompatible with double base propellant due to the migration of the NG into the polyurethane foams, therefore affecting the ballistic performance of the weapon.
2. Molybdenum disulfide, or graphite have not been found to be good anti-erosion additives, regardless of their effectiveness as lubricants.

G. A. Warlick:

1. This migration may be true but Navy systems do not presently utilize the NG type double base systems.
2. I disagree. Although these two additives may not reduce the theremochemical contributions to erosion they do cut down on mechanical attrition of the barrel material.

RESULTS OF WEAR-REDUCTION PROGRAMS ASSOCIATED WITH NAVY GUN SYSTEMS

D. E. Ayer, M. A. Henderson, & R. M. Montoya
Naval Ordnance Station
Indian Head, Maryland

Details of life improvement obtained using wear-reducing techniques in conventional systems such as 20mm (aircraft), 5-inch caliber, 8-inch caliber, and 16-inch caliber guns are reported. Wear in high velocity, long range sabot projectile is also reviewed.

INTRODUCTION

The problem of gun barrel erosion has long been a limiting factor both from a cost effectiveness standpoint and in optimizing performance of Navy guns. Recent development programs carried out by the Naval Ordnance Station, Indian Head, Maryland, provide feasible solutions to the gun barrel erosion problem.

Deterrent-coated propellants have been employed successfully in 20mm gun systems and feasibility studies are under way in the 3"/50 caliber system. NACO (Navy Cool) propellant has been utilized in most major caliber Navy gun systems with significant wear-reduction. Similarly, wear-reducing additives have been evaluated in many of the major caliber gun systems and a great deal of success observed.

Although the use of low force, low flame temperature propellants has proven effective in limiting the extent of gun barrel erosion, this approach does not appear feasible

for future gun systems. These lower force propellants dictate larger chamber volumes resulting in a corresponding excessive mount weight. High impetus, high flame temperature propellant compositions have traditionally been avoided in the past because of their known high erosivity. However, with wear-reducing additive materials or perhaps, deterrent coatings, these high impetus propellants may be effectively utilized in our rapid fire gun systems of the future.

EXISTING AIRCRAFT GUN SYSTEMS

The development of the 20mm, Mk 11 machine gun, having a rapid fire capability of 4,000 rounds per minute, provided a serious barrel erosion problem with the use of existing dinitrotoluene-deterred SPD propellant. Erosion was found to be as high as .048 inch per podful when using this propellant.

Based on limited prior experience with methyl centralite (dimethyldiphenylurea) as a deterrent, experimental batches of methyl centralite-deterred, 20mm SPD propellant were evaluated in both the Mk 11 and 12 machine guns. Significantly less barrel erosion was obtained, with erosion in the Mk 11 gun barrel being as low as .004 inch per podful. Erosion results with varying 20mm propellant formulation are compared in Table I.

TABLE I
EROSION DATA IN THE MK 11 GUN

Propellant Type	Increase in Insert Diameter/Pod
MC powder (7.95% MC level)*	0.004 inch
MC powder (5.7% MC level)	0.006 "
MC powder (5.3% MC level)	0.008 "
DNT powder (CIL)**	0.025 "
DNT powder (master lot)	0.034 "
DNT powder (DuPont)	0.048 "
Ball powder (double-base)***	0.012 "

* Methyl centralite-deterred
** DNT-dinitrotoluene-deterred
*** Dibutylphthalate-deterred

In the processing of the propellant, methyl centralite is applied as a coating to the finished extruded grains or granules with levels of from 4-8% having been evaluated for this application. Impregnation of the methyl centralite into the propellant granule is accomplished by a hot water steeping process. Steeping temperature and duration are important factors in obtaining satisfactory results without adversely affecting stability characteristics of the finished product. Agitation within the steeping system has also been found to improve the efficiency of the process and provide improvements in the degree of impregnation possible. The importance of adequate impregnation of the methyl centralite into the propellant granule was established during development. It

has been found that substantial changes in the relative quickness and progressivity of methyl centralite-deterred propellant can be obtained as a result of various degrees of deterrent impregnation. Providing a surface coating with only slight granule impregnation has resulted in excessive action time values and a high propellant charge weight to attain a particular muzzle velocity. In the particular application cited, cartridge case loading volume restrictions and ballistic performance requirements have necessitated an assurance of proper deterrent impregnation in addition to the usual consideration of factors such as web size, granule length of cut, and volatile content. Adjustment of these latter factors, in an attempt to fully compensate for the effects provided by insufficient impregnation, have not, for the most part, been successful.

Methyl centralite in conformance with Military Specification M-19719 is used for this application with the melting point so specified that a stereochemically symmetrical structure of the compound is necessary. Sources of supply for methyl centralite are somewhat limited as present manufacture involves the use of phosgene as a raw material.

In conclusion, it has been demonstrated that with the use of methyl centralite as a deterrent coating for 20mm propellant, significant improvement in barrel wear can be

obtained over dinitrotoluene-deterred formulations. Assurance of proper granule impregnation has also been found to be critical in its effective usage.

EXISTING MAJOR CALIBER GUN SYSTEMS

The principle method for reducing gun barrel erosion in major caliber Navy gun systems while utilizing standard pyro propellants is via the gun coolant additive approach. Since heat transfer to the gun barrel wall arises from the high temperature gradient at the surface, it is conjectured that a cool boundary layer between the hot propellant gases and the gun barrel reduces maximum surface temperature during firing.[1,2] The coolant materials that have been investigated to date may be grouped as 1) oxides suspended in a wax matrix, or 2) plastic foams. The Navy has investigated two specific materials, titanium dioxide suspended in a wax matrix (Swedish Additive), and high density polyurethane foam. It is hypothesized that the ablative degradation of the polymer backbone in the case of the foam and the wax with the Swedish Additive generate the cool boundary layer.

The effectiveness of the wear-reducing additive approach in Navy systems is found to be dependent on 1) the position of the ablative material within the chamber or cartridge case (see Figure 1), 2) the material bulk density, and 3) the chemical/physical nature of the material. Although the

Swedish Additive has been employed successfully in many Navy gun systems, chamber residue considerations favor the utilization of the polyurethane foam additive.

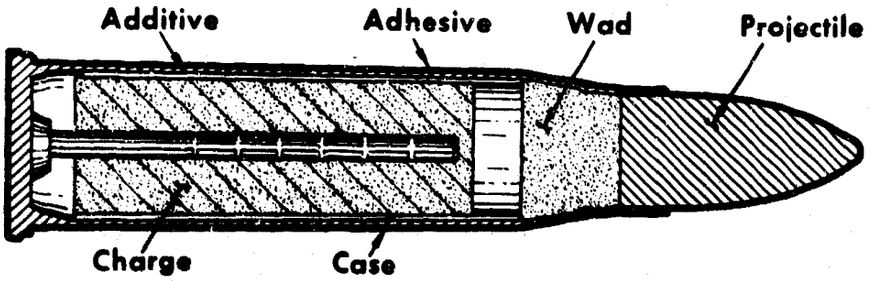
The polyurethane foam formulation utilized by the Navy (Table II) yields a high density, semi-rigid foamed plastic, chemically compatible with standard propellants. The material should meet the requirements of the Naval Ordnance Systems Command's Weapon Specification 12790 of 15 February 1969, "Weapons Specification for Sheets, Polyurethane Foam, for Use In Wear-Reducing Gun Jackets and Liners".

Although immense improvements in gun barrel wear have been obtained with the foam formulation specified in Table II, efforts are continuing at Indian Head to optimize the wear-reducing properties of the foam as well as physical parameters, by modifying the formulation.

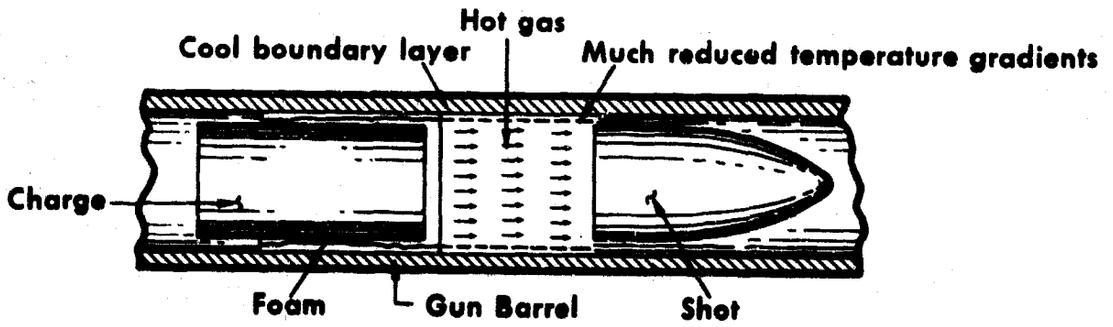
TABLE II
URETHANE FOAM COMPOSITION

		Parts by Weight
A.	Resin Prepolymer Ingredients:	
	Polyethylene glycol 200	10.5
	Polypropylene glycol 1200	6.5
	Castor oil	36.5
	2,4 tolylene diisocyanate	46.5
B.	Catalyst Mixture Ingredients:	
	Polypropylene glycol 2025	10.0
	Glycerine (4.35% water)	7.5
	Polyethylene glycol 200	3.75
	Ferric acetyl acetonate	0.15
	Nigrosine black	0.25
	Dibutyl tin dilaurate	0.15

NOTE: Fillers may be added as desired to obtain specific properties.



Assembled Round Using Foam Coolant (Cartridge Type)



Concept of Boundary Layer Cooling

FIGURE 1

CONCEPT OF BOUNDARY LAYER COOLING

Evaluation of wear-reducing additives has been monitored by Indian Head in both test firing programs conducted at the Naval Weapons Laboratory, Dahlgren, Virginia, and in the fleet. Table III summarizes the erosion data obtained in test firing programs in all Navy gun systems investigated to date.

The Table notes the number of rounds fired employing either the Swedish Additive or polyurethane foam and the extension of barrel life realized when compared to a like number of rounds fired without the additives. The barrel life extension ratios are given for each of the two criteria upon which barrel life is based. Additionally, the residue remaining in the chamber after firing is noted; Navy gun systems cannot tolerate even trace amounts of residue.

Data suggest that unquestionable reduction in barrel wear may be obtained by employing wear-reducing additives in major caliber gun systems, and evaluation in the fleet confirms these test results. While in Southeast Asia waters, from a period beginning 30 August 1968 and ending 1 May 1969, the 16"/50 caliber guns of the USS New Jersey exhibited extensive reduction in barrel erosion while utilizing wear-reducing additives. Table IV summarizes these data.

Examination of the data in Table IV leaves little doubt regarding the effectiveness of wear-reducing additives. The equivalent service round figures may be interpreted as a

TABLE III
GUN BARREL EROSION TEST PROGRAMS

Gun	Rounds Fired Additive With	Rounds Fired Additive Without	Type Additive Swedish	Type Additive Foam	Indicated Barrel Life Extension Ratio BE *	Indicated Barrel Life Extension Ratio EGR **	Extent Residue
5"/38	144	144	X		***	7/1	Excessive
5"/54	144	144	X		3/1	1.6/1	None
6"/47	40	40		X	***	60/1	None
8"/55	10	10		X	***	***	None
16"/50	13	13	X		4/1	-	None
16"/50	79	79		X	4/1	-	None

* BE - Bore Enlargement ratios

** EGR - Erosion Gage Reading ratios

*** No measurable wear was observed

TABLE IV
EROSION DATA - USS NEW JERSEY

(Based upon equivalent service rounds fired.)

Gun No.	FCR*	ESR**	FCR + A***	ESR
400	165	71	331	8
444	193	83	221	-6
391	182	78	266	-10
317	148	63	124	11
399	184	79	196	-31
395	200	86	178	-22
320	164	70	137	13
454	188	81	275	2
449	182	78	248	6
TOTALS:	1606	689	1976	-29

* Full charge rounds fired utilizing the 1900 pound projectile with standard Navy pyro propellant.
** Equivalent service round figure obtained.
*** Full charge rounds fired utilizing the 1900 pound projectile with standard Navy pyro propellant with wear-reducing additive.

measure of wear in a major caliber Navy gun based upon the following definition: one ESR unit corresponds to that amount of gun barrel wear in a given gun system attributable to the firing of the Navy heavy (2,700 pound) armor piercing projectile, employing a full propellant charge of hot (pyro) propellant. Therefore, from the data presented in Table IV,

we can conclude that the gun wear obtained, utilizing wear-reducing additives, is negligible in comparison to the wear attributed to those rounds fired without additives.

The negative ESR's obtained reflect upon a phenomenon that has been observed in Navy gun systems employing the wear-reducing additive. It is hypothesized that a residual wear-reducing effect occurs when additive-containing rounds are followed by non-additive rounds. This phenomenon is being investigated further at the Naval Ordnance Station, Indian Head.

LONG RANGED, HIGH VELOCITY GUN SYSTEMS

With the use of higher energy gun propellants to attain substantial range performance improvements, barrel erosion has become a critical area. The development of the 8-inch fin-stabilized Long Range Bombardment Round (LRBR) under Project Gunfighter required the use of an M-26 double-base formulation to achieve the necessary muzzle velocities. Swedish Additive boundary layer coolant was used in the development of the 8" LRBR as a liner around the forward bag charge to minimize barrel erosion. For the standard 8"/55 caliber rounds in which the lower energy, single-base propellants are used, only 2.8% of the charge weight can be tolerated before residue problems are encountered. With the 8" LRBR, a level of 4.6% was used successfully. Barrel wear developed in firings of the 8"/55 caliber LRBR in a Mk 15,

Mod 3 barrel (which does not contain any chrome plating) using the higher energy propellant, show that in the first quarter of barrel life the wear rate is only 1.08 times that of the standard round using single-base propellant. However, in third and fourth quarters of barrel life an average wear rate of 2.23 times that of the standard round was obtained. This would indicate that while erosion could be controlled effectively with boundary layer coolant under new barrel conditions that as wear advanced the coolant became less effective and other factors in the metallurgical deterioration of the barrel were predominant. The wear factors indicated above are based on the standard origin of bore diameter enlargement.

Looking at the wear in the entire length of the barrel, it has been found that in the forward 250 inches (muzzle end) a lower wear rate is obtained for the LRBR as compared to the 8-inch standard round. This is attributed to the design differences in the projectile obturation systems. In the case of the LRBR, a center-riding sabot with a traveling seal polypropylene wedge is used, as opposed to the standard round copper-driving band configuration. The advantage of less mechanical attrition with the plastic material is evident, with the differences in propellant flame temperatures in this area of the barrel not being the predominant factor in wear. It is felt that further significant reductions in

erosion with coolants other than Swedish Additive (such as polyurethanes) can be accomplished with such higher energy systems as the LRBR and further evaluation programs being proposed.

ACKNOWLEDGMENT

Appreciation is expressed to LCDR G. L. Littell of the USS New Jersey for his cooperation in assembling and interpreting data contained in this report.

REFERENCES

1. McLennan, D. E.; "Ammunition Sleeve for Guns"; Canadian Patent 718,214.

2. Dickinson, L. A., McLennan, D. E., and MacDonald, R.; "Ammunition Sleeve for Cooling Gun Barrels"; Canadian Patent 742,908.

2.5 DISCUSSION:

C. M. Dickey: What would you say is the correct concentration of methyl centrallite as a function of distance into grain?

D. E. Ayer: Tests show that 8% mc level by weight is the optimum concentration. The location (penetration) is regulated by processing technique.

H. Gisser: Has polystyrene foam been studied as an erosion preventive?

D. E. Ayer: Yes. We have problems therein regulating the foam density. Also, the volatiles in our existing solvent processed propellants attack polystyrene.

H. P. Gay: I vaguely remember that in the early days of work on foams by the BRL and CARDE density was of prime importance. Would you comment on that?

D. E. Ayer: It certainly is. An increase in density serves to increase the reduction in wear; but if densities are excessively high, residue problems are encountered.

2.5 DISCUSSION:

I. Ahmad: What would you expect, if wear reducing agents such as TiO_2 or talc are mixed with the polyurethane foam? Will the performance of the latter improve considerably?

D. E. Ayer: Since the wear reducing properties of the inorganic oxide additives are well known and an increase in bulk material density would be realized if it were incorporated in the foam, I think the wear reduction would be definitely improved. A problem in complete consumption of the wear package would have to be contended with. Some data has already been generated with the TiO_2-polystyrene combination by Picatinny which suggests improvement. I will be glad to furnish the reference on request.

E.L.Bannister: What is the effect of polypropylene rotating band on 8/55 projectile, with regards to down tube wear?

D.E.Ayer: Cuts down on mechanical attrition due to lower coefficient of Kinetic friction.

E.L.Bannister: Statement regarding polyurethane liners: Polyurethane reduces wear primarily by forming a cool layer of gas that flows laminarily along the base surface thus reducing the heat flow from the hot gas into the base surface.

2.5 DISCUSSION:

D. E. Aver: True, but chemical thermodynamics must also be considered. This mechanism (chemical) has never been clearly defined.

J.M.Frankle: Can you calculate the detailed interior ballistic performance of weapons with deterrent-coated propellants?

F.S.Hodgson: Gun propulsion technologists at NOS simulate the interior ballistic performance of gun systems by the digital computer program developed by Paul G. Baer and Jerome Frankle. Some work has been done to simulate 20^{mm} ballistics obtained in firings using M. C. deterred propellant. The work, while incomplete, does indicate the feasibility of obtaining good simulation.

As a first approximation it is assumed that gradients in adiabatic flame temperatures and propellant impetus do not contribute a first order influence on deterred propellant ballistics. The deterrent coating most strongly influences the burning rate profile. It is possible to derive burning rate versus pressure data from standard closed vessel firings. This information is supplied as basic input to the Baer-Frankle program. A more accurate

2.5 DISCUSSION:

F.S.Hodgson: simulation can be envisioned if initial and intermediate flame temperature and impetus values are known. This is accomplished by programming the computer to accept new basic input data as a function of fraction of web burned. Simulations of this type are currently being investigated at NOS.

C.M.Crenshaw: What is the long term storage stability of the inhibited propellants at 160°F or at -40°F as in arctic and tropical desert sites?

F.S.Hodgson: Various studies have been conducted to determine the long term storage stability of methyl centralite and dinitro toluene deterred propellants at high and low service temperatures. In general these tests indicate that the deterred single base compositions have superior storage characteristics when compared with double base ball propellant. Ballistic irregularity in the ball propellant is attributed to the gradual migration of the dibutyl phthalate deterrent into the nitro-glycerin. No similar solubility problem exists in the case of the deterred single base composition.

BALLISTIC STABILITY OF PICRITE PROPELLANT CONTAINING TITANIUM DIOXIDE

Mrs. D.J. Taylor, Royal Armament Research and Development Establishment, Fort Halstead, U.K.

ABSTRACT

Picrite propellant containing 2% Titanium Dioxide has been stored for four years in sealed kilner jars and in unsealed wooden boxes in heated magazines. Closed Vessel firings have been carried out at frequent intervals and have not detected any changes in the ballistic properties of the propellant.

Introduction

In 1964 it seemed probable that the requirement to reduce wear in high performance guns would be met in U.K. by the actual addition of titanium dioxide, TiO_2 to the propellant. Since any departure from standard propellant compositions is inevitably viewed with grave suspicion, particularly in fear that the stability of the propellant may be changed, it was decided to start trials to investigate the effect on ballistic stability of incorporating TiO_2 on picrite propellant. The propellant chosen for the experiment was NQ (NG 20.6%, NC 20.8%/Picrite 55%/Carbamite 3.6%) which has a flame temperature of 2800°K and a calorific value of 880 cal/gm (M.L.). This propellant was selected as it is used in virtually all U.K. high performance rounds and inevitably gives a high wear rate. Any reduction in wear would give a useful bonus in life of the gun and maintenance of new gun performance.

Method

Two lots of the standard composition were selected to act as controls. One lot was 2 years old and the other was a new lot just completed manufacture. Lots of different ages were selected to minimise the risk of both lots altering at the same time. The third lot was specially manufactured and was of the same composition but with the addition of 2% TiO_2. After preliminary Closed Vessel tests for homogeneity the lots were put on magazine storage. The old lot, half the new lot and half the experimental lot were stored in sealed kilner jars. The remainder of the new and experimental lots were stored in normal wooden propellant boxes, to allow the propellant to change easily if it was going to do so.

The propellants were stored in nominally heated magazines but neither temperature nor humidity was controlled though both were recorded. Temperatures varied from 36°C to -1°C (when the heating broke down). Temperatures were normally above 15°C. Relative humidities varied between 39 and 97% but was normally above 60%.

Samples of all variants were fired in the Closed Vessel (CV) from February 1965 until December 1966 and then every four months approximately until May 1969. At the same time total volatile material (TVM) content was determined for each variant.

Results

The CV and TVM results are shown in the table attached as Appendix 1. The CV results were worked out in terms of the percentage variation in Force, Quickness and Vivacity of each sample from the group mean of all five samples.

The spreads in Force recorded during the trial with any one sample were small varying from 0.4% with the old lot to 0.7% with the new lot in wooden boxes and the experimental lot in kilner jars. No variant showed any trend with time.

Spreads in vivacity were also small varying from 1% with the new lot in jars to 1.3% with the old lot and the new lot in boxes. Variations in quickness were similar varying from 0.9% with the new lot (both types of storage) to 1.4% with the old lot. There were no trends with time in either vivacity or quickness with any sample.

The TVM content of all samples dropped from about 0.2% to 0.1% approx. during the trial. There was no difference between samples stored in sealed jars and unsealed boxes.

Conclusions

Propellant NQ containing 2% TiO_2 showed no sign of any ballistic instability during the 51 month period of this trial. As it was unaffected by storage in wooden boxes it seems probable that it will have an adequate ballistic life. It is concluded therefore that TiO_2 may be incorporated in picrite propellants to reduce gun wear without any fear that ballistic stability of the propellant will be adversely affected.

APPENDIX I

Closed Vessel Results and TVM Content

Variants

Sample A:- NQ/S 207-047 (2 years old at start of trial) Stored in sealed kilner jars.
Sample B:- NQ/S 207-047 (new lot) Stored in sealed kilner jars.
Sample C:- NQ/S 207-047 (new lot) Stored in wooden boxes.
Sample D:- NQ/S 207-047 (including 2% TiO_2) Stored in sealed kilner jars.
Sample E:- NQ/S 207-047 (" ") Stored in wooden boxes.

Table I

TVM Content and Percentage Variation in Force from Group Mean

Date	Sample A		Sample B		Sample C		Sample D		Sample E	
	TVM (%)	Variation in Force (%)	TVM (%)	Variation in Force (%)	TVM (%)	Variation in Force (%)	TVM (%)	Variation in Force (%)	TVM (%)	Variation in Force (%)
2/65	.23	+ 1.6	.19	+ 1.5	.19	+ 1.3	.20	- 2.4	.20	- 2.2
3/65	.20	1.5	.24	1.5	.21	1.4	.19	2.2	.18	2.4
4/65	.22	1.3	.24	1.4	.27	1.3	.24	1.9	.25	2.2
6/65	.12	1.4	.09	1.4	.13	1.4	.11	2.0	.09	2.3
8/65	.17	1.4	.21	1.3	.18	1.4	.20	2.1	.20	2.2
10/65	.16	1.5	.19	1.4	.20	1.2	.20	2.1	.23	2.2
12/65	.20	1.3	.21	1.3	.16	1.5	.27	2.1	.20	2.1
2/66	.14	1.2	.19	1.4	.15	1.2	.15	2.0	.15	1.9
4/66	.14	1.6	.14	1.4	.11	1.5	.19	2.5	.15	2.2
6/66	.18	1.3	.13	1.3	.13	1.1	.17	1.9	.17	1.9
8/66	.19	1.4	.20	1.1	.19	1.7	.20	2.0	.19	2.3
10/66	.08	1.4	.12	1.3	.17	1.3	.09	1.9	.14	2.3
12/66	.19	1.4	.18	1.3	.17	1.5	.14	2.1	.13	2.2
4/67	.09	1.4	.17	1.6	.19	1.4	.17	NR	.17	2.3
6/67	.15	1.3	.15	1.4	.17	1.4	.15	2.1	.13	2.2
10/67	.11	1.3	.13	1.0	.17	1.3	.12	1.8	.15	2.0
2/68	.08	1.5	.08	1.5	.10	1.3	.08	2.2	.10	2.3
5/68	.11	1.5	.11	1.5	.14	1.4	.15	2.3	.11	2.3
11/68	.11	1.5	.13	1.1	.11	1.0	.12	1.9	.10	2.0
2/69	.08	1.5	.07	1.4	.07	1.3	.06	2.3	.06	2.0
5/69	.11	1.3	.07	1.4	.10	1.5	.11	1.9	.11	2.4
Spread	-	0.4	-	0.6	-	0.7	-	0.7	-	0.5

Table II

Vivacity and Quickness
Percentage Variation from Group Mean

Date	Sample A		Sample B		Sample C		Sample D		Sample E	
	Variation in		Variation in		Variation in		Variation in		Variation in	
	V(%)	Q(%)	V(%)	Q(%)	V(%)	Q(%)	V(%)	Q(%)	V(%)	Q(%)
2/65	+ 2.6	+ 4.1	+ 3.5	+ 5.0	+ 3.6	+ 4.8	- 5.1	- 7.7	- 5.5	- 7.8
3/65	2.4	3.7	3.6	4.9	4.0	5.2	5.7	8.0	5.2	7.8
4/65	3.0	4.2	3.4	4.7	3.2	4.3	5.4	7.5	5.0	7.5
6/65	3.3	4.5	3.0	4.3	3.4	4.7	5.5	7.7	5.0	7.5
8/65	2.5	3.8	3.4	4.6	3.5	4.7	5.0	7.3	5.2	7.7
10/65	2.5	3.9	3.7	4.9	3.8	4.9	5.2	7.4	5.7	8.1
12/65	3.4	4.5	3.4	4.5	3.2	4.5	5.5	7.8	5.4	7.7
2/66	2.9	4.0	3.5	4.8	3.9	4.9	5.6	7.8	5.6	7.8
4/66	2.4	3.9	3.4	4.7	3.5	4.9	4.7	7.4	5.4	7.7
6/66	3.2	4.4	3.6	4.8	3.6	4.5	5.6	7.7	5.7	7.9
8/66	3.0	4.3	3.6	4.6	2.7	4.3	5.1	7.3	5.0	7.5
10/66	3.7	5.0	3.5	4.7	3.4	4.6	5.8	7.8	5.8	8.3
12/66	2.7	4.0	3.6	4.8	3.9	5.2	5.6	8.0	5.5	7.8
4/67	2.4	3.6	3.3	4.8	3.6	4.9	NR	NR	5.0	7.5
6/67	2.7	3.9	3.5	4.9	3.4	4.6	5.2	7.4	5.2	7.6
10/67	2.6	3.9	3.5	4.4	3.9	5.1	5.3	7.3	5.6	7.7
2/68	2.8	4.2	3.8	5.2	3.7	4.9	5.2	7.6	6.1	8.6
5/68	3.0	4.4	3.5	4.8	3.9	5.1	5.5	8.0	5.8	8.4
11/68	2.5	3.9	3.7	4.6	3.6	4.5	4.9	6.9	5.7	7.9
2/69	2.6	3.9	4.0	5.2	3.4	4.5	5.2	7.7	5.6	7.8
5/69	3.2	4.1	3.5	4.8	3.3	4.7	5.0	7.0	6.0	8.6
Spread	1.3	1.4	1.0	0.9	1.3	0.9	1.1	1.1	1.1	1.1

2.6 DISCUSSION:

M. E. Levy: 1. Does UK attach much significance any more to concept of accelerated stability testing (e.g., NATO-150°F-30 day test)?

2. Is UK concerned about desert storage conditions any more?

Mrs. D.Taylor: 1. Picrite propellants deteriorate rapidly on cycle storage where temperature goes up to 140°F or higher. Australian storage trials at Manus Island have shown that these propellants withstand 5 years under genuine tropical conditions and that a cycle going up to 115°F is more realistic.

2. UK is not concerned about desert storage conditions. We expect the user to protect his ammunition. Ballistic tests have been carried out on ammunition stored at Bahrein for a year or two. The ballistic changes had occurred.

A. Victor Nardi: What do you consider a realistic high temperature for storage of propellant?

Mrs. D. Taylor: At temperature above 120°F, picrite propellants start deterioriating ballistically within a few weeks.

PRELIMINARY STUDY OF THE EFFECT OF SWEDISH ADDITIVE ON THE 175MM GUN TUBE

Reinier Beeuwkes, Jr.
Arthur Kant
Kenneth Moon

Army Materials and Mechanics Research Center
Watertown, Massachusetts

ABSTRACT

The nature of the gaseous environment in the 175-mm gun tube was studied in terms of possible chemical equilibria and simple stoichiometric relationships. Possible effects of the gases on cracking in the gun tube were discussed, but no definite conclusions seem possible without additional experimental study. It was concluded that the Swedish Additive must remain segregated at the tube wall to be effective in reducing erosion. Some comments have been included concerning the possible mechanism by which the Additive reduces erosion.

Introduction

Recently, bore cracking has been observed in the 175-mm gun tube, and has caused concern to the extent that there have been proposals to eliminate chromium plating of the bore on the assumption that the cracking might be due to hydrogen embrittlement induced by plating. Since chromium plating is effective in reducing erosion, it seemed unwise to eliminate the plating without a better fundamental understanding of the entire system, including the gaseous environment to which the gun steel is exposed during firing. In particular, the chemical behavior of the Swedish Additive (TiO_2 plus paraffin) is not well understood. Some work bearing on this problem has been done at Picatinny Arsenal[1] and a contract has been placed with the Illinois Institute of Technology,[2] but at present there seems to be available no systematic study of the possible chemical reactions in the system, based on free energy

criteria. The purpose of this report is to provide such a systematic study, at least in a preliminary fashion, and to point out possible implications of the calculated data for the problem of cracking in the gun tube.

Conditions Prevailing in Burned Propellant Without Swedish Additive

The propellant in question is M6, whose chief components are 85% nitrocellulose and 10% dinitrotoluene.[3] The loading density is 0.20, 0.36, or 0.53 g/cc.[4] The observed peak pressure is 11,600, 22,200, or 51,000 psi, respectively,[4] which is much lower than the expected pressure[3] if burning were completed before the projectile began to move. To estimate the temperature corresponding to peak pressure, we have assumed that the conditions prevailing at the time of peak pressure are the same as would have resulted if the projectile had not begun to move until burning was completed, and then had advanced up the gun tube at constant gas entropy until the pressure had dropped to the observed peak value. This approach admittedly has weaknesses, but we think it provides the best estimate that is easily computed. From Figure 5 of Reference 3, this estimated temperature is about 2000 to 2100 K, with little dependence on loading density. The chief gas species are CO_2, CO, H_2O, H_2, and N_2. To a good approximation, the first four species exist in proportions determined by the composition of the propellant and the temperature, as defined by the reaction

$$CO_2(g) + H_2(g) = CO(g) + H_2O(g), \qquad (1)$$

for which the free energy of reaction, ΔF°, is 7520 - 7.05 T calories at T degK.* As the gas cools, the relative amounts of the gas species change until about 1600 K, below which no further change occurs for kinetic reasons.[5] Typical values of the mole fraction of hydrogen in the gas are 0.19 at 2100 K

*See Appendix I for an outline of the method of calculating equilibrium proportions from free energy data.

and 0.18 at 1600 K.[3] Thus, peak partial pressure of hydrogen will be around 2100, 4000, or 9200 psi, depending on the loading density.

These high hydrogen pressures clearly represent a potential for dissolution of substantial quantities of hydrogen in the gun steel. Whether or not dissolution occurs will depend on the presence or absence of a passivating layer of adsorbed oxygen (or perhaps other material) on the surface. If hydrogen can enter the steel, the ease with which it can depart after the high-pressure pulse is over may be strongly influenced by presence or absence on the surface of substances which inhibit recombination of hydrogen atoms. Depth of penetration during the pressure pulse would be no more than, say, one micron, but subsequent diffusion could proceed to depths of the order of millimeters, even at room temperature. However, the course of diffusion of hydrogen in steel is known to be highly complicated by the existence of traps, such as carbide particles, grain boundaries, and other imperfections. The kinds and mechanisms of damage which the hydrogen might produce in the steel are also highly complex.[6,7,8,9] There is a vast literature bearing on all these points, but a critical review is not within our present scope. The four references cited are given merely as examples. It is our opinion that a thorough literature review, essential though it will be, will not by itself provide complete answers to the practical problem of cracking in the 175-mm gun.

If it should turn out that hydrogen does dissolve in the gun steel when the gun is fired, it would follow as a corollary that any hydrogen embrittlement produced by chromium plating would have to be attributed to spontaneous damage of the steel after plating but before firing. This is not a novel interpretation of chromium-plating induced hydrogen embrittlement; never-

theless, we wonder whether scrupulous attention has been paid to the baking operation[10] following plating.

Effect of Swedish Additive if Homogeneously Distributed

The Swedish Additive consists of a blanket of a TiO_2-paraffin mixture placed around the propellant charge.[11] The ratio by weight of TiO_2 to paraffin is specified[11] as 46:54, and the ratio by weight of the Additive[11] to the propellant[4] is 2.9%, 4.3% or 7.9%, depending on loading density.

If thorough mixing of the Additive and propellant occurs rapidly in comparison with the burning time of the propellant, a slightly lower gas temperature will prevail, and the proportions of the various gas species will differ slightly from those which would exist in absence of the Additive. These effects could be calculated by the method described in References 3 and 5, but for the present purposes a less laborious approach will serve. General knowledge of hydrocarbon chemistry gives us confidence that the paraffin (assumed to be decane, $C_{10}H_{22}$) will contribute all its carbon and hydrogen atoms to the gas mixture, but it is not possible to make intuitive assumptions about the fate of the TiO_2. We have made calculations of the type described in Appendix I, which showed that in a typical burned propellant environment TiO_2 can be reduced to Ti_3O_5 but not to lower oxides, TiC, or TiN. Thus just one sixth of the oxygen in the Additive is available chemically, and the remaining solid oxide is inert. For the temperature effect, we note that the heat of formation of $C_{10}H_{22}$, on a weight basis rather than mole basis, is much smaller than that of ethyl alcohol, C_2H_5OH. (See Table A-1 of Appendix I, where the temperature-independent term in the expression for ΔF° is the heat of formation.) We therefore assume that the cooling effect of the Additive will be less than that of ethyl alcohol, for which calculations have

already been made.[3] As a measure of the change in composition of the gases, we define an index of the composition of the charge, thus:

$$I = [(H) + 4(C) - 2(O)] / [(H) + 2(C)], \qquad (2)$$

where (H), (C), and (O) are the numbers of atoms of hydrogen, carbon, and oxygen, in the charge. The significance of the index is that as I approaches unity, the amounts of H_2O and CO_2 in the burned charge approach zero; for $I > 1$ there would be free solid carbon and/or hydrocarbons. As I approaches zero, the amounts of H_2O and CO in the burned charge approach zero; for negative I there would be free oxygen. Thus, I is a measure of the chemical reducing power of the gases.

Applying these ideas to the 175-mm gun at highest loading density, for which the Additive produces a marked reduction of erosion,[11] we find from Figure 16 of Reference 3 that the cooling produced by the Additive should be less than 200 K, and that the index I would be changed from 0.76 to 0.80. It is our opinion that these changes are too small to account for the observed effect of the Additive, and we therefore conclude that the effectiveness of the Additive depends upon its remaining essentially segregated and in contact with the surface of the gun tube. This points up the importance of applying the Additive snugly to the wall of the chamber.

Effect of Additive if Remaining Segregated

If the Additive remains segregated for an appreciable time, it is probable that the pressure of the Additive will very rapidly equalize with that of the propellant gases, and that the temperature will equalize less rapidly than the pressure but more rapidly than the composition. We cannot be sure whether temperature equalization will occur in the time available, however, so we must consider possible reactions within the Additive layer at

high pressure and low temperature, as well as at high pressure and high temperature.

The specified composition of the Additive corresponds to 1.5 moles of TiO_2 per mole of decane, which suggests that we investigate reactions such as

$$2C_{10}H_{22}(g) + 3TiO_2(s) = 3TiC(s) + 6CO(g) + 11CH_4(g) \qquad (3)$$

or $2C_{10}H_{22}(g) + 3TiO_2(s) = 3TiC(s) + 6H_2O(g) + 8CH_4(g) + 9C(s)$

Calculations of the type in Appendix I give the following results for percent completion of the reaction, in each case assuming that no other reaction occurs:

T deg K	P psi	Percent Completion (3)	(4)
1000	51,000	7	52
2000	51,000	100	100
2000	11,600	100	100
1000	5,000	100	100

Actually, hydrogen and other hydrocarbons would also be expected. If the temperature is high enough to permit equilibrium, the amount of hydrogen which must exist if solid carbon is present and the mole-fraction of methane is 0.5 would be:

T deg K	P psi	X_{H_2}
1000	51,000	0.02
2000	51,000	0.16
2000	11,600	0.34
1000	5,000	0.05

Similarly, if the mole-fraction of hydrogen is 0.1, and solid carbon is present, we calculate:

T deg K	P psi	X_{CH_4}	$X_{C_2H_2}$	$X_{C_2H_4}$	$X_{C_2H_6}$	$\frac{X_{CO}}{X_{H_2O}}$
1000	51,000	-	0.00	0.00	0.27	.01*
2000	51,000	0.19	0.00	0.00	0.00	24
2000	11,600	0.04	0.00	0.00	0.00	105
1000	5,000	-	0.00	0.00	0.00	.11+

* The corresponding value for $X_{H_2} = 0.02$ is 0.05.

\+ The corresponding value for $X_{H_2} = 0.05$ is 0.22.

It is, of course, open to question whether the reactions will be possible kinetically, even when favored thermodynamically. If the TiO_2 does not react for kinetic reasons, the decane will very likely decompose anyhow, because its free energy of formation is large and positive at elevated temperature, and decomposition is not likely to be kinetically difficult. If TiC does form, and later the Additive and propellant gases become homogeneously mixed, the TiC will be reoxidized to Ti_3O_5 if the temperature is still high enough to permit the reaction kinetically.

It will be noted that if the Additive temperature does not rise much above 1000K, the thermodynamic calculations indicate that the hydrogen concentration at the gun tube surface may be much lower when Additive is used than when it is not used. This might help to reduce the tendency for crack formation in the tube. On the other hand, the Additive provides a strongly reducing atmosphere adjacent to the tube wall, in contrast to the relatively neutral propellant gases. (The index I for the Swedish Additive alone is 1.33 if the TiO_2 reacts as in equations 3 or 4, and is 1.48 if the TiO_2 is inert.) If the gun tube surface, in absence of Additive, is rendered passive by an oxygen film, the strongly reducing layer of Additive

might open the way to penetration of hydrogen into the steel, with results comparable to those described by Hancock and Johnson.[9]

Although we are not primarily concerned here with the problem of erosion, it may be worth while to mention a few suggestive points which arise from our calculations. If the Additive reduces erosion by providing a relatively cool and reducing blanket adjacent to the gun steel surface, as seems probable,[1] one may ask what is the role of the TiO_2 in the Additive. Two possibilities not considered in Reference 1 occur to us. One is that the TiO_2 enhances the cooling effect by making possible reactions like (3) or (4), which are highly endothermic, and depend on the entropy term for a favorable free energy. The heats of reaction are 284 kcal and 155 kcal, respectively. A second possibility is that erosion reduction is due, at least in part, to deposition of TiC (a very hard material) on the surface of the metal.

Another point is that reactions (3) or (4) probably would not occur unless the temperature were really quite high. Thus, in guns operating at relatively low temperature the TiO_2 might be of little benefit in reducing gaseous erosion, and might accelerate abrasive erosion. Abrasive erosion would be particularly objectionable if it produced faster than normal erosion at some distance along the tube, away from the origin of rifling, because it might produce a hiatus in the rifling which could be more serious than a comparable amount of erosion at the origin. We do not mean to imply that an observed peak in erosion part way along the rifled tube is necessarily evidence that abrasive erosion is occurring; a peak could also occur if the beneficial effects of the Additive decreased, as a function of distance along the tube, more rapidly than normal erosion without Additive decreases.

The above comments about the role of TiO_2 are highly speculative, but they are worth following up, because if it turns out that TiO_2 is not essential, it would be possible to design an Additive that would be cheaper and much easier to handle.

Concluding Remarks

It is clear that the gaseous environment could play a very important part in tube cracking, but it also seems clear that no convincing theory of such an effect is possible in our present state of knowledge. More experiments will be needed, and we believe that in such a complex system, experiments are likely to prove fruitful only if carefully tailored to an appropriate conceptual framework, so that critical points may be recognized and tested. The conceptual framework involves such diverse fields as propellant chemistry, internal ballistics, metallurgy, flow and fracture of solids, etc., so the experimental study should be a team effort, with the team including experts in all pertinent fields.

Acknowledgement

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APPENDIX I

Given a chemical reaction

$$aA + bB + \ldots = cC + dD + \ldots \quad \text{(A-1)}$$

the free energy of reaction, ΔF°, can be computed by the relation

$$\Delta F^\circ = c\,\Delta F^\circ_{fC} + d\,\Delta F^\circ_{fD} + \ldots - a\,\Delta F^\circ_{fA} - b\,\Delta F^\circ_{fB} - \ldots \quad \text{(A-2)}$$

where ΔF°_{fi} is the free energy of formation of species i from its component elements, all in their standard states. We have listed values of ΔF°_{fi}, for the species with which we are concerned, in Table I. From ΔF° the equilibrium constant K can be computed by use of the relation

$$-RT\ln K = \Delta F^\circ \quad \text{(A-3)}$$

where R is 1.986 cal/(°K mol), and

$$K = \frac{(\text{thermodynamic activity of C})^c(\text{thermodynamic activity of D})^d\ldots}{(\text{thermodynamic activity of A})^a(\text{thermodynamic activity of B})^b\ldots} \quad \text{(A-4)}$$

where the activities are those existing in an equilibrium mixture of the several species involved. For solids in their standard state the activity is unity, and for gases the activity is PX_i where X_i is the mole fraction of species i in the equilibrium bas mixture, and P is the total pressure of the gas in atmospheres. When dealing with gas mixtures, it is convenient to define an effective equilibrium constant K', such that

$$K' = KP^{(a + b + \ldots - c - d - \ldots)} \quad \text{(A-5)}$$

$$= \frac{X_C^c \cdot X_D^d \ldots}{X_A^a \cdot X_B^b \ldots} \quad \text{(A-6)}$$

it being understood that solid phases and their coefficients are omitted.

Given a specified mixture of various chemical species at a specified temperature and pressure, we can find whether a given hypothetical reaction

may occur by calculating K' from equation A-5 and comparing it with a number K'_0 computed by using the actual (specified) concentrations in the expression for K'. If $K' > K'_0$, the reaction will proceed (unless kinetically inhibited) until $K'_0 = K'$.

Computations of this type suffer from several uncertainties. First, we usually have to extrapolate ΔF°_{fi} to temperatures above those at which the original measurements were made. See Table I. Second, the use of P_{X_i} for thermodynamic activity assumes ideal gas behavior. Third, omission of solid species from the equilibrium constant expression is valid only if the solid phase has a fixed composition and zero compressibility. Fourth, we cannot always be sure that some stable reaction product whose presence is overlooked or unsuspected will not intervene. Fifth, the reaction may be kinetically inhibited even though the free energy considerations are favorable.

THERMAL THEORY FOR EROSION OF GUNS BY PROPELLANT GASES

Ernest L. Bannister
Interior Ballistics Laboratory
Ballistic Research Laboratories

ABSTRACT

A paper is presented reviewing some of the erosion studies that were conducted by the Ballistic Research Laboratories during the period 1945-1951. Only thermal theory is discussed, with the primary emphasis being placed on the development of equations describing the erosion in guns. The equations were used to calculate the wear per round for a number of Army and Navy guns for which erosion data were available. The calculated values are compared with the observed values.

LIST OF SYMBOLS

c_p	specific heat of gun barrel material, cal/gm/°C
t_1	beginning of erosion interval, sec
t_2	end of erosion interval, sec
A	erosion function
B	amount of heat necessary to melt one cubic centimeter of gun barrel material, cal
C_a	actual propellant charge, lbs
C_s	service propellant charge, lbs
H(t)	instantaneous rate of heat input to hot spots, cal/cm^2
K_1	constant
L	heat of fusion of gun barrel material, cal/gm
N_a	number of rounds fired with charge C_a
N_c	number of equivalent rounds
Q	calculated total heat input per square centimeter per round, cal
Q_s	total heat input per square centimeter per service round, cal
T_g	average propellant gas temperature, °C

T_m melting temperature of gun barrel material, °C

T_c initial temperature of gun barrel material, °C

V mean flow velocity of propellant gas over surface, cm/sec

V(t) instantaneous average speed of surface regression, in/sec

W average recession of surface, in.

W_o observed wear per round, in.

δ density of gun barrel material, gm/cc

Introduction

This paper is a partial review of erosion studies performed by the Ballistic Research Laboratories (BRL) from 1945 to 1951. Early work was, in general a study of the erosion of vent plugs or nozzles such as those used in rockets and recoilless guns. Later the work was expanded to include relatively high performance guns with muzzle velocities up to 3000 feet per second (fps).

The BRL Erosion Program was designed to gain the best possible understanding of the weapon erosion phenomena and to develop a theory for describing it. I shall discuss some of the results of the program.

Discussion

There are two general mechanisms that cause erosion of guns by propellant gases. They are chemical and thermal. With high performance guns, thermal erosion appears to be the prime source of trouble. BRL has not considered chemical erosion in any of its work; therefore only a Thermal Theory for Erosion of Guns by Propellant Gases will be presented as developed by Jones and Brietbart of BRL.

The belief has been generally accepted that the erosion in guns near the origin of rifling is primarily caused by the removal of material by the washing action of the hot propellant gases. This is the most important area of consideration. It is supposed that the material is first converted to a plastic or molten state by heating before it is possible for the gas stream to remove it. Indications that the erosion is related to the heating of the bore is shown in Figure 1 where the observed wear per round, W_o, is plotted vs the calculated total heat input per centimeter squared per round, Q. The values of Q were calculated by the method of Nordheim, Soodak, and Nordheim[1] presented in NDRC Report A-262. The observed wear, W_o, is the initial rate of wear on the radius in a new gun, that is, one half the initial slope of the curve obtained by plotting the land diameter against the number of equivalent service rounds fired. For any Army gun, the number of equivalent service rounds was taken as the total propellant charge fired in the gun divided by the charge required to produce the normal service velocity. For Navy guns, the formula used was

$$N_e = \Sigma N_a \left(\frac{C_a}{C_s}\right)$$

where

N_e = number of equivalent rounds

C_s = service charge

C_a = actual charge

N_a = number of rounds fired with charge C_a.

because the values for Q are computed theoretically and the values of the parameters entering the computation are somewhat uncertain, possible large

1. Nordheim, Soodak, and Nordheim, Op. Cit.

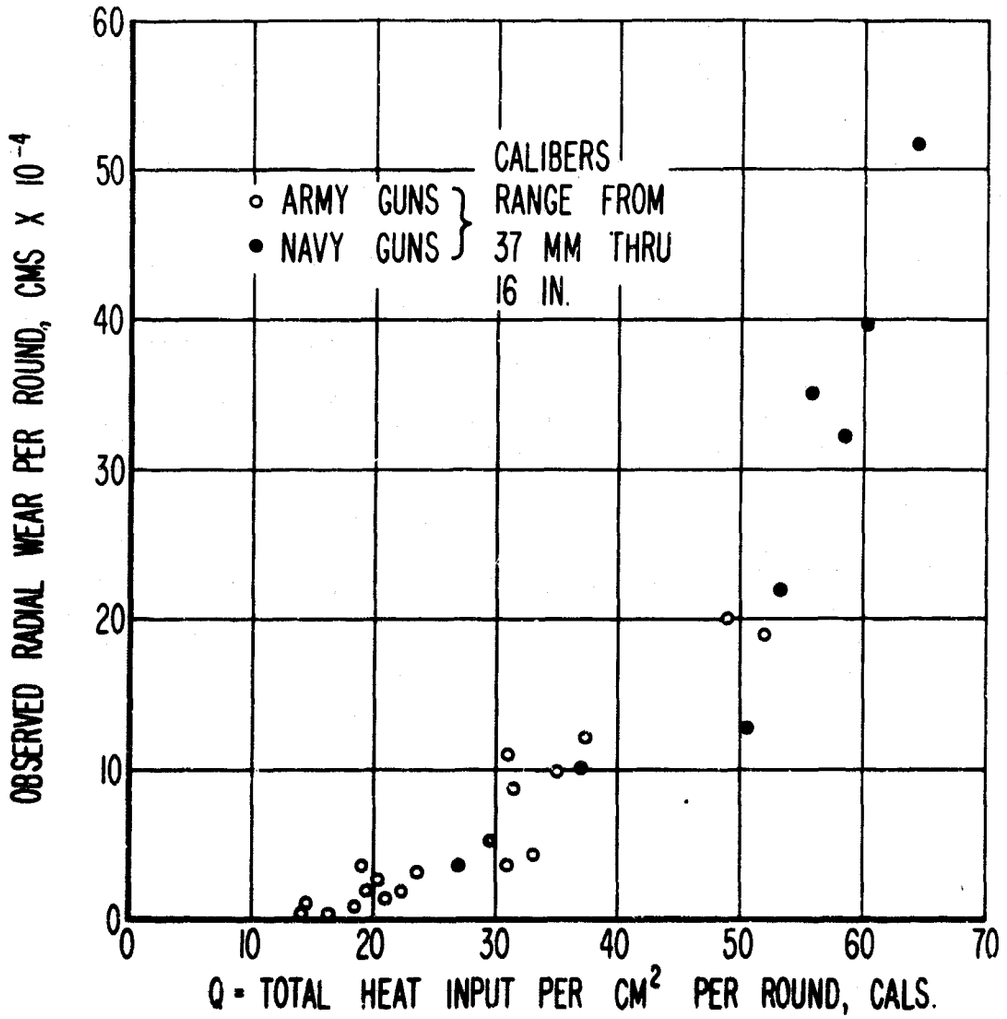

Figure 1. Observed Radial Wear per Round vs Calculated Heat Input per square centimeter per round

errors may exist in Q_s where Q_s is defined as the total heat input per square centimeter per service round.

The values of W_o for different guns cannot be determined with high precision from the available data. Data were generally recorded during firing of the guns for purposes other than erosion measurements so that the firing schedules on different tubes tend to vary greatly. Also, the data on some guns are more extensive than on others. The result is that the values of W_o, derived from the data for different guns, do not have the same statistical reliability. For the Army guns W_o was derived for only a few tubes in which data were carefully obtained and taken specifically to determine the erosion characteristics. Wear data for these tubes were measured along the vertical land diameter. For the Navy guns, W_o was an average value derived for several tubes in which the measurements were more extensive and the test conditions were more carefully controlled. The wear for the Navy guns was measured on the radius. Data taken on a single tube are shown in Figure 2. Figure 3 shows the type of data available for most of the Navy guns. For the above reasons, it is difficult to make an exact assessment of the significance of the plot in Figure 1, but at least it suggests that the chief cause of erosion near the origin of rifling is heating.

The problem of gas erosion in vents, based on the assumption that material is removed in the molten state by the frictional stress on the surface, has been treated by Nordheim, Soodak, Nordheim, and Landau[2].

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2. Landau, Quar. Appl. Math. 7 81 (1950).

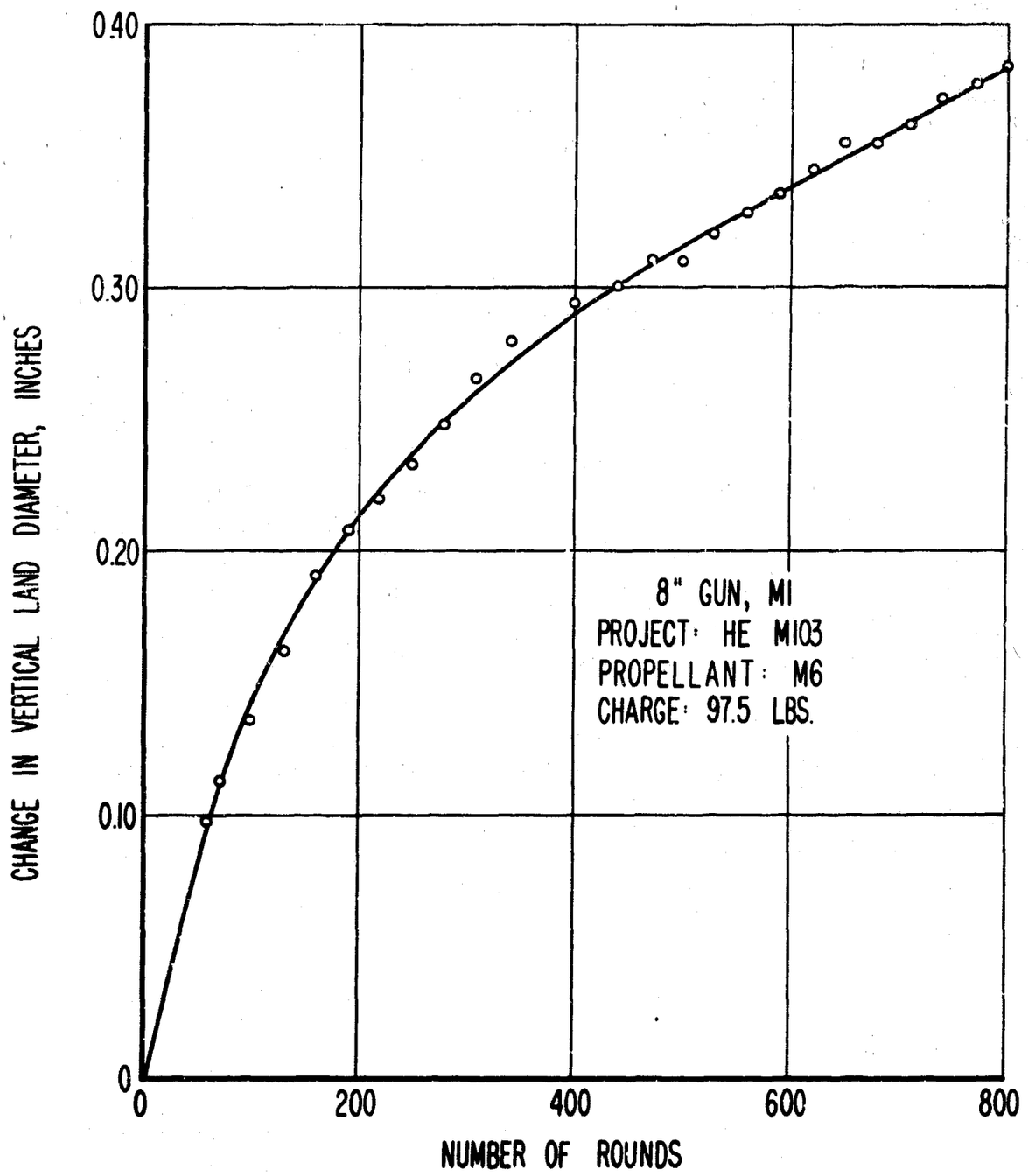

Figure 2. Change in Vertical Land Diameter at 0.1 in. from Origin of Rifling vs Number of Rounds

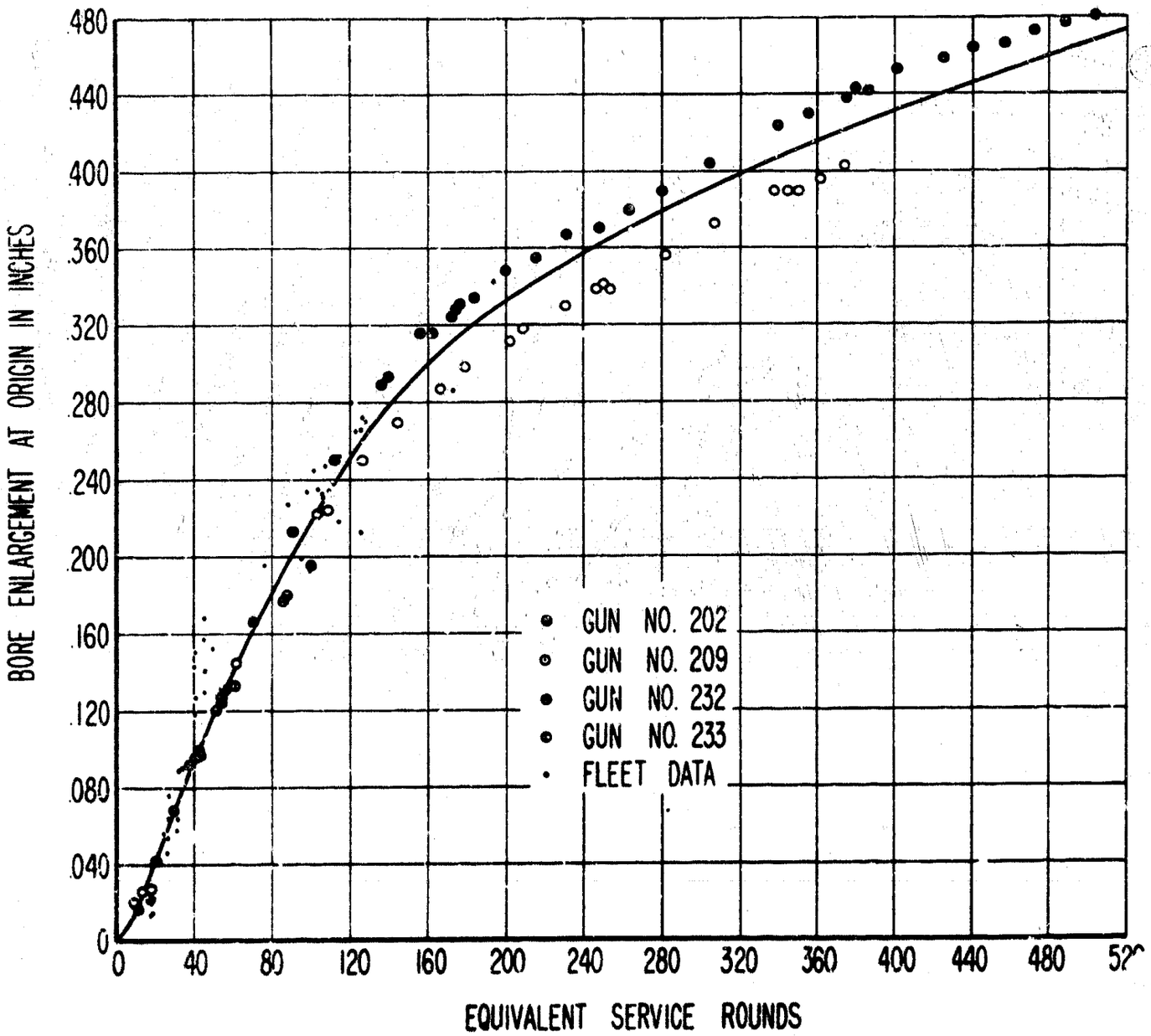

Figure 3. 16 in./45 Caliber Guns Mark 6 and 8 Bore Enlargement at Origin vs Equivalent Service Rounds

In these papers it is assumed that the surface can be represented by a sharply defined mathematical surface over which the temperature has a constant value at each instant. When the temperature of the surface reaches the melting point of the material the surface starts to regress uniformly, and for a uniform rate of heat input a steady state regime is established. After a predictable interval, when the temperature distribution ahead of the regressing surface is constant, the surface regresses with a constant velocity.

Attempts to fit the observed data from vent firings to the equations derived from this approach have not been successful. The principal difficulty arises from the fact that the derived rates of heat input from the erosion data are of such magnitude that the calculated time for the surface to reach the melting point is much longer than the time required for the efflux of the gases. A similar difficulty arises in the case of the melting theory of erosion in guns. The calculated maximum bore surface temperatures reached during the firing of the round are below the melting point of steel in most cases. A somewhat different approach is necessary based on a more realistic description of the phenomenon.

The surface is heat-checked and quite irregular. Indeed, from a molecular point of view even a ground and lapped surface would appear quite rough. The gas moving along the surface flows around projections and through cracks striking some parts of the surface at higher angles of incidence than others. Therefore the rate of heat input must be highly variable from point-to-point on the surface. Furthermore, because of the erosion, the contour of the surface is changing continuously and with extreme rapidity. It appears highly improbable that anything like a surface temperature exists except as a theoretical value. There will be "hot spots",

caused by the frictional force of the hot turbulent propellant gases striking small irregular metal protrusions distributed randomly over the bore surface which will erode if the local surface temperature is at the melting point. These "hot spots" will shift about on the surface in an irregular and quite unpredictable manner, and because of the high rate of heat input, "hot spots" at the melting point may exist even when the calculated average surface temperature is much below the melting point. There is no possibility of separating the erosion on melting from the overall heating or dividing the time of the event into two intervals - a warm up interval and a melting interval. The two phenomena go on together. Actually, if one computes the thickness of material that could be melted off the bore surface by the values of Q used in Figure 1 and compares these thicknesses with the observed values of W_o, one finds that the thicknesses calculated are from about 6 to 200 times as large as the observed values. The amount of heat entering into the erosion is evidently a relatively small part of the total heat input. It would appear that erosion near the origin of rifling must be considered as a secondary surface phenomenon which accompanies the heating of the barrel by the propellant gases.

If this theory is correct, the equations of Landau and others would be applicable only to the limiting case when the temperature of the whole surface is at the melting point. This condition does not seem to be reached in guns in general, and is reached in vents only under extreme conditions. What is required is the specification of an erosion function which relates the erosion to the interior ballistics and effectively determines what fraction of the heat input is responsible for the erosion in different cases. In the

following, an attempt is made to describe the erosion function. It is based on the assumption that the foregoing discussion of the probable nature of the phenomenon is correct, together with a number of plausible assumptions that lead to equations which yield results in good agreement with the observations.

The following situation exists. A turbulent stream of hot gas moves over the surface of the bore heating it and acting upon the surface as described previously. During a certain interval the surface will be eroded by melting at "hot spots." The instantaneous rate at which material is being removed may be averaged over the surface and will define an instantaneous average speed of surface regression V(t). The surface will recede on the average the amount W for each round fired. The value W is described by Equation (1).

$$W = \int_{t_1}^{t_2} V(t)dt \qquad (1)$$

where t_1 and t_2 specify the beginning and end of the erosion interval.

The value H(t) is the instantaneous rate of heat input to the "hot spots" per square centimeter

$$H(t) = V(t)B \qquad (2)$$

where B is the amount of heat necessary to melt a cubic centimeter of the bore material. B is given by

$$B = \delta[c(T_m - T_o) + L] \qquad (3)$$

where δ is the density, c the specific heat, and L the heat of fusion of

the bore material. T_m and T_o are the melting and initial temperatures of the bore respectively. For a typical gun steel (4140) values of δ = 7.8 gm/cc, c = 0.13 cal/gm/°C, and L = 60 cal/gm, with $T_m - T_o$ = 1400°C, B = 1.9×10^3 cal/cc.

It is assumed that H(t) is proportional to the difference between the average gas temperature, T_g, and the melting temperature of the bore material, T_m, and depends upon the specific heat at constant pressure, C_p; the density of the gas, δ_g; and upon the mean flow velocity, V, in the gas stream according to the relation

$$H(t) = AC_p \delta_g V(T_g - T_m) \qquad (4)$$

"A" is the erosion function mentioned above. It is assumed that C_p can be treated as a constant with δ_g, V, and T_g being time dependent variables that can be calculated with fair precision by the standard methods of interior ballistics.

By substituting Equations (2) and (4) in Equation (1), the resulting equation becomes

$$W = \frac{AC_p}{B} \int_{t_1}^{t_2} \delta_g V(T_g - T_m)dt = \frac{AC_p}{B} \int_{t_1}^{t_2} F(t)dt \qquad (5)$$

There are two quantities in this equation that must be determined, the time interval, $t_2 - t_1$, during which erosion takes place and the function A. To determine t_1 and t_2 the following procedure has been followed; theoretical values of F(t) are plotted, as shown in Figure 4 for the 8-inch gun. It is then assumed that if F is below the value required to form "hot

spots" on the surface, no appreciable erosion will take place. The minimum value for a gun such as a low-velocity Howitzer for which the erosion is negligible, is 200 x 10^4 cgs units. A horizontal line drawn at this level intersects the F(t) curve at two points for all guns having the same values of F. It is assumed that these two points define t_1 and t_2 and hence the interval during which erosion occurs.

The quantity A is probably not strictly independent of the time but it is assumed that a time average value can be determined which can be used for any particular case. "A" contains a part which takes account of the fact that not all of the area is eroding at once-but only the "hot spots." This part can be separated, but it is not quite clear how. Schemes other than the one presented may yield the same results. It appears plausible that the fraction of the eroding surface should be dependent on two factors. The first is the magnitude of the rate of heat input. If this rate is high, the occurrence and speed of the "hot spots" will be increased and A should depend directly on it. The second is the timing of the process. If the rate of heat input is high and reaches a high maximum value in a relatively short time, there will be a larger variation in temperature from point-to-point on the bore surface and in the fraction of the area at the melting point, hence erosion will be increased. In addition, the temperature gradient beneath the surface will be higher and the eroding areas will not spread so rapidly on the surface or be as well maintained as the molten material is removed. "A" should therefore depend inversely on the initial slope of the heat input curve.

The F(t) curve must be similar to the average heat input curve so that the same arguments hold, at least to a good approximation when the function F(t) is used in place of the overall heat input-time curve. It has therefore been assumed that the effects described previously may be considered by setting A proportional to F_m, which is the maximum value of F and is inversely proportional to F'_o which is the average slope of the F(t) curve up to the time t_1. Therefore

$$A = K_1 \frac{F_m}{F'_o} \tag{6}$$

where K_1 is a constant. Since F'_o is inversely proportional to t_1, Equation (6) can be rearranged to

$$A = Kt_1F_m \tag{7}$$

where K is also constant. With this value for A introduced, Equation (5) becomes

$$W = \frac{KC_p}{B} t_1F_m \int_{t_1}^{t_2} F(t)dt \tag{8}$$

To test the validity of this equation, data on wear were gathered from 18 Army and 11 Navy guns and values of W_o were determined as described earlier. Values of the increase in radius per round fired were calculated using Equation (8) and graphs similar to those presented in Figure 4 resulted. These graphs were prepared from theoretical calculations using the method of Nordheim, Soodak, and Nordheim.

The quantity K must be determined experimentally. This was done for each gun and the results are presented in Table I. Examination of the data shows that there are four guns for which the values of K depart widely from

the average value. These are the 57mm, M1 (firing HF rounds); the 90mm, T54E2; and the 155mm, M2 Army guns and the 3in./50 Navy gun. Of these the T54E2 has rifling of unconventional design, and the 155M2 has a much more gradual rise to full height of the lands than usual. Some of the Navy guns are chrome plated and the initial rate of wear is small until the thin chrome layer begins to strip off, then the rate of wear rises sharply. Values of W_o have been obtained for these guns from the slope of the wear curve in this latter region with questionable precision. This could account for the low value of K for the 3in./50. Also for this gun the data are very badly scattered and the value of W could vary considerably from that chosen. If the drastic departures can be explained in this way, it appears that K will be nearly constant for a homologous family of guns.

Results

The average value of K for all guns considered is 3.28×10^{-8}, and if the four "erratic ones" are omitted it is 3.26×10^{-8}. The average deviation from the mean in Condition I is 21 percent and in Condition II, 14 percent. The average value has been used to calculate W for the different guns. The results are listed in Table I and plotted in Figure 5 against the observed values of W_o. It can be seen that the points fall, in general, near the 45° line.

If one examines the equations for $w(\delta)$, it becomes evident that W and the individual empirically determined values of K will be very sensitive to the values of δV and $(T_g - T_m)$ since they enter the equation approximately to the second power. It is probable that T_g is less well known than the other quantities. For an M1 propellant, T_g is approximately 2400°K and $(T_g - T_m)$ about 700°K. An error of one percent in T_g is equivalent to

Table I. Tabulation of Wear Data for Weapons Considered in Erosion Research Program

Gun	Powder	Proj.	Nominal M.V.	$W(obs)_3$ cm x 10^3	K x 10^8	$W(calc)_3$ cm x 10^3	$W_{calc} - W_{obs}$	$\frac{W_{calc} - W_{obs}}{W_{obs}}$
Army			ft/sec					%
37mm M3	M2	A.P.	2300	.11	3.74	.097	-.013	-12
40mm M1	M1	H.E.	2870	.043	2.79	.050	.007	18
57mm M1	M6	APC	2700	.28	3.85	.239	-.041	-15
57mm M1	M6	H.E.	2700	.13	1.71	.250	.120	92
75mm T22	M1	H.E.	2300	.049	3.33	.048	-.001	- 1
76mm T91	M6	A.P.	4000	.38	3.96	.315	-.065	-17
3" M7	M6	APC	2600	.19	3.24	.192	.002	1
90mm M3	M6	H.E.	2700	.30	4.04	.244	-.056	-19
90mm T19	M2	APC	2650	1.10	3.18	1.137	.037	3
90mm T5	M6	APC	3300	1.90	4.27	1.462	-.438	-23
90mm T54	T12	APC	3300	2.00	3.41	1.920	.080	4
90mm T54E2	M6	APC	3200	1.20	8.40	.469	-.731	-61
120mm M1	M6	H.E.	3100	1.00	2.99	1.100	.100	10
6"	M6	TP	2800	1.20	3.28	1.202	.002	.1
155mm M2	M6	H.E.	2800	.36	1.57	.528	.168	47
155mm M1 How.	M1	H.E.	1850	.058	3.07	.062	.004	7
8" M1	M6	H.E.	2800	2.00	3.44	1.911	-.089	- 4
240mm M1 How.	M1	H.E.	2300	.44	3.50	.382	-.058	-13

Table 1, Cont'd

Gun	Powder	Proj.	Nominal M.V.	$W(obs)_3$ cm x 10^3	K x 10^8	$W(calc)_3$ cm x 10^3	$W_{calc} - W_{obs}$	$\frac{W_{calc} - W_{obs}}{W_{obs}}$
Navy			ft/sec					%
3"/50 Mk2	NH		2700	.15	1.77	.279	.129	86
5"/38 Mk12-1	NC		2600	.34	1.61	.498	-.158	-46
5"/51 Mk7&8	NC		3150	.86	3.84	.735	-.125	-14
5"/54 Mk16	NC		2650	.51	2.87	.583	.073	14
6"/47 Mk16	NC		2500	.83	2.25	1.212	.382	46
8"/55 Mk15	NC		2500	1.27	2.60	1.605	.335	26
12"/50 Mk8	NC		2500	2.21	2.58	2.815	.605	27
14"/45 Mk12	NC		2600	3.95	3.37	3.852	-.098	2
14"/50 Mk11	NC		2700	3.55	3.55	3.287	-.263	- 7
16"/45 Mk6	NC		2300	3.25	3.12	3.424	.174	5
16"/50 Mk7	NC		2500	5.13	3.84	4.390	-.740	-14

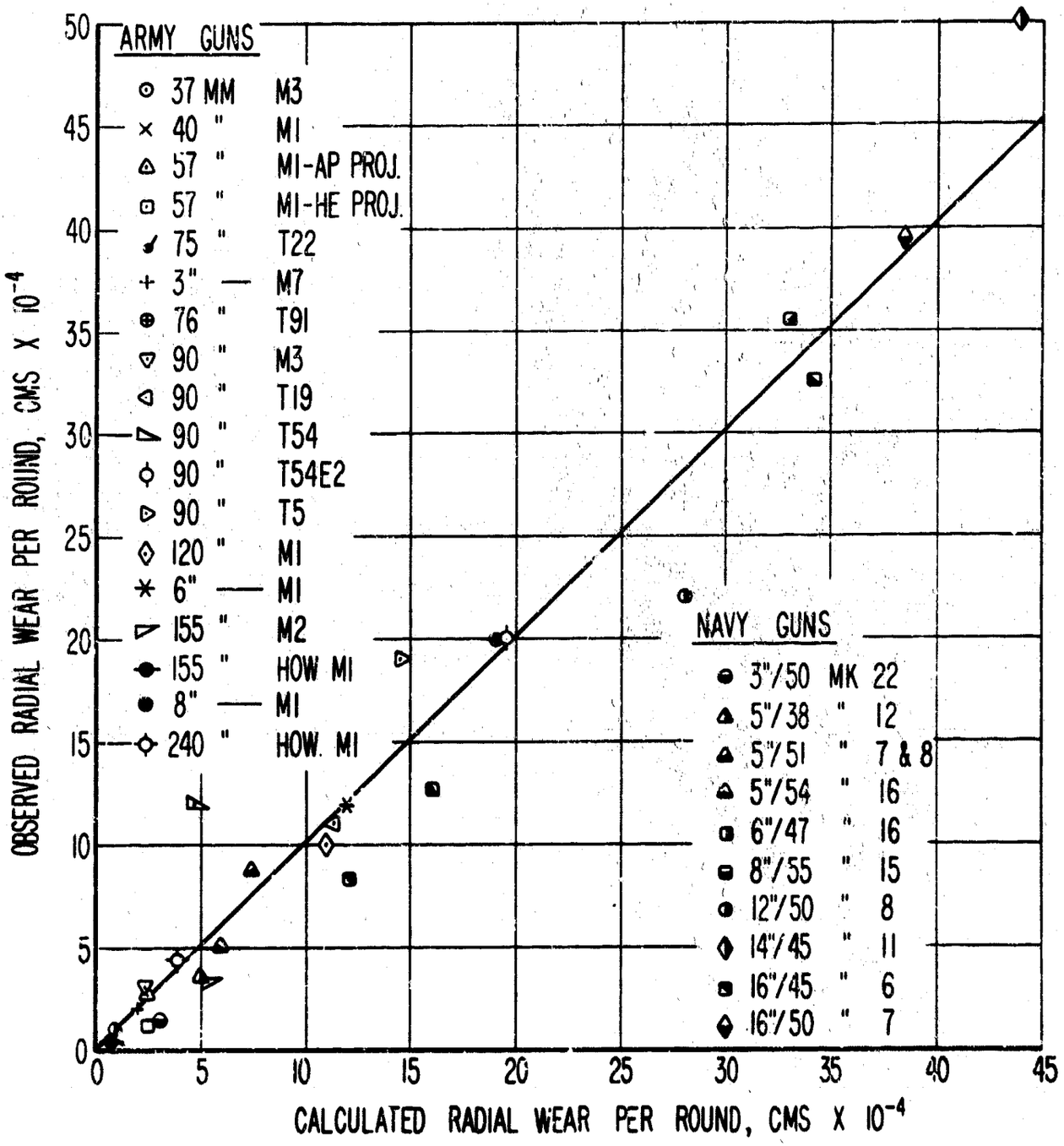

Figure 5. Observed vs Calculated Radial Wear per Round

3.5 percent in $(T_g - T_m)$ which could produce an error in W of over 10 percent. It is improbable that the theoretical value of $(T_g - T_m)$ is better than $\pm$ 50°C or about 7 percent. This alone is large enough to account for most of the variations in W and in the individual values of K. A study of Table I reveals that a wide range of calibers, peak pressures, muzzle velocities and propellant can be covered with a single value of K.

Conclusion

How K will change from one type of gun to another is unknown. It is dependent upon the bore material, but this dependence will be important only for guns with liners of materials other than steel. The worst cases in Table I indicate that K is quite sensitive to the design of the forcing cone, origin of the lands, type of rifling, and the design and material of the projectile rotating band. The present theory is entirely thermal and the dependence of K on different gun designs is believed to be due mainly to differences in preheating of the bore surface by passage of the projectile. If this is so, it should be possible to develop a new function of the initial bore temperature in Equation (7) so that a new and more universal K could be obtained. Since preheating effects are almost completely unknown, the numerical value of the new function would be rather difficult to determine and showing it explicity in Equation (8) would be of no practical value.

An understanding of the dependence of K on the bore surface temperatures is unimportant if the theory is to be applicable to guns fired rapidly. K will probably increase rapidly as the gun heats up. In this

connection some data on vents is interesting. The wear per round as a function of initial vent temperature is shown in Figure 6. This figure shows that the relationship between the wear per round and initial vent temperature is reasonably well represented by a straight line, and that the rate of wear approximately doubles for an increase in vent temperature of about 600°C.

Equation (8) relates the wear to the interior ballistics of the gun. The caliber does not enter specifically but affects the results only insofar as it determines the course of the plot in Figure 4. The theory, as developed, leads to the conclusion that two guns of similar design would have equal values of K and the same radial wear per round, regardless of bore diameter.

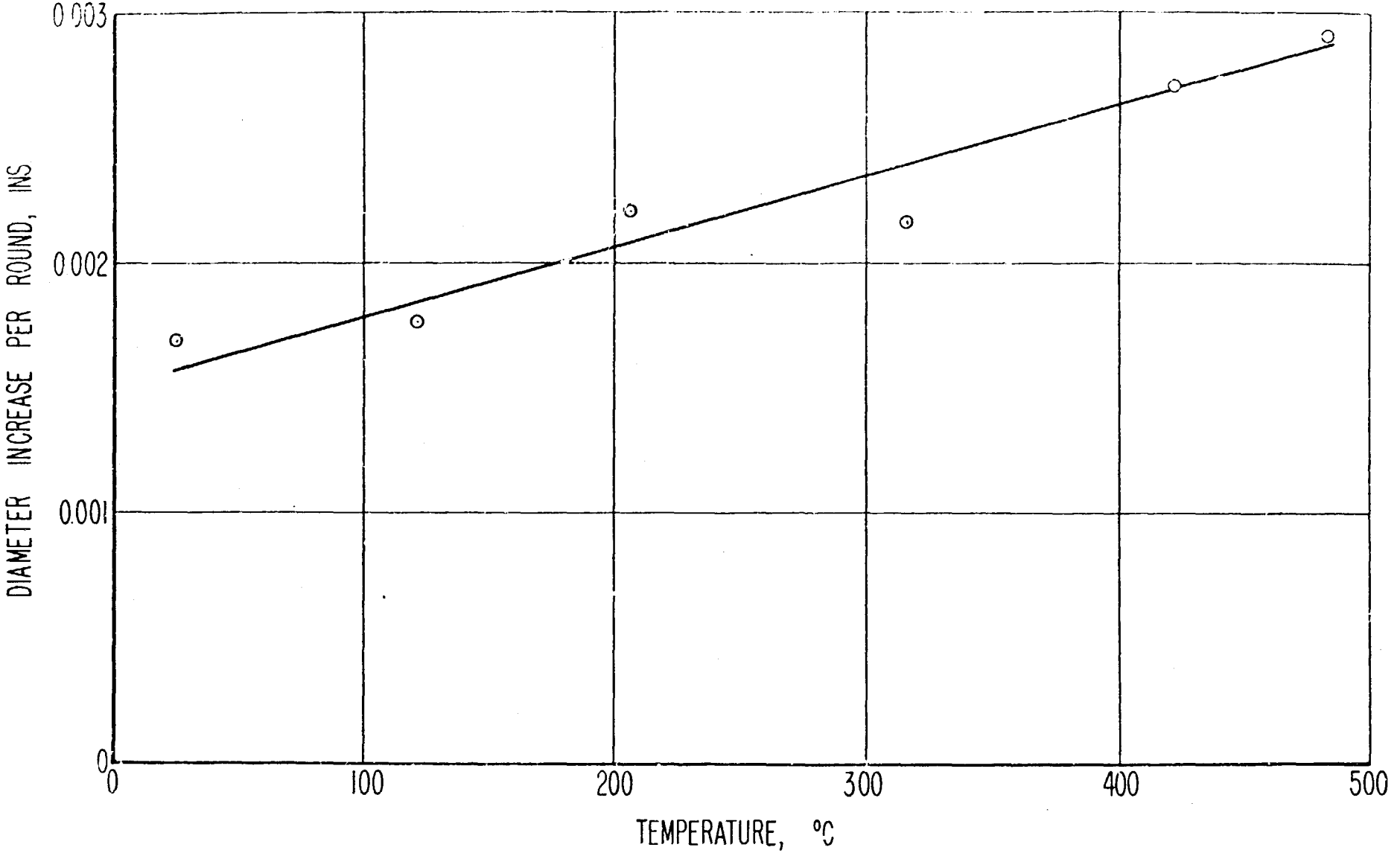

Figure 6. Effect of Initial Vent Temperature on Erosion

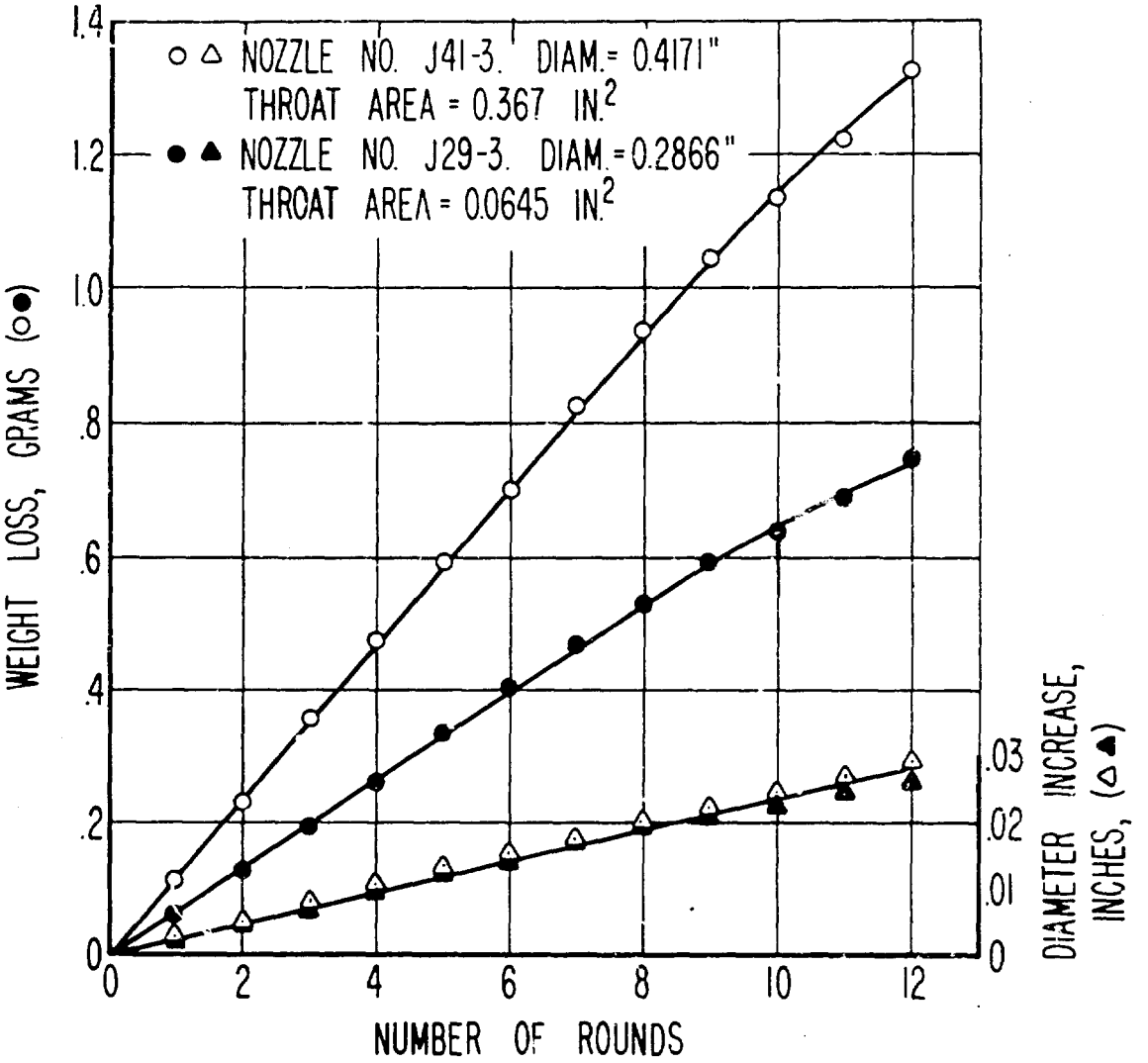

Figure 7. Weight Loss and Diameter Increase Vs Number of Rounds

GUN BARREL EROSION

IN SMALL CALIBER WEAPONS

R. P. O'Shea
T. Watmough

IIT Research Institute
Chicago, Illinois 60616

ABSTRACT

Erosion of barrel materials is a factor which is posing limitations on the design, development, and rate of fire of high performance rapid-fire weapons. This problem essentially revolves around the lack of specific thermal properties which are obtainable in the majority of current gun barrel materials. Melting point, thermal diffusivity, specific heat, high-temperature strength, and resistance to thermal cracking are properties which must be optimized for the anticipated application. IIT Research Institute, under contract with the U.S. Air Force is conducting a program to characterize the nature of the problem and to evaluate a series of refractory metals to standard gun steels.

A vented bomb fixture, developed at IITRI, has been utilized as the prime test apparatus. This simulates the thermal environment and pressure-time pulse encountered in the bore of a high performance gun. Materials which have been evaluated in this fixture have been examined for changes in weight, dimension, metallographic structure, hardness, and surface condition.

INTRODUCTION

Ballistic erosion of gun barrels has been a problem in ordnance for many years. The problem has become acute more recently with the development of rapid-firing guns and the demand for higher projectile velocity. These objectives require higher propellant-to-projectile ratios, resulting in the necessity for higher performance barrel materials than are obtained by current gun steels. Gun erosion not only limits the length of burst in current rapid-fire weapons, but has also inhibited the development of new weapon systems.

The major factors controlling the performance life of a material for a rapid-fire gun barrel are:

1. Thermal resistance--material interaction with a high temperature, high velocity, chemically reactive gas stream.
2. Thermal fatigue resistance--cracking phenomenon associated with repeated temperature cycling in a reactive environment.
3. Corrosion fatigue resistance--crack initiation and propagation produced by stress cycling in a reactive environment.

Additionally, thermal-mechanical factors which arise from interaction of the rotating band of the projectile with the gun barrel may also be of importance. The present consensus, however, is that these phenomena are of secondary importance for most materials.

The materials problem can therefore be stated as that of developing a material which has sufficient high-temperature strength and corrosion resistance properties to withstand the extremely severe environment which exists in or near the breech area of weapons.

EXPERIMENTAL WORK

The present study was undertaken to evaluate the erosion resistance of certain metallic materials in a high-performance gun barrel environment. The vented bomb experimental technique was utilized to evaluate the erosion resistance of the candidate materials. The IITRI vented bomb is schematically shown in Figure 1; it consists of a breech modified to accept a shortened 20mm cartridge case, a lead-in section which narrows the bore to 0.308 in., a 2 in. test section, and a burst diaphragm.

For this study M2 propellant was specified. A maximum of 52,500 $\pm$ 3,000 psi pressure was to be achieved in a rise time of about 1 millisecond. It was estimated that about 28 to 30 g of propellant would be required to produce severe erosion in AISI 4140 steel in one shot. A computer analysis with the above input data indicated that M2 propellant with a webbing of 0.030 in. would be required.

Proof testing with AISI 4140 steel inserts revealed that a peak pressure of 52,500 $\pm$ 3,000 psi in a rise time of 1.5 milliseconds could be consistently achieved. A typical pressure-time pulse is shown in Figure 2. In this figure, there are two traces:

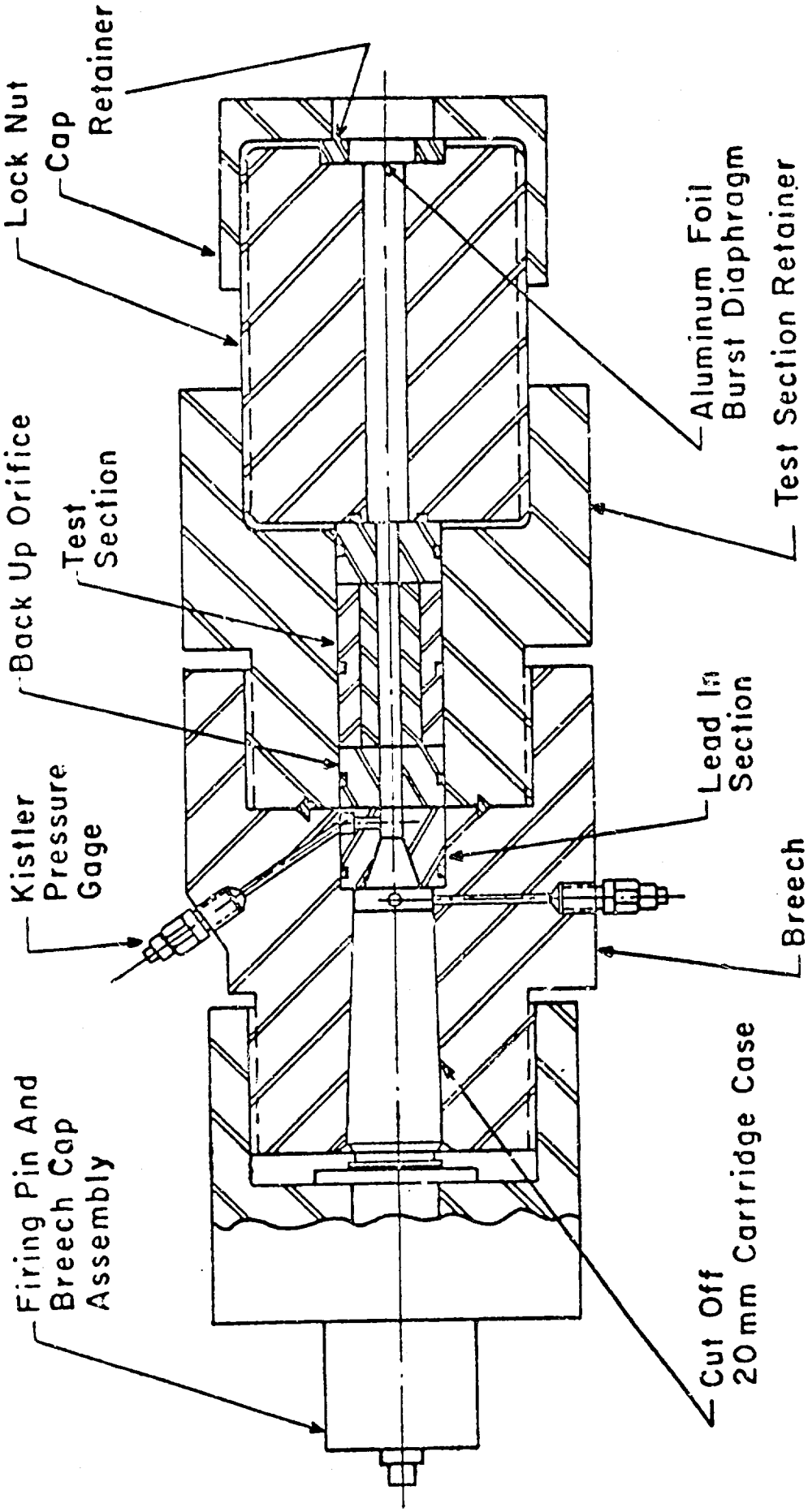

Figure 1. Schematic View of the Vented Bomb Fixture.

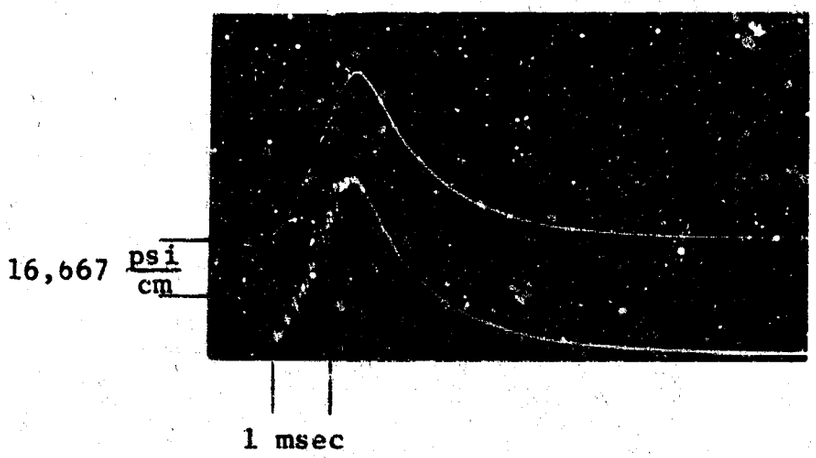

Figure 2. Typical Time-Pressure Pulse of Vented Bomb Test with 28.25 g of Propellant.

one is the unfiltered pressure-time signal, and the other is the signal after passing through a filter. Three shots at 50,000 psi produce a weight loss of 0.948 g for AISI 4140 steel.

The experimental plan was to evaluate candidate materials after 1 and 3 shots. Table I lists the candidate materials and some of their relevant physical properties. The evaluation consisted of a determination of weight loss, boroscope measurements along the length of the test specimen, detailed metallographic analysis, and examination of bore surface under the scanning electron microscope (SEM).

EXPERIMENTAL RESULTS

It should be stressed that the program is still underway; however, the results of the single-shot tests can be reported. Table II summarizes the weight loss and peak pressure data for the single-shot firings. Table III summarizes the boroscope measurements associated with these specimens. Examination of these data indicate that the relative weight loss experienced is relatively constant within any one family of materials--e.g., comparing molybdenum alloys which exhibit minimal weight change to the group of columbium alloys. Some of the materials (hafnium alloys, zirconium, and titanium alloys) experienced large weight losses, and in these instances the peak pressures were significantly increased over the basic 52,500 psi. The boroscope measurement generally reflects the trend shown for the weight loss data.

The photomicrographs of transverse sections of selected materials, after firing 1 shot, are shown in Figures 3 through 12. Evidence of surface reactions can clearly be observed in Figures 10,

TABLE I

THERMAL PROPERTIES OF MATERIALS SELECTED FOR EVALUATION

Material	Melting Point °F	Thermal Conductivity at 212°F Btu/hr/ft^2/°F/ft	Specific Heat at 70°F, Btu/lb/°F	Heat of Fusion, Btu/lb
Tungsten	6200	96 0	0.034	70
Tantalum	5420	31.5	0.036	68
Ta-10W	5520	30	0.036	-
T-222 (Ta base)	5400	30	0.036	-
Molybdenum	4730	84.5	0.065	125
Mo-0.5Ti	4730	84.5	0.065	-
TZM (Mo base)	4700	84.5	0.065	-
Columbium	4474	31.5	0.065	124
Cb-752	4400	31.5	0.060	-
C-129Y (Cb base)	4300	31.5	0.065	-
Hf-50Ta	3950	15	0.035	-
Hf-20Ta-3Mo	3900	10	0.035	-
Zirconium	3350	9.6	0.07	110
Titanium	3040	9.8	0.125	188

TABLE II

WEIGHT LOSS AND PEAK PRESSURE DATA FOR EROSION SPECIMENS

Material	Initial wt, grams	Final wt, grams	Wt Loss, grams	Pressure, ksi
Tungsten	221.1004	221.0934	0.0070	52.5
		Tantalum Alloys		
Tantalum	192.4388	192.2474	0.1914	52.5
Ta-10W	195.5627	195.4866	0.0761	52.5
T-222	193.6252	193.5350	0.0902	52.5
		Molybdenum Alloys		
Molybdenum	117.4457	117.4470	-0.0013	52.5
Mo-1/2%Ti	117.3675	117.3724	-0.0049	52.5
TZM	117.4170	117.4155	0.0015	-
		Columbium Alloys		
Columbium	97.6269	97.3432	0.2837	52.5
Cb-752	104.3738	104.1288	0.2450	52.5
C-129Y	109.0647	108.8656	0.1991	52.5
		Hafnium Alloys		
Hf-50Ta	96.1781	90.4709	5.7072	58
Hf-20Ta-3W	159.7351	147.6817	12.0534	67
Zirconium	75.2558	58.1962	17.0546	70
Ti 8-1-1	50.4943	41.5543	8.9400	60

TABLE III

BOROSCOPE MEASUREMENTS AFTER ONE SHOT

Material	Total Weight Loss, g	Specific Weight Loss, mg/cm^2	Average Diametral Bore Increase, mils	
			Inlet	Outlet
Zirconium	17.0596	1360	73.2	153.5
Mo-1/2%Ti	-0.0049	--	-0.8	-0.3
Ti 8-1-1	8.9400	712	75.4	121.7
C-129Y	0.1991	15.9	1.0	0.4
TZM	0.0015	0.120	-0.4	-0.3
Tantalum	0.1914	15.3	1.3	0.6
Columbium	0.2837	22.6	2.2	1.5
Cb-752	0.2450	19.5	1.6	1.1
T-222	0.0902	7.19	-0.3	-0.1
Tungsten	0.0070	0.558	-0.1	-0.2
Molybdenum	-0.0013	--	-0.4	-0.4
Ta-10W	0.0761	6.16	+0.1	-0.5
Hf-50Ta	5.7072	455	5.1	30.0
Hf-20Ta	12.0534	961	11.2	64.1

Neg. No. 37659 500X Neg. No. 37666 500X

(a) Unetched

(b) Etchant: 10 w/o HF, 10 w/o $K_3FE(CN)_6$, 80 w/o H_2O.

Figure 3. Transverse Section Showing the Bore Surface of the Tungsten Insert.

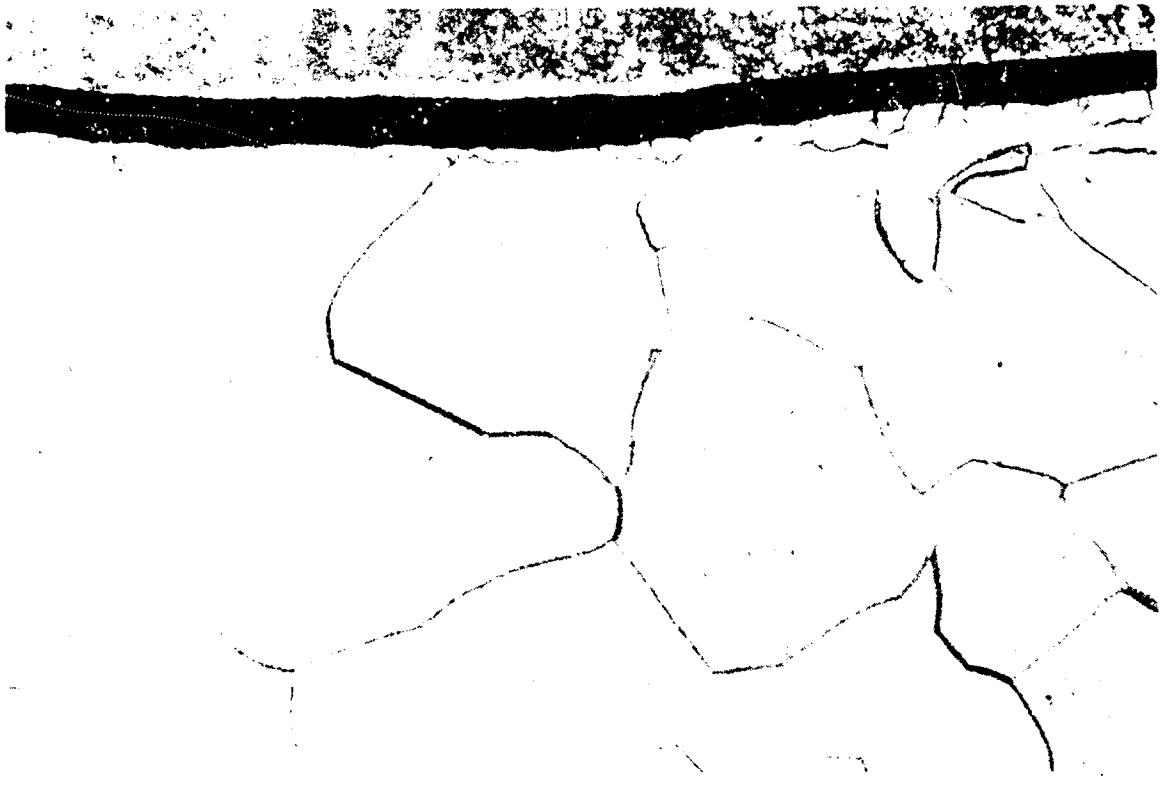

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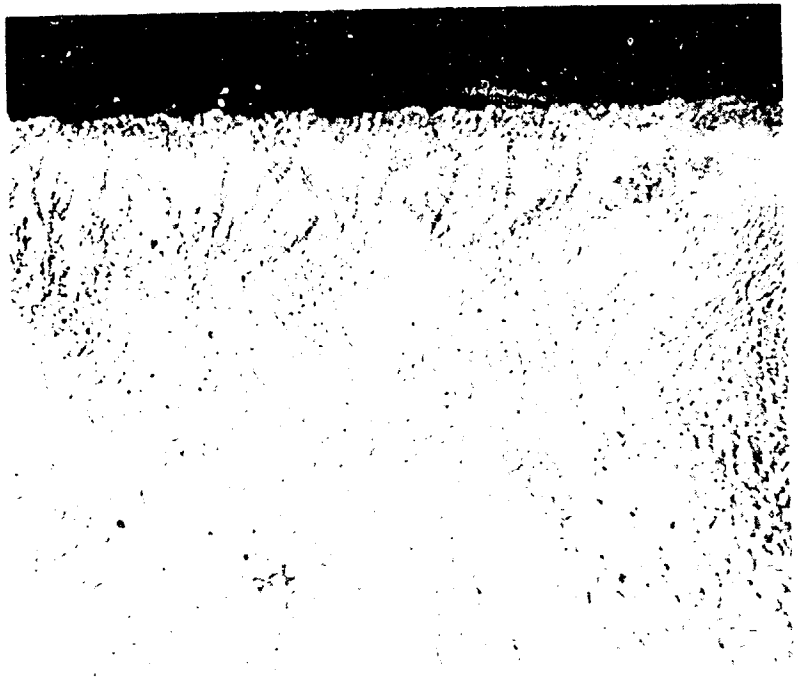
Figure 4. Transverse Section Showing the Bore Surface of the Tantalum Insert.

Etchant: 30 ml H_2SO_4, 30 ml HF, 30 ml H_2O, 2 drops H_2O_2.

Neg. No. 37657 500X

(a) Unetched



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(b) Etchant: 12.5 ml HF, 25 ml HNO_3, 50 ml H_2O, 4 drops H_2O_2.

Figure 5. Transverse Section Showing the Bore Surface of the Ta-10W Insert.

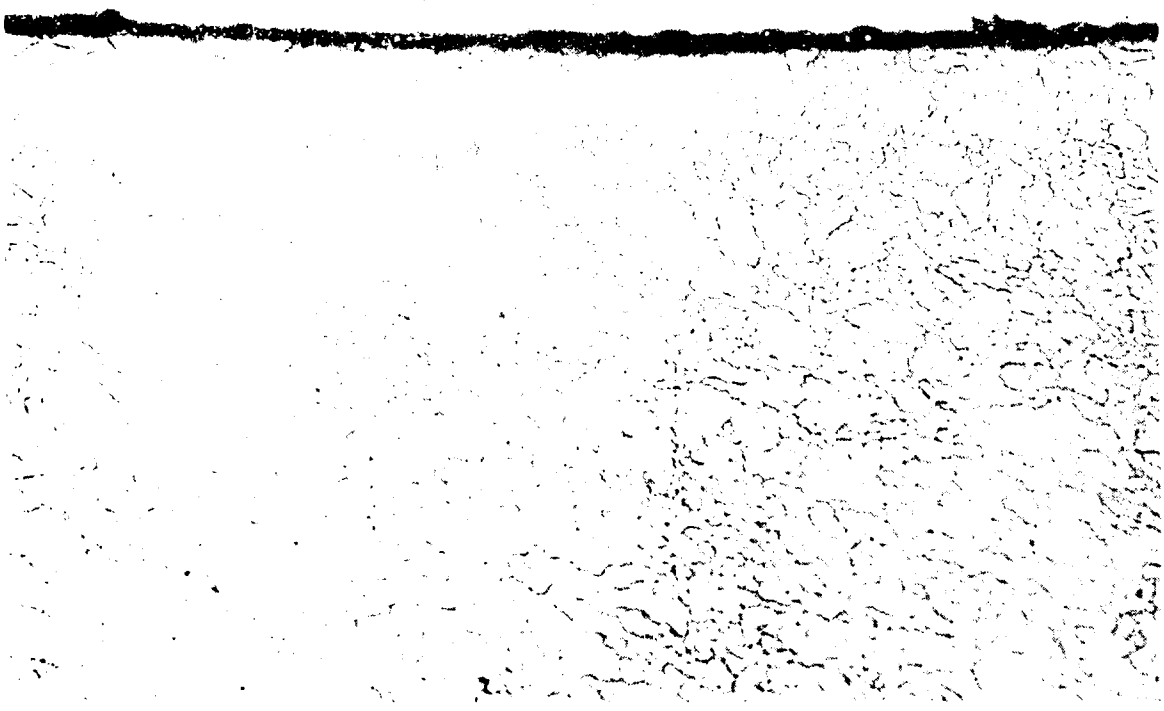

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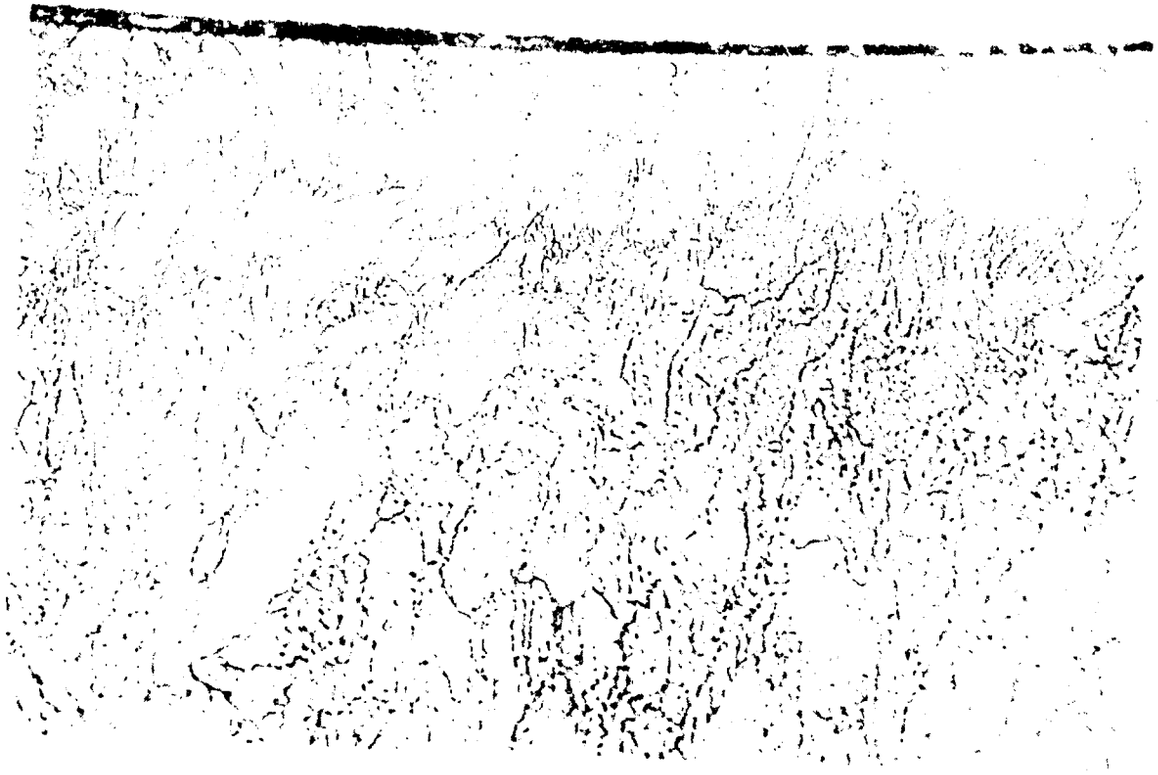
Figure 6. Transverse Section Showing the Bore Surface of the Mo Insert.

Etchant: 10 w/o NaOH, 10 w/o $K_3Fe(CN)_6$, 80 w/o H_2O.



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500X

Figure 7. Transverse Section Showing the Bore Surface of the Mo-1/2% Ti Insert.

Etchant: 10 w/o NaOH, 10 w/o $K_3Fe(CN)_6$, 80 w/o H_2O.

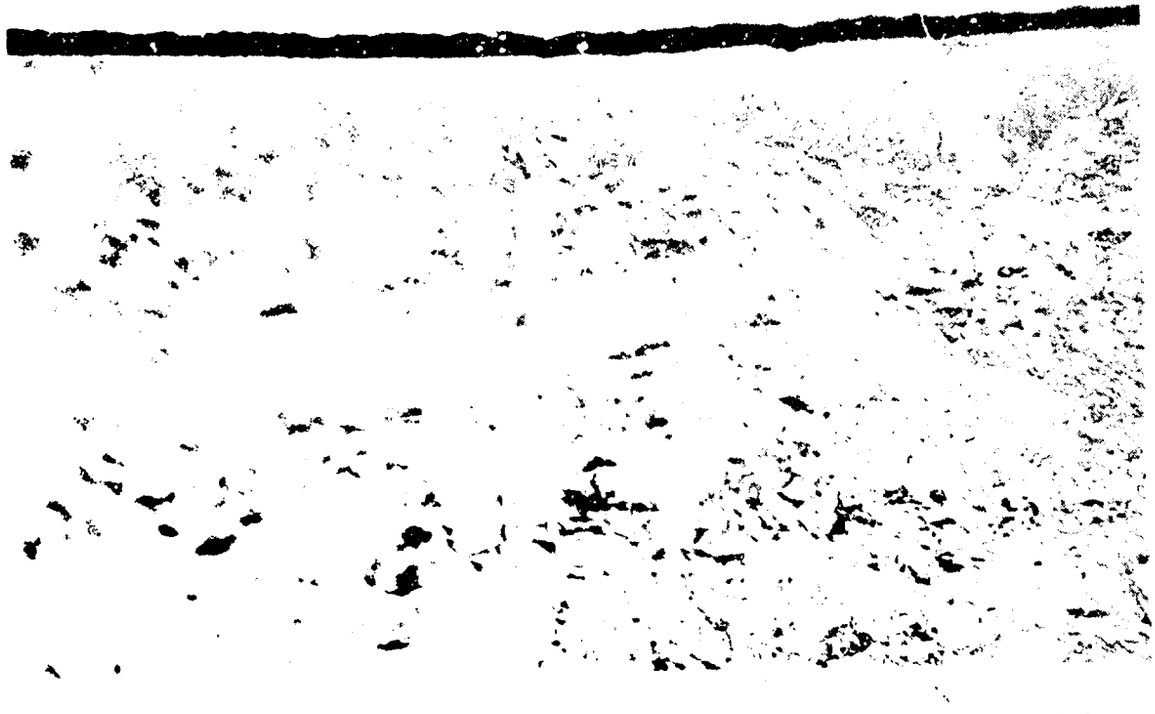

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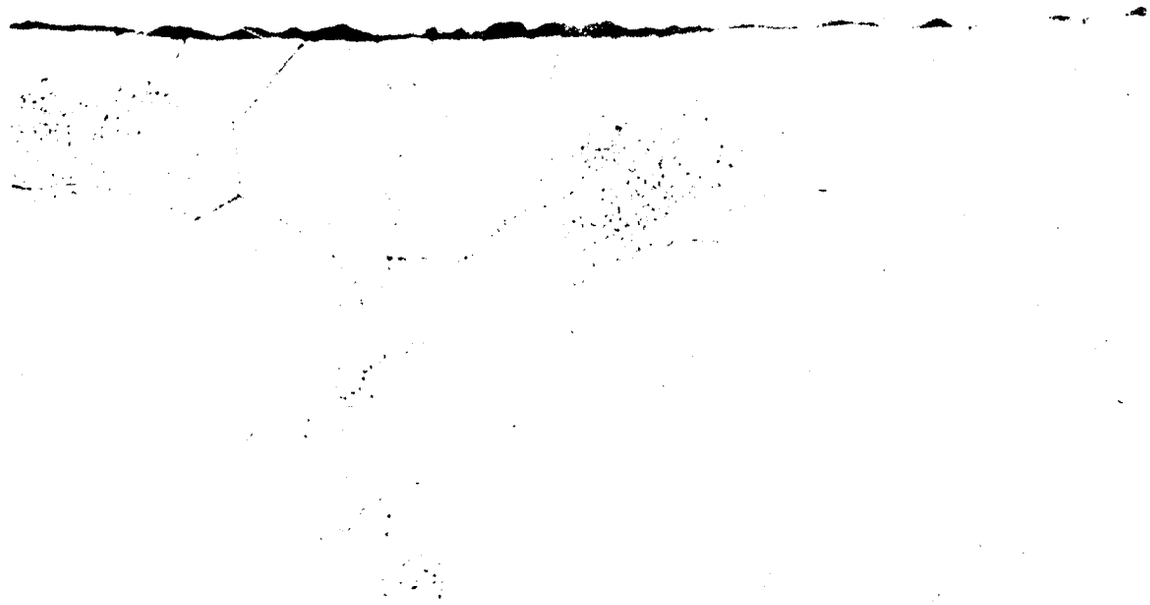
Figure 8. Transverse Section Showing the Bore Surface of the TZM Insert.

Etchant: 10 ml HF, 10 ml HNO_3, 30 ml glycerin.



Neg. No. 37665 500X

Figure 9. Transverse Section Showing the Bore Surface of the Cb-752 Insert.

Etchant: 10 ml HF, 10 ml HNO_3, 30 ml glycerin.

Neg. No. 37669 500X

Figure 10. Transverse Section Showing the Bore Surface of the Hf-50Ta Insert.

Etchant: 30 ml H_2SO_4, 30 ml HF, 30 ml H_2O, 2 drops H_2O_2.

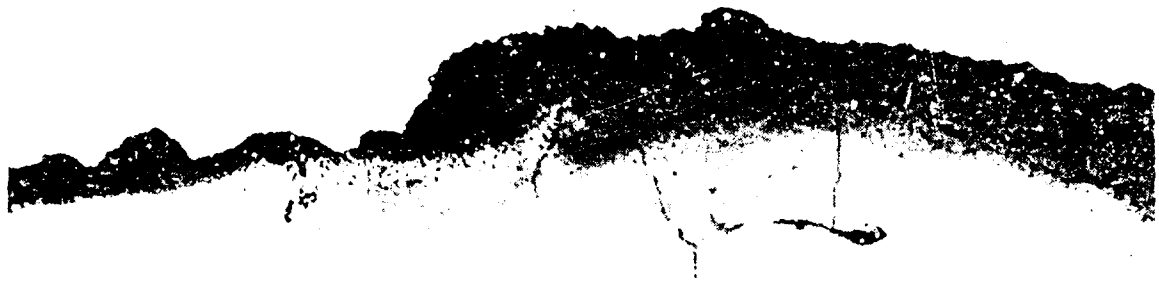


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Figure 11. Transverse Section Showing the Bore Surface of the Zirconium Insert.

Neg. No. 37662 500X

Figure 12. Transverse Section Showing the Bore Surface of the 8Al-1Mo-1V Titanium Alloy Insert.

Etchant: 10 ml HF, 10 ml HNO_3, 30 ml glycerin.

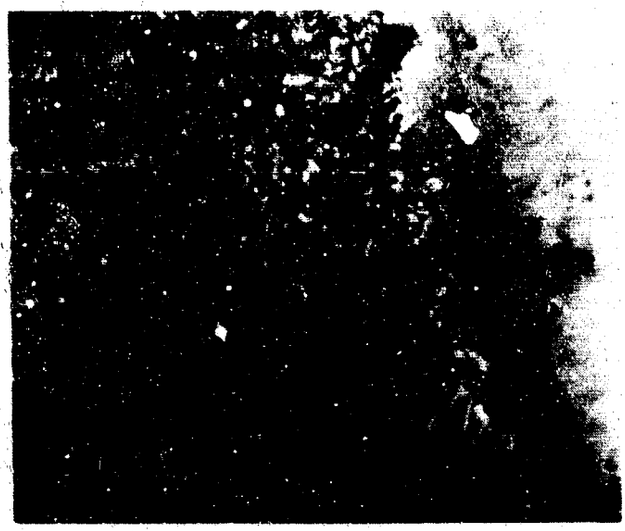
11, and 12 for Hf-Ta, zirconium, and titanium alloys, respectively. Figure 4, the commercially pure tantalum alloy shows a most unusual surface behavior where the large grains appear to be fragmenting at the bore surface. In the tungsten insert and the Ta-10W insert deep cracks were detected by the standard metallographic examination.

The scanning electron micrographs of bore surfaces further revealed that cracking had occurred in many of the materials. Figure 13, commercially pure tungsten, shows a longitudinal surface crack of considerable magnitude at the inlet end of the insert. Figures 14 through 16 show that cracking occurred in all the tantalum-base alloys which were examined. Figure 17, columbium-base alloy Cb-752, shows that cracking can be induced in this alloy from a single shot.

DISCUSSION

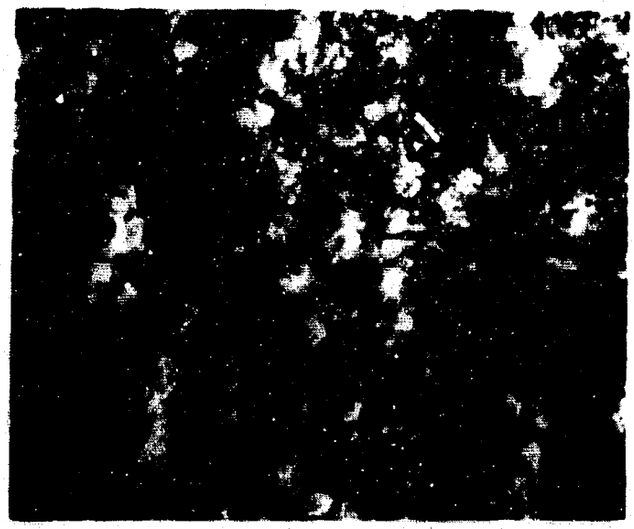
Material Reactivity

Tungsten, the tantalum alloys, the molybdenum alloys, and the columbium alloys behaved in a similar manner in the vented bomb environment. For these materials the peak pressure remained at 52.5 + 3 kpsi. The hafnium alloys, zirconium, and the 8Al-1V-1Mo titanium alloy underwent a gas-metal reaction in the test environment. This is apparent because of the excessive weight losses and the increases in peak pressure. Examination of thermodynamic data on the oxidation of these materials indicates that they would be highly reactive in a typical high-temperature propellant gas environment.



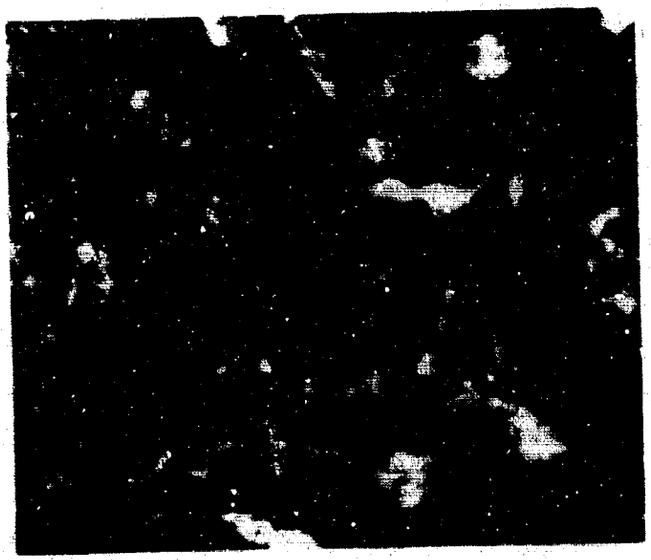
300X

Figure 13. Scanning Electron Micrograph of the Bore Surface of the Tungsten Insert Near the Inlet End.



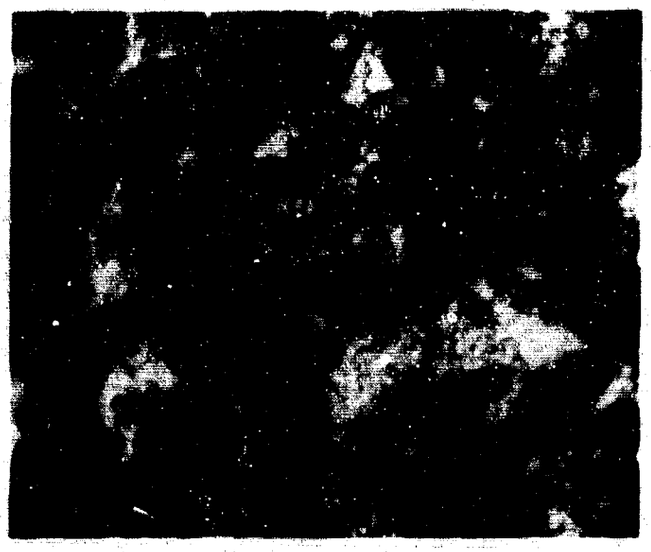
3000X

Figure 14. Scanning the Electron Micrograph of the Bore Surface of the Ta-10W Alloy Insert Near the Inlet End.



1000X

Figure 15. Scanning Electron Micrograph of the Bore Surface of the T-222 Tantalum Alloy Insert Near the Inlet End.



1000X

Figure 16. Scanning Electron Micrograph of the Bore Surface of the Tantalum Insert Near the Inlet End.

5000X

Figure 17. Scanning Electron Micrograph of the Pore Surface of the Cb-752 Columbium Base Alloy Insert Near the [illegible]

Effect of Thermal Properties

The melting points, specific heats, thermal conductivities, and heat of fusion for the materials test fired are listed in Table I.

Excluding the highly reactive materials, there does not appear to be an exclusive dependence of erosion on the melting point of the bore material. This observation is based on the outstanding performance of the molybdenum alloys which have a melting point of 4730°F vs. 5500°F for the tantalum alloys, 6200°F for tungsten, and 4400°F for the columbium alloys. It should be emphasized that this observation is based on a restricted spectrum of materials and their performance in only an M2 environment. Within this realm, it appears that for erosion resistance against a specific propellant, a combination of physical and chemical properties is required.

Examination of the combined thermal properties of the Cb alloys, the Mo alloys, the Ta alloys, and tungsten provides a rationale for the relative material performance in a one-shot environment. In the tests, the flame temperature of the M2 propellant (~5850°F) exceeds the melting point of all the materials except tungsten. In considering the probability or degree of incipient melting, the specific heat, thermal conductivity, and heat of fusion of the material are of importance. For the Cb alloys, the heat available from the gas could readily cause melting. Opposing the melting is the relatively high specific heat, high melting point, and high heat of fusion but the relatively low thermal conductivity of Cb would tend to promote local melting. An additional

factor which should be considered is the reactivity potential of Cb in the hot gas environment to form an oxide. If Cb_2O_5 is formed on the bore, the melting point of this surface would drop to about 2700°F, and the probability of melting would be increased.

The tantalum alloys have a high melting point but low specific heat, thermal conductivity, and heat of fusion. The flame temperature exceeds that of the Ta by about 400°F so that, in spite of the other poor thermal properties, only limited melting could occur. The reactivity of Ta in the burning propellant environment is expected to be less than Cb and more than Mo and W. If Ta_2O_5 is formed, it would be a relatively minute quantity; and since its melting point is about 3950°F, melting resistance would be higher than Cb_2O_5.

The molybdenum alloys have high melting points, high thermal conductivity, high specific heat, high heat of fusion, and low reactivity potential in a propellant gas environment. Because of these factors, this class of materials has excellent erosion resistance to the propellant considered.

Tungsten had the highest melting point of the alloys evaluated. With the M2 environment, the tungsten bore surface would not melt. Since the reactivity of tungsten in this type of environment would be low, it would encounter no thermal deficiencies and would perform quite well in the vented bomb.

Cracking

Tungsten, columbium alloy Cb 752, and all of the tantalum alloys exhibited longitudinal cracks on the bore surface after one

shot in the vented bomb. This behavior could be particularly dangerous since a gun barrel of one of these materials could fail catastrophically in a service test. Considering the fair ductility in tensile tests, particularly of the Ta-10W alloy, cracking in one shot was not the result anticipated. Obviously, the rate of application of both mechanical and thermal stresses in this program was far greater than heretofore considered. The existing experimental data indicate that the ductility of most alloys decreases with an increasing rate of loading. The data of this program show that the ductility decreases with increasing loading rate. Consequently, the strain-rate sensitivity of the material is of more importance than low strain-rate ductility.

At this time, the exact mechanism of cracking in these materials is not clear. In any case, cracking should have occurred under conditions which generated a tensile stress at the bore surface. This condition could prevail as a result of either (1) mechanical stress induced by pressurization, or (2) a thermal stress generated by the temperature excursion.

During the cooling cycle, the bore surface stress will become tensile, if, at any time, the surface region cools to a temperature below that of the underlying material. This is possible on test inserts because of the very short heat-pulse followed by dissipation of the energy by conduction during cooling. The depth of crack propagation on the first cooling cycle is dependent on the magnitude of the transient thermal stress. Cracking will progress as long as the thermal stress in the insert exceeds the critical

fracture stress at the base of the crack. Once a longitudinal crack is generated, rapid propagation by the stresses on subsequent firings can proceed. The depth of crack propagation per cycle is then controlled by the critical fracture stress (fracture toughness) of the material.

It should be emphasized that the results reported are preliminary and work is continuing.

ACKNOWLEDGMENTS

The work reported in this paper was performed under Contract F08635-69-C-0108 and supported by the Air Force Armament Laboratory, Eglin Air Force Base, Florida. The guidance and assistance of Mr. D. Davis and Lt. D. Ingram is gratefully acknowledged.

3.2 DISCUSSION:

William T. Ebihara: In evaluating the results of the weight loss data for W-, Ta- and Mo alloys, could the formation of the volative oxides account for the unexpected results for the Mo alloys?

R. P. O'Shea: W- and MO oxides would sublime. Consequently, a weight decrease would occur. Since W- and Mo are only slightly more reactive than Fe, it would be expected that only slight oxidation would occur. For Ta, Ta_2O_5 probably formed and this accounts for the relatively poor performance.

Thomas O'Keefe: Were any X-ray analyses of the chemical reaction layers on the surfaces made?

R. P. O'Shea: At this time no X-ray work has been performed. However, based on thermodynamics oxidation of Hf, Ta, Cb, Zr, Ti would be expected.

A NEW TECHNIQUE FOR RETARDING EROSION OF GUN BARRELS BY PLATING THE BORES WITH TUNGSTEN

Karl H. Meyer
John W. Gehring
General Motors Corporation, AC Electronics - Defense Research Laboratories
Santa Barbara, California
and
Ralph Blair
U. S. Air Force Armament Laboratory
Eglin Air Force Base, Florida

ABSTRACT

Sponsored by the Air Force Armaments Laboratory, Eglin Air Force Base, Florida, General Motors' AC Electronics - Defense Research Laboratories developed a process of tungsten coating the bores of gun barrels. The pure tungsten coating is deposited with a firm metallurgical bond in a predetermined and uniform thickness. This coating retards the erosion rate of the bore of a gun barrel, extending the usable life of the barrel.

The process involves the vapor deposition of tungsten in the bore of oversized gun barrel blanks made of various alloy steels. The bore is initially 0.004" oversized and, after deposition of a 0.002" thickness of tungsten, the barrel has a resulting I.D. of 0.220". By proper surface preparation methods and deposition parameters (such as deposition temperature, flow rates and flow ratios of tungsten hexafluoride and hydrogen) and other factors, a firm bond between the tungsten plating and the substrate is obtained. Tungsten plated barrels and standard unplated barrels in caliber .220 have been test fired using .220 Super Swift ammunition under identical high-rate-of-fire conditions. Substantial reduction in the erosion rate was obtained in the tungsten plated barrels when compared to the unplated barrels.

The paper describes the tungsten plating process, the high-rate-of-fire test conditions, and gives detailed test results.

influence of interstitial elements such as hydrogen, nitrogen and carbon and their oxides in the form of molecules, atoms and ions in various states of ionization and with a high chemical reactivity. To withstand these environmental conditions for a substantial length of time the following requirements are given for an erosion resistant material:

- High melting point
- High strength (impact, yield, tensile and compression) at elevated temperature
- High specific heat
- High thermal conductivity
- Thermal expansion comparable to that of substrate material
- Low compressibility
- No hydrogen embrittlement.

In examining the physical and mechanical properties of available materials, the selection points towards the superalloys and refractory metals and shows that the element tungsten comes closest to the ideal material. Tungsten cannot be deposited electroytically with any quality, but can be applied using a chemical vapor deposition process. The properties of tungsten are as follows. (Most properties are given for commercially pure tungsten, since the information is not available for vapor phase plated tungsten yet.)

1. Tungsten has the highest melting point of all known metallic elements. MP = 6170^{o} F (3410^{o} C)
2. Tungsten retains a substantial amount of strength above 2000^{o}F. Ultimate tensile strength of commercial tungsten at 2400^{o}F is 45,000 psi.

BACKGROUND

The objective of the program was to find a material or method which reduces the erosion of small-caliber gun barrel bores and increases the operational life of guns before the acceptable limit is exceeded.

To reduce the erosion rate of a gun barrel bore several approaches can be taken. One is to use a more erosion-resistant material for the entire gun barrel. The second is to use that material as an insert or co-extruded liner within the gun barrel. The third is to plate a thin coating of an erosion-resistant material on the bore surface of a gun barrel made from a conventional barrel material such as 4150 steel. For the purpose of the investigation the third approach was chosen and a survey of potential materials for plating of a conventional gun steel bore was carried out.

MATERIALS PROPERTIES SURVEY

For a proper selection of gun barrel material, it was first necessary to determine the requirements and define the environmental conditions to which the gun barrel bore is exposed during firing of a round of ammunition and especially during high rate firing in a machine gun. The combustion of the prevalent gun propellant, nitro-cellulose, takes place according to the equation:

$$2\ C_6H_5(OH)_2(NO_3)_3 = 4\ CO_2 + 8\ CO + 6H_2O + H_2 + 3N_2 \qquad (1)$$

resulting in products of a chemically reducing nature. The environmental conditions for the gun barrel bore during propellant combustion consist of short time, cycling high pressures and temperatures and the corrosive

3. Pure tungsten has the lowest thermal expansion coefficient of all metals, (range 2.2 - 6.3 x 10^{-6} in./in./^{o}F), depending on mechanical and thermal history.

4. The fact which makes this metal especially attractive is that strength, hardness and toughness and probably also other properties of vapor deposited tungsten can be varied over a wide range depending on deposition parameters such as temperature and WF_6/H_2 flowrates and ratios. Hardness range of VPP tungsten: R_C40 - 60 (DPH 393-695).

5. Tungsten has one of the highest thermal conductivities (range 31.5 - 96.9 BTU/hr/ft^2/^{o}F/ft).

6. Tungsten has the lowest compressibility of any known metal (0.28 x 10^{-6}/megabar). This means a smaller temperature increase after release of compression stresses and therefore a lower bore surface temperature.

7. A computer study described in the next paragraph shows that a thin tungsten coating in a gun barrel bore will considerably reduce the bore surface temperature.

A comparison of the mechanical and physical properties of tungsten and 4150 gun steel is listed in Table I. The mechanical and physical properties of tungsten listed in the literature vary considerably depending on the type of manufacture (pressed and sintered powder, arc cast, etc.) or thermal history.

As a result of the evaluation of the properties of materials, a combination of a standard gun steel plated with tungsten appears to be a practical and efficient method to reduce erosion in a gun barrel insert, provided that it is possible to establish a strong metallurgical bond between the steel and the tungsten.

HEAT TRANSFER COMPUTER STUDY OF THIN TUNGSTEN PLATINGS

Symbols

ν	Temperature
K	Thermal conductivity

Table I

MATERIALS PROPERTIES

	Tungsten ** Comm. Pure.	Gun Steel*** 4150
Density g/cm^3 (lb/in.^{3})	19.3 (0.70)	~7.8 (.28)
Impact Str. (Charpy) kg-m (ft-lb)		1.4 (10)
Tens. Yield Str. kg/cm^2 (ksi)	15500 (220)	8930 (127)
UTS kg/cm^2 (ksi)	15500 (220)	9910 (141)
Elongation (%)	0—95	19
Red. of Area (%)	0—46	56
Melting Point (^{o}C)	3410	~1510
Melting Point (^{o}F)	6170	~2750
Spec. Heat C_p (cal/g/^{o}C)	0.033	0.10—0.11
Spec. Heat (BTU/lb/^{o}F	0.033	0.10—0.11
Therm. Cond. (cal/cm^2/cm/^{o}C/sec)	~0.40	~ 0.1
Therm Cond. (BTU/hr/ft^2/^{o}F/ft)	~31.5, 96.9	~8
Coeff. of Thermal Exp. (^{o}Cx10^{-6})	~ 4.5	~ 11
Coeff. of Thermal Exp. (^{o}Fx10^{-6})	~ 2.5	~ 6
Hardness R_C (DPH)	Plating 40-60 (393-695)	30 (301)
Coeff. of Friction μ_s (μ_k)*		0.58
Hemispherical Total Absorptance α	RT 0.022, 1600^{o}C 0.27	RT ~0.50
Atom Diameter (Å)	2.82	2.52
Crystal Structure	BCC, Cub. Diam.	BCC,
Ductile-Brittle Trans.	(VPP) 130—270 (265—510)	540—815 (1000—1500)
Recrystallization Temp. ^{o}C (^{o}F)	>1260 (>2300)	>840 (>1550)
Cost ($/lb)	2.00—40.00	0.50
Heat of Form. of Oxide (kcal/mol)	WO_2 130.5	Fe_2O_3 198.5
Velocity of Sound (10^{3}ft/sec)	14.0	16.7

* Against same material (steel against bronze 0.12)
** Tungsten properties vary in literature depending on preparation and thermal history
*** 4150 steel mechanical properties given for "as forged" condition.

Symbols (Cont'd)

$\dot{Q}_s$	Heat input rate per unit area
C_p	Heat capacity
ρ	Material density
Δx	Thin slab increment
Δx_1	Surface slab increment
Δ_t	Small time increment

The study of heat transfer through thin tungsten platings is achieved by using a computer program which solves the equation of linear flow of heat:(A)

$$\frac{\delta^2 \nu}{\delta x^2} - \frac{\rho C_p}{K} \frac{\delta \nu}{\delta t} = 0 \qquad (2)$$

by finite-difference methods. The material is considered as several very thin slabs, of size Δx, and very small time increments Δt are used in conjunction with stability criteria. A finite difference formulation of Equation (2) is as follows:(B)

$$\frac{\nu_{i+1}^{n+1} - 2\nu_i^{n+1} + \nu_{i-1}^{n+1}}{(\Delta x)^2} - \frac{\rho C_p}{K} \frac{\nu_i^{n+1} - \nu_i^n}{\Delta t} = 0 \qquad (3)$$

$\nu_i^n \simeq \nu (i \Delta x, n \Delta t)$: Temperature

(A) Carslaw, H.S., and Jaeger, J.C., Conduction of Heat in Solids, Oxford University Press, 1959.

(B) Richtmyer, R.D., Difference Methods for Initial-Value Problems, Interscience Publishers, 1957.

The computer program used is a general 1-dimensional heat transfer code, and has options to solve the above Equation (2) in cylindrical coordinates, with several materials and with arbitrary heat pulses. The program is written in FORTRAN IV and is run on the IBM 360 computer.

The heat pulse used in this study is approximately equivalent in shape and duration to those of the heat transfer study done at Cornell Aeronautical Laboratory.(C) The pulse used is shown in Figure 1. The integral of this pulse is equal to twice the average heat input per unit barrel area per shot—representative of the heat input at the breech, where maximum temperature will occur.

The heat is transferred to the surface slab increment Δx_1 by increasing its temperature as follows:

$$\nu_1^{n+1} = \nu_1^{n+1} + \frac{\dot{Q}_s \Delta t}{\rho_1 C_{p_1} \Delta x} \qquad (4)$$

The heat then flows into the material according to Equation (3). Accuracy is achieved by using very thin slabs ($\Delta x = 0.1$ mil) and very small time increments.

The effect of a thin tungsten plating of the bore of a gun barrel is a reduction of the bore surface temperature during the high heat pulse of a single shot.

(C) F. A. Vassallo, D. E. Adams, and R. D. Taylor, "Caseless Ammunition Heat Transfer," Cornell Aeronautical Laboratory (CAL) Report No. GI-2433-Z-1, October 1967.

The maximum surface temperature increase at the breech for a solid-steel barrel is 1420°R for one shot; with a 0.002" layer of tungsten, the temperature increase is only 1020°R, a reduction of 400°R. This is due to the high thermal conductivity of tungsten — during the shot the heat is transferred rapidly through the tungsten, thus reducing the surface temperature. Thickening the tungsten will decrease this short-duration temperature peak. As seen in Figure 2, however, 2 msec after the shot the surface temperature is almost the same as for solid steel. The temperature of the steel-tungsten interface is given in Figure 3. It is seen that very little temperature gradient exists in the tungsten after 2 msec after the shot. The tungsten plating thus broadens and flattens out the heat pulse to the steel; maximum temperatures are reduced, but residual temperatures remain unchanged.

The maximum temperature during a sustained rate of fire (which would occur during the last shot) would be reduced by a tungsten coating by the same amount as in a single shot (see Figure 4). The residual temperatures shortly after the shot would be the same, however, as the thin tungsten plating does not increase the total thermal capacity of the gun.

THE VAPOR DEPOSITION OF TUNGSTEN

To deposit a coating of tungsten on steel the chemical vapor deposition method was selected because of its high deposition rate and the high purity, density and strength of the deposited tungsten film.

In this process, a mixture of tungsten hexafluoride (WF_6) and hydrogen is brought into contact with the specimen at a temperature between 600°F and

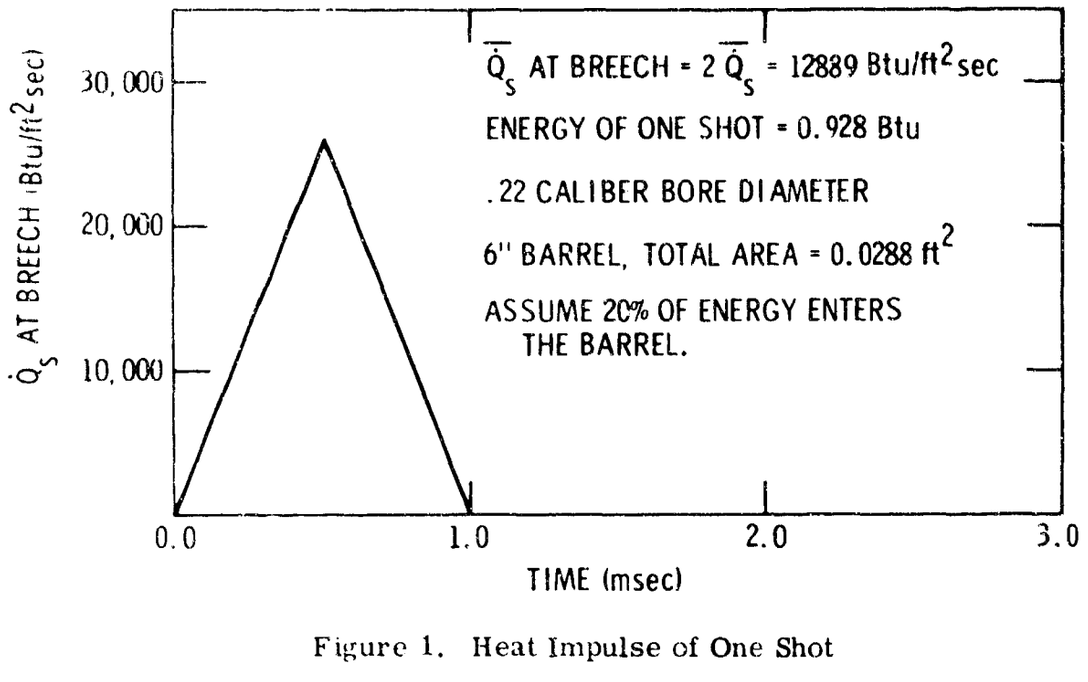


Figure 1. Heat Impulse of One Shot

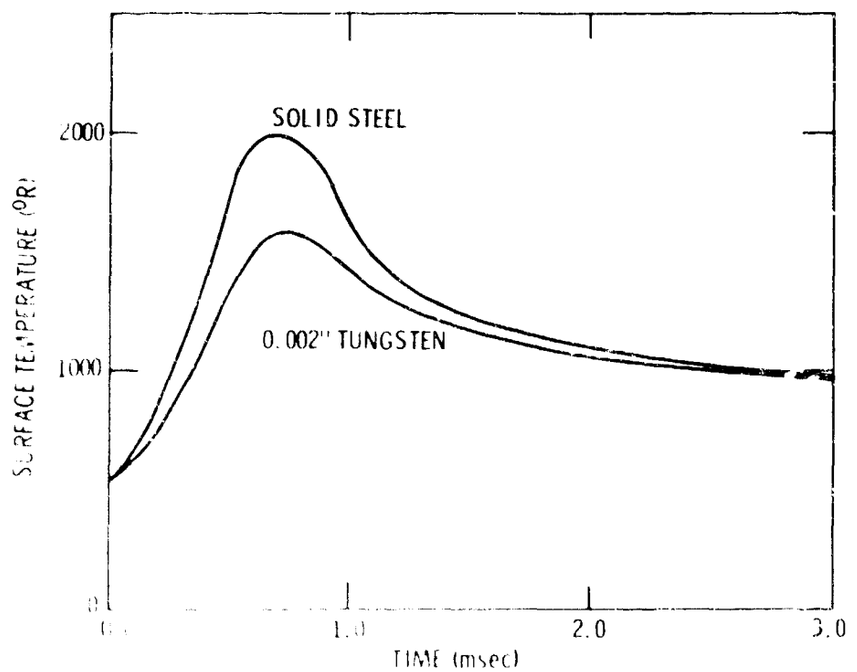


Figure 2. Comparison of Thermal Response at Surface of Solid Steel Barrel and 0.002" Tungsten Plated Barrel for One Shot

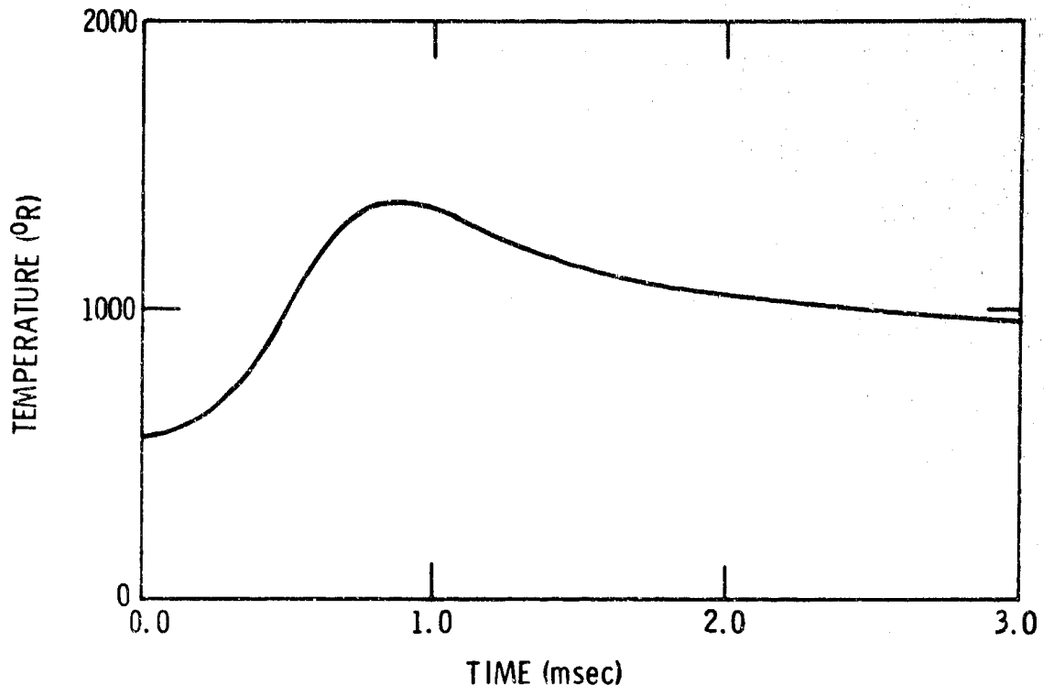


Figure 3. Temperature at Steel/Tungsten Interface for One Shot (0.002" Tungsten Plated Barrel)

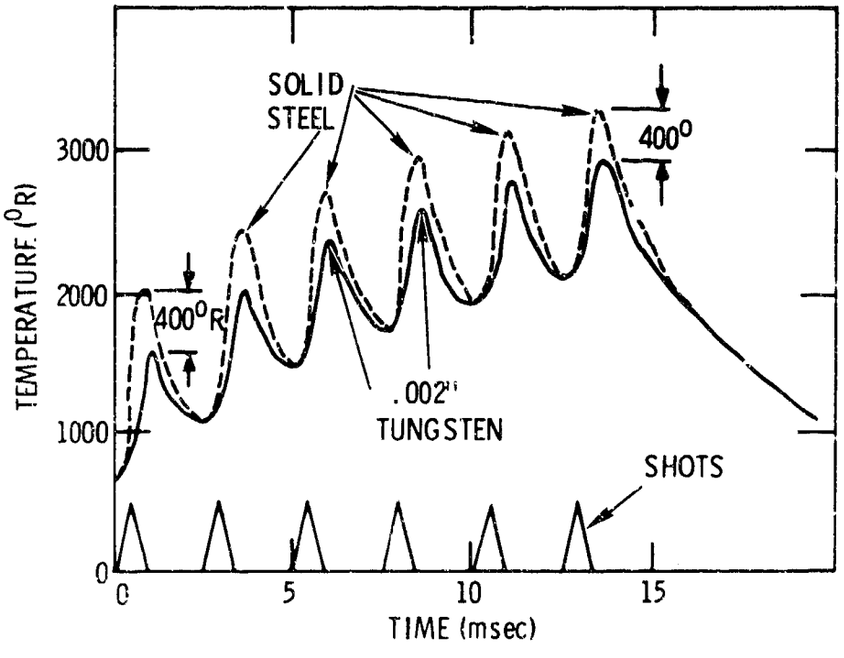


Figure 4. Temperature at Surface for Several Shots. Schematic Comparison of Solid Steel Barrel and 0.002" Tungsten Plated Barrel

1300°F. Within this temperature range a reaction between WF_6 and hydrogen takes place according to the equation:

$$WF_6 + 3\ H_2 = W + 6\ HF \qquad (5)$$

The tungsten is reduced by the hydrogen from its hexavalent state to the elementary form and deposits on the hot substrate as a metallic film of high density. The adherence of the film is determined by the surface preparation of the substrate such as degreasing, treatment with a mixture of acids, and removal of the etching products. The deposition takes place in the experimental apparatus shown in Figure 5. A basic schematic diagram of the process is shown in Figure 6.

During the process it is very important to keep out traces of air, oxygen, and water vapor. These elements react with tungsten hexafluoride in an undesirable side reaction forming tungsten oxide in the form of a blue film on the substrate surface, preventing a good bond from forming, as well as causing flaking of the tungsten plating. The equations for these side reactions are:

$$WF_6 + 3\ H_2O = WO_3 + 6\ HF \qquad (6)$$

$$2WF_6 + 3O_2 + 6\ H_2 = 2WO_3 + 12\ HF \qquad (7)$$

The mechanical and physical properties of the vapor deposited tungsten should represent a compromise between high strength and high hardness on one hand, and a large elongation (ductility) on the other, resulting in good impact strength (toughness) and erosion resistance under the

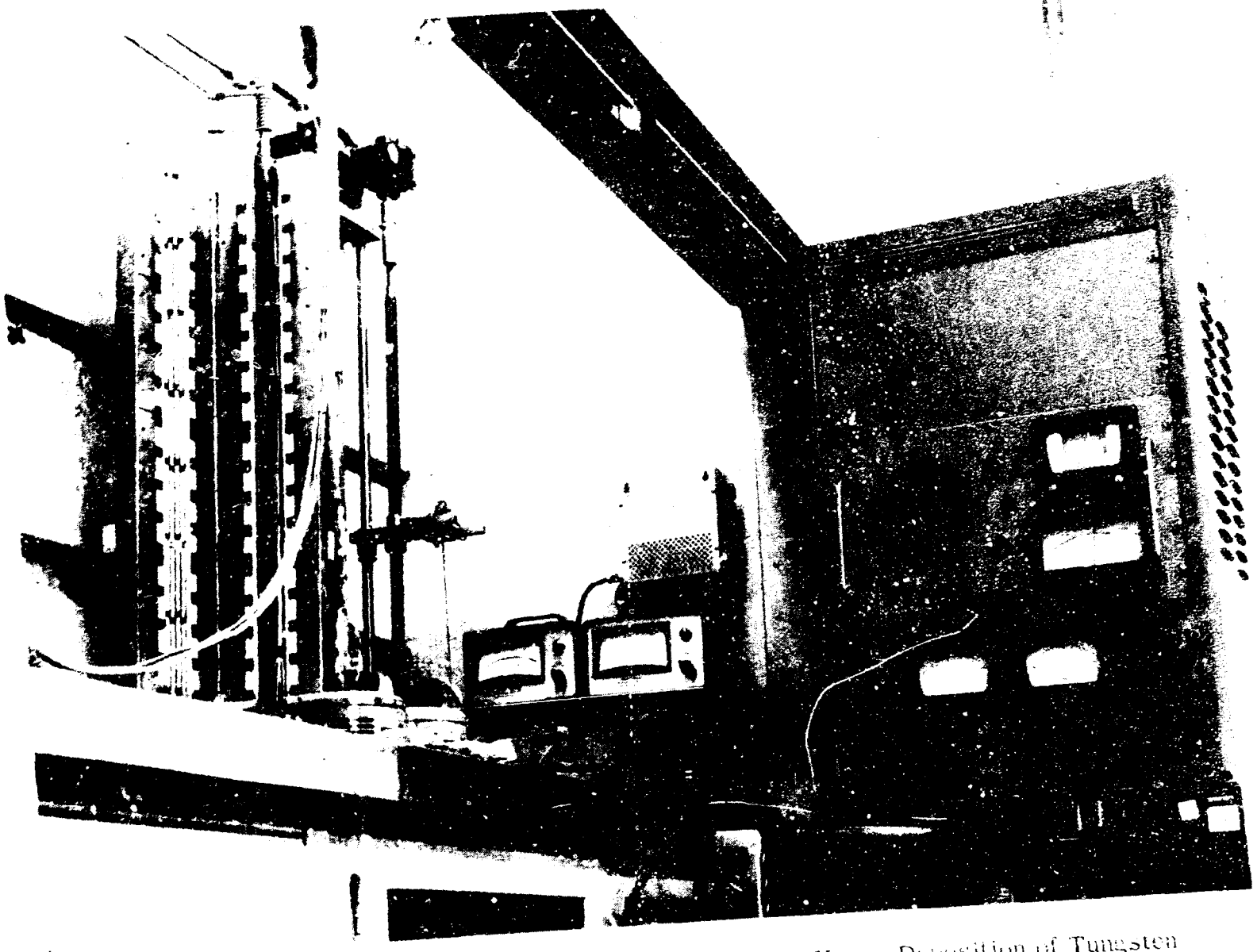


Figure 5. Experimental Apparatus for Vapor Deposition of Tungsten

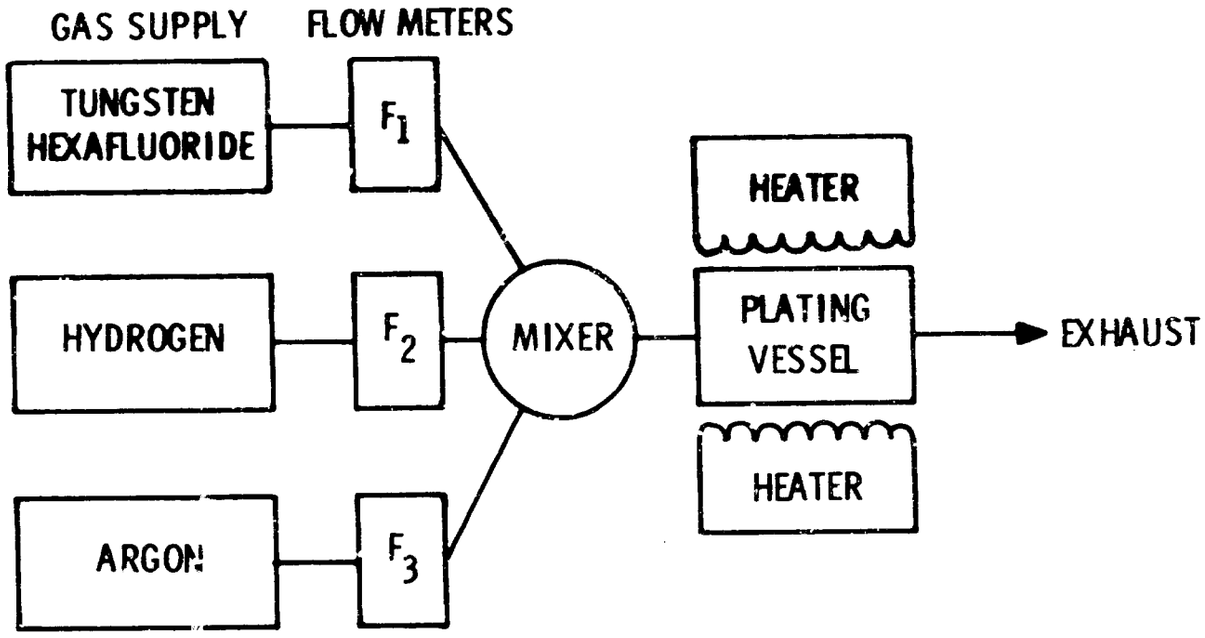


Figure 6. Schematic Flow Diagram for Vapor-Phase Plating Process

environmental conditions existing in the gun barrel bore during firing of a round. To obtain these desired properties, the deposition parameters such as temperature, tungsten hexafluoride and hydrogen flowrates and ratios can be varied to obtain tungsten plating, for example, in the hardness range between R_C40 and 60.

Before plating gun barrels the process was applied to small plate and tube specimens of the same type of steel. Process parameters such as etching chemicals, temperatures and tungsten hexafluoride and hydrogen flowrates and ratios were varied. The resulting plated specimens were sectioned and analyzed metallographically and by microhardness indentations for the quality of the bond between steel and tungsten. Some typical tungsten platings obtained on 4140 steel are shown in Figures 7, 8, and 9. Figure 7 shows a cross section at 200x with microhardness indentations indicating a hardness of R_c46 for the tungsten plating and R_c25.5 for the 4140 steel. In Figure 8, microhardness indentations in the interface under loads of 500g, 1000g, and 2000g respectively from left to right were made to test the adhesion of the tungsten plating to the 4140 steel substrate. Figure 9 is a photograph of the interface between tungsten and steel at a magnification of 1000x.

Figures 7 and 8 also show that the tungsten plating consists of columnar crystals growing in a direction normal to the substrate surface. The columnar crystals start to grow from a microcrystalline deposit on the surface. With the increasing thickness of the plating, some of the smaller

Figure 7. Transverse Cross Section with Microhardness Indentations Under 500g Load (220x) (Before Honing)

	Diamond Pyramid Hardness,	Rockwell C. Hardness
Tungsten	458	46.0
4140 Steel	266	25.5

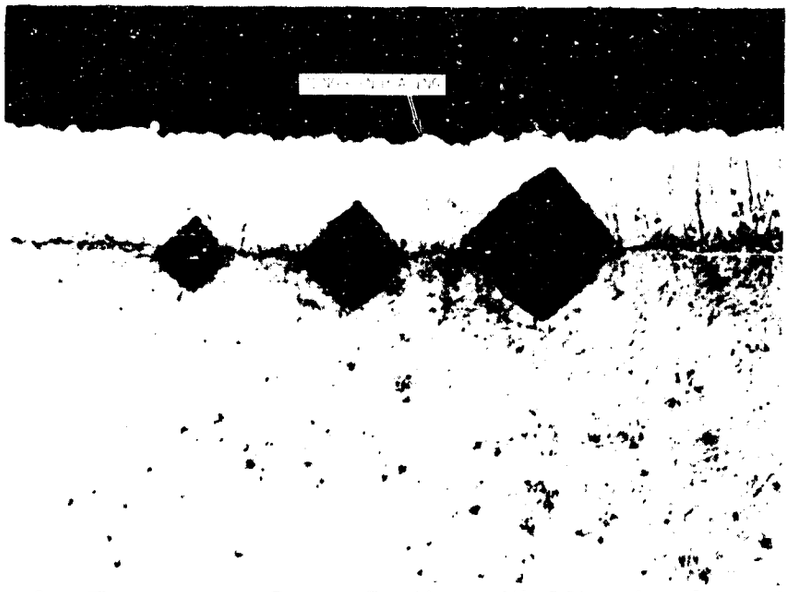


Figure 8. Transverse Cross Section with Microhardness Indentations under 500g, 1000g, 2000g Load on Interface to Show Quality of Bond Between Tungsten and Steel (200x) (Before Honing)

Figure 9. Transverse Cross Section Showing Interface Between Tungsten and Steel at 1000x

crystals disappear and the diameter of the larger crystals increases. With the increasing grain size, the hardness decreases. The columnar crystals grow in the form of pyramids on the surface as shown by an electron scanning micrograph in Figure 10. The distance between the tips of the pyramids and their base is approximately 0.0002 inch. This surface roughness is removed from the surface of the lands by honing to obtain a smooth surface with minimum friction between bore and projectile.

INVESTIGATION OF THE TUNGSTEN-STEEL INTERFACE

After a good bond was obtained by variation of the deposition parameters, an electron probe scan across a typical interface between tungsten and steel was taken to determine the composition of the interface and the depth of the

Figure 10. Electron Scanning Micrograph of the Surface of Vapor Phase Plated Tungsten. Distance Between Tips and Bases of Pyramids Approx. 0.0002 in. (600x)

diffusion bond. Three scans were made across the interface with the detectors of the instrument set for three different pairs of elements using a recording of the specimen current as a reference trace in each scan. These pairs of elements are: iron vs tungsten, oxygen vs iron and nitrogen vs tungsten. The scan of iron vs tungsten (Figure 11) shows how the concentration of tungsten (distance from bottom edge of chart) increases slowly. The specimen current increases and decreases during the scan across the interface with the concentration changes of iron and tungsten, and indicates a depth of the interface of approximately 9 μ (~0.0003 in.). In the other scans, checks for impurities such as oxygen and nitrogen were made but none above background concentration were found.

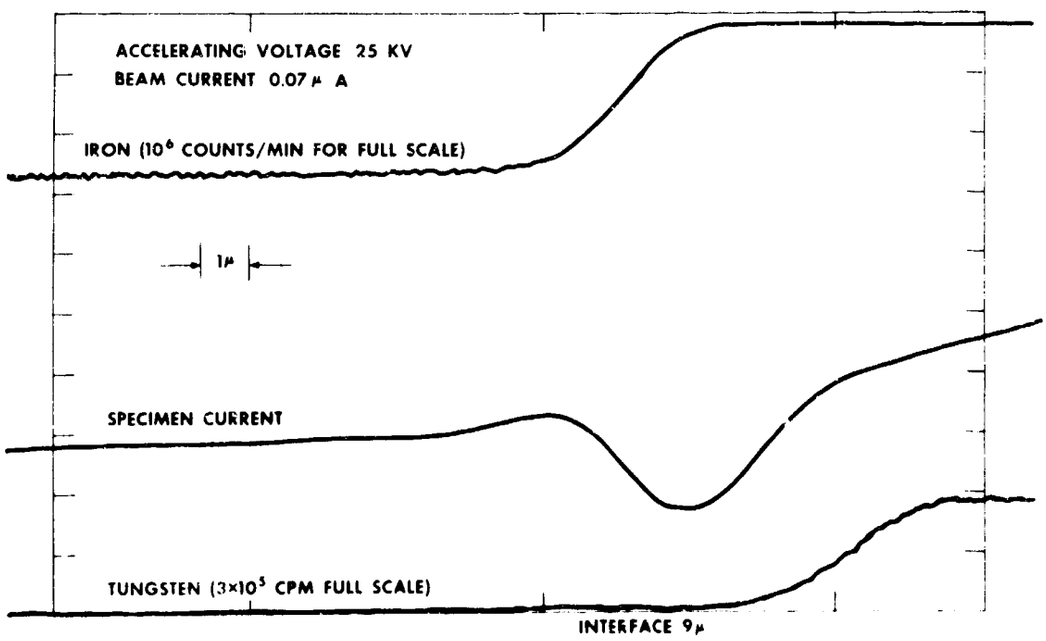


Figure 11. Electron Microprobe Scan of Iron vs Tungsten

TEST FIRING OF TUNGSTEN PLATED AND UNPLATED BARRELS

Early in the program it was decided that for reasons of economy and availability, the Remington .22-caliber Super Swift gun and ammunition would be used for the firing test. The .22-caliber Super Swift ammunition yields chamber pressures and muzzle velocities of approximately 50,000 psi and 4000 fps, respectively. This ammunition, because of its high performance, causes severe erosion of gun barrels and, hence, life test of barrels could be conducted with a minimum number of test firings.

Since the rate of erosion is highly dependent on the temperature of the barrel, it was necessary first to establish a firing cadence to be used during the test. The first series of firings was conducted in a single-shot mode by using either a Universal receiver or a modified Winchester 70 action shown in Figure 12. In the single-shot mode of fire, maximum barrel temperatures of 130°F were recorded by thermocouples placed on the outside surface of the chamber. The result of the single-shot firings with a standard unplated barrel are shown in Figure 13, labeled "B-Single Fire Mode."* The rate of erosion is plotted as a function of the number of rounds fired. Also shown in this illustration are the results of firing standard unplated barrels in an interrupted mode and in a high rate-of-fire mode. These barrels are labeled "A" and "T and U" on Figure 13. The high rate-of-fire tests were carried out by using a modified M-60 machine gun. A standard M-60 machine gun was adapted in the receiver to feed the .22-caliber Super Swift ammunition, and a .22-caliber barrel was substituted for the standard 7.62mm barrel. This gun, an M-60/220 (Figure 14), was then capable of firing at approximately 600 rpm (rounds per minute).

* Barrels are designated by letters, A, B, T, U, etc.

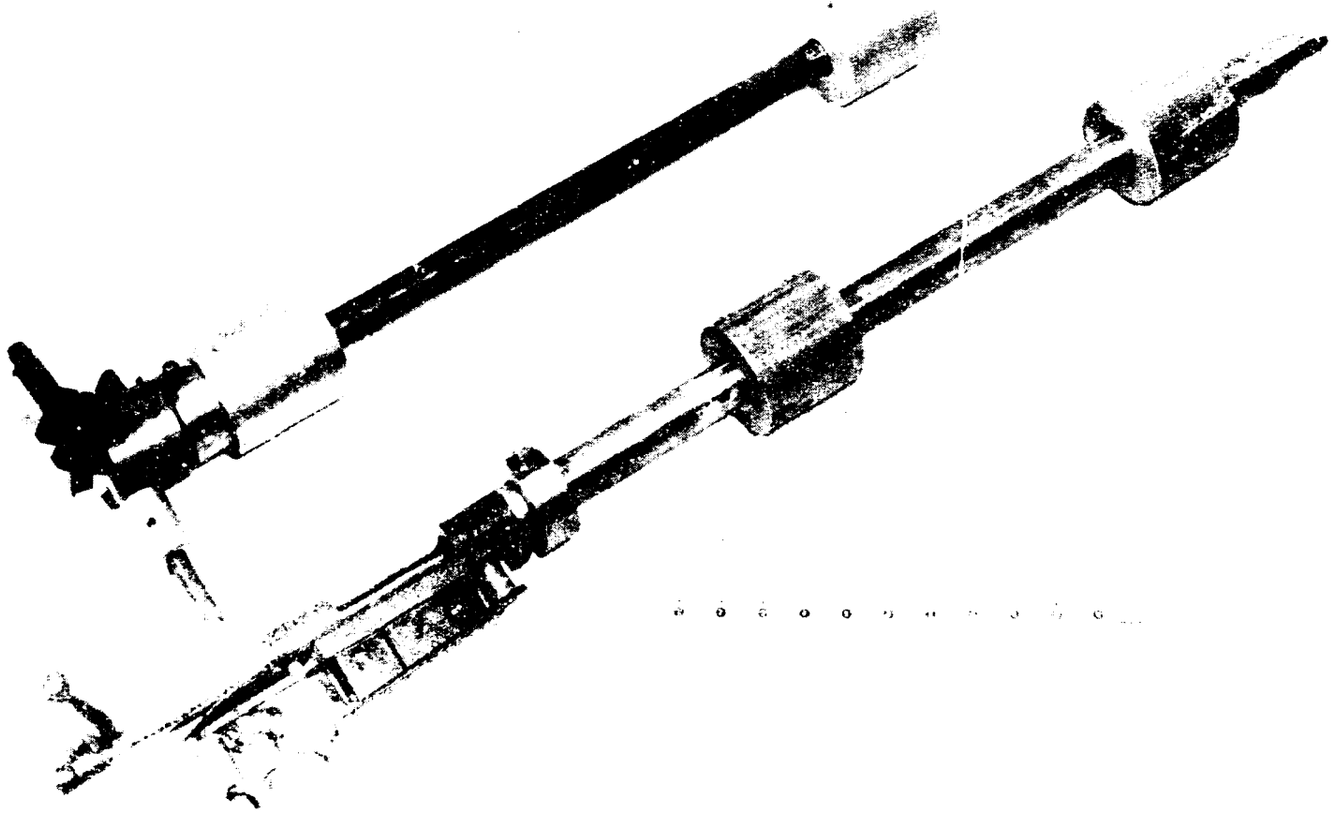


Figure 12. Single Shot Test Fixture

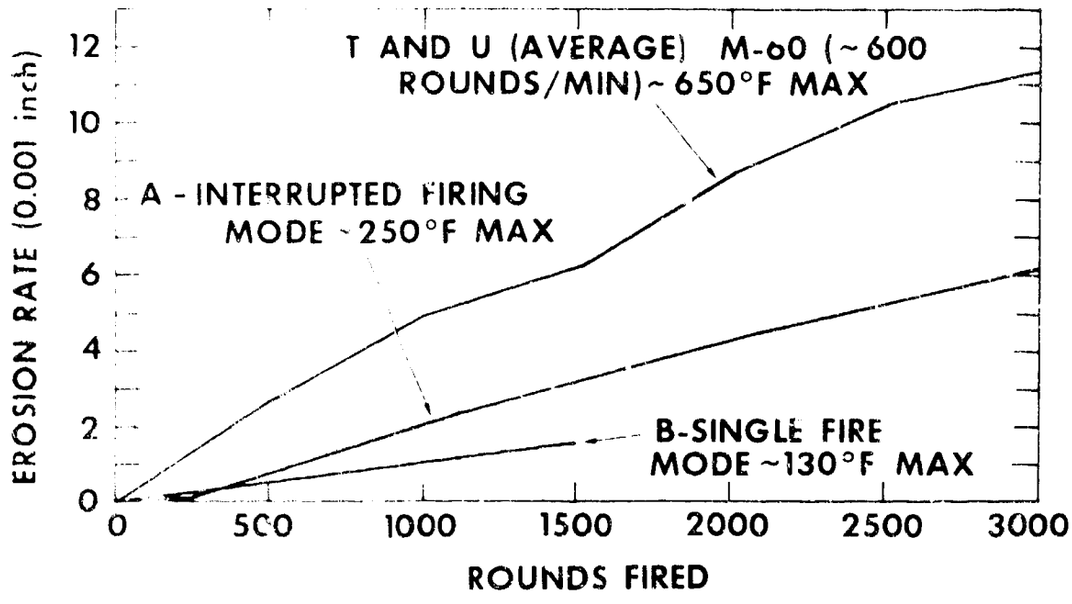


Figure 13 Relationship between Erosion and Firing Rates (All barrels unplated)

At a slow interrupted cadence in which barrel temperatures did not exceed 250°F, the erosion of the barrel was measured and is plotted in Figure 13, labeled "Interrupted Firing Mode." Note that the higher barrel temperatures encountered in the "Interrupted Firing Mode" vs the "Single-Fire Mode" increased the rate of erosion.

To test barrels "T" and "U" (Figure 13), a high rate-of-fire cadence of 600 rpm (50-round bursts being fired at one minute intervals) was established. The erosion rates were determined by measuring the inner diameter of the bore before and after firing each set of 500 rounds (10 bursts).* In this

* The average I. D. of eight measurements over the first 2.0 inches of rifling is reported.

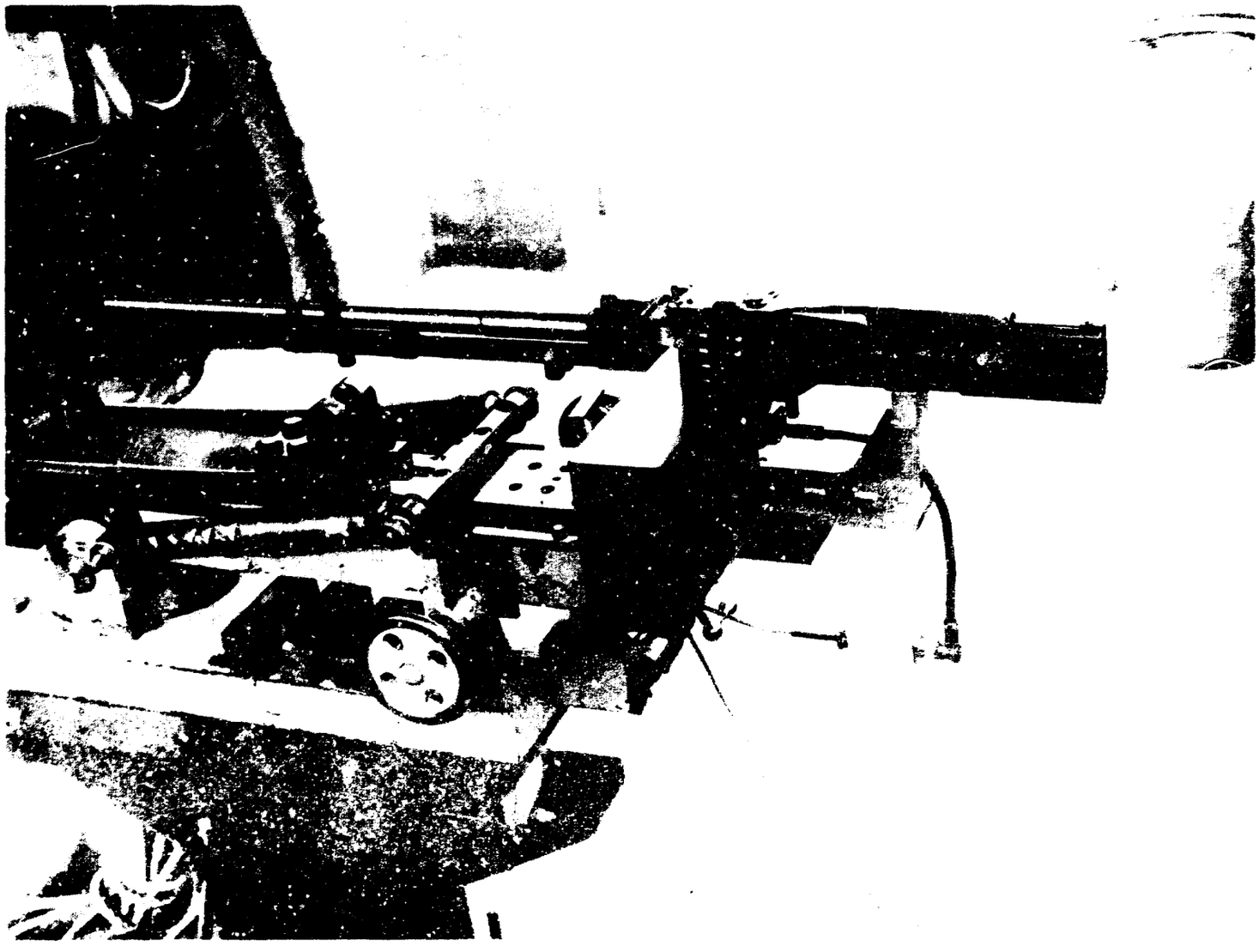


Figure 14. M-60C Machine Gun Converted to Accept .220 Cal. Barrel

series of tests, maximum barrel temperatures between 500°F and 650°F were measured. Recall that the single fire mode yielded 130°F and the interrupted mode, 250°F. Hence, it is evident that maximum barrel temperature increases significantly with rate of fire; since high rates of fire are representative of true combat conditions, all subsequent tests were conducted under full automatic rate-of-fire conditions.

The next series of tests attempted to establish the advantages or disadvantages of varying the substrate material, i.e., the steel used for the gun barrel on which the plating was applied. Three materials were tested: 4340, 4150, and 4140 alloy steels. These barrels were tested under high rate-of-fire conditions and their rates of erosion are plotted in Figure 15. The 4340 barrel shows the highest erosion rate, apparently out of range with the other two alloys, so all subsequent tests were made by using the 4140 or 4150 gun steel as the substrate material.

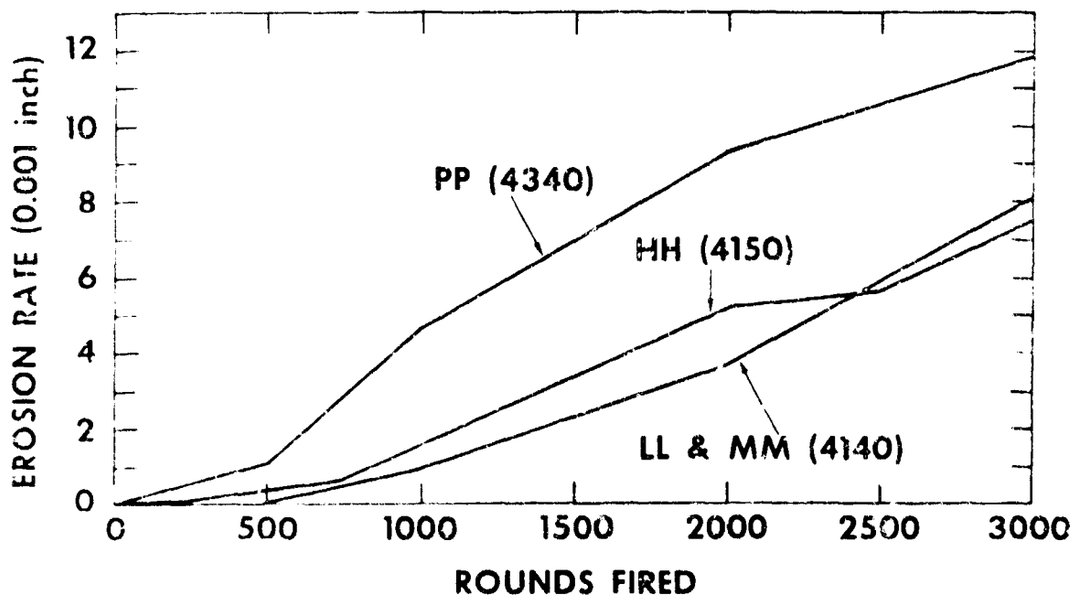


Figure 15 Comparison of Candidate Substrate Materials
(All barrels tungsten plated)

Figure 16 shows the test results of the tungsten-plated .22-caliber barrels. Three of the barrels were fired in the high rate-of-fire mode while an additional barrel, barrel "G," was fired in the single-shot mode. Again, the increased erosion under high rate-of-fire conditions can be seen.

SUMMARY

This report has described the techniques and test results of a program aimed at reducing the rate of erosion in the bore of a gun barrel and thereby increasing its life. The effective life of a gun barrel is usually defined in terms of its accuracy, the reduction in velocity of the projectile, and in the amount of erosion. During the conduct of the experimental tests described herein, each of these parameters was measured; however, this report has concerned itself only with recording the rate of erosion of the barrel. Therefore, the effective life of a gun barrel cannot be precisely determined from erosion data alone; one can only evaluate the comparative rates of erosion as a function of number of rounds fired for each of the barrels tested in this program.

To judge the effectiveness of the tungsten plating process in reducing barrel erosion, a comparison should be made of barrels fired under identical test conditions. This is particularly true when the gun system (i.e., gun and projectile) was selected for reasons of the stringent requirements that would be placed on the barrel. Also, the tungsten-plated barrels should be compared to chrome-plated barrels, chrome plating being an accepted military practice for increasing barrel life. In the course of the test firing program, a chrome-plated barrel was fired under conditions identical to those of the unplated- and tungsten-plated barrels. The experimental results are plotted in Figure 17.

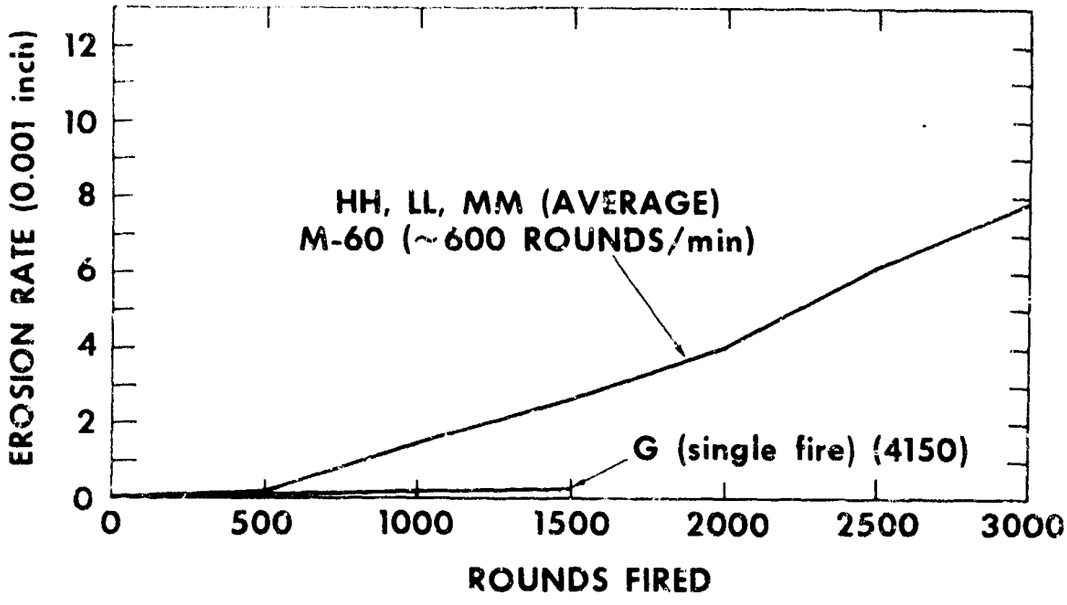


Figure 16 Relationship between Erosion and Firing Rates (All barrels tungsten plated)

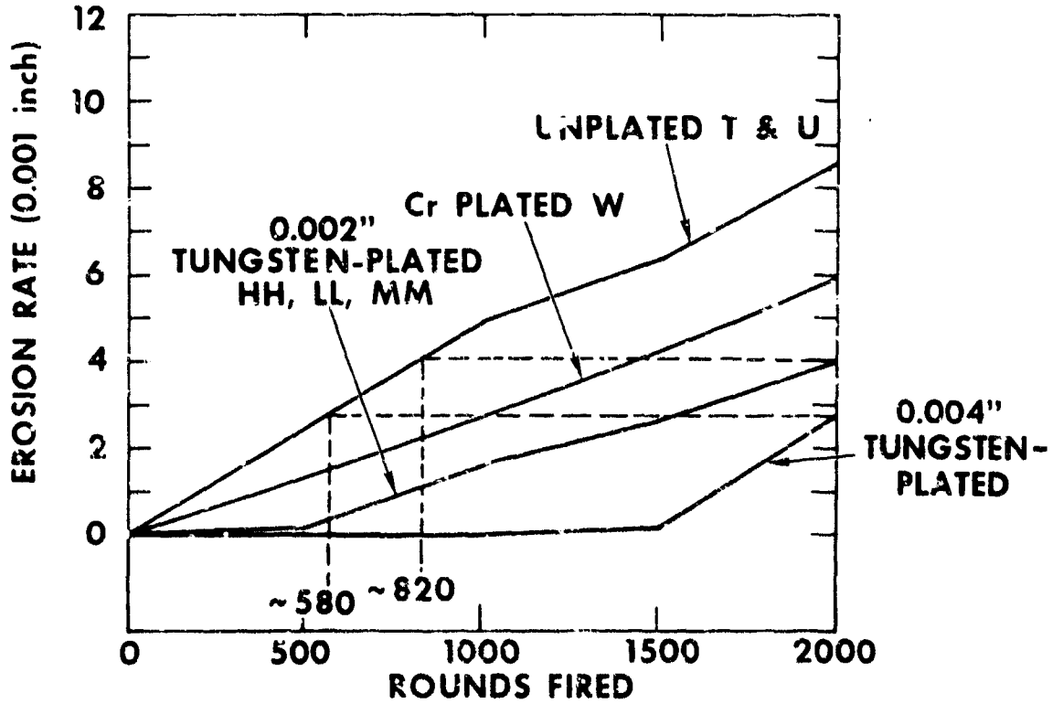


Figure 17 Erosion of Unplated, Chrome-Plated, and Tungsten-Plated Barrels

The rate of erosion vs the number of rounds fired was averaged for the unplated barrels "T" and "U" in one curve and for the tungsten-plated barrels "H", "L", and "M" (plated with 0.002 inch tungsten on the radius) in another curve. The erosion of a barrel with 0.004 inch tungsten on the radius is shown under "VV" in the lower right corner. A separate curve shows the erosion of a chrome-plated barrel "W", which is between the erosion rates of the tungsten-plated barrels and the unplated barrels. It can be seen that the 0.002 inch tungsten plated barrels have the same amount of erosion at 2000 rounds as the unplated barrel at 820 rounds. The 0.004 inch tungsten-plated barrel has the same erosion at 2000 rounds as the unplated barrels have at 580 rounds. This represents a reduction in the amount of erosion of 250% and 350%, respectively, for the tungsten-plated barrels.

Attention is directed to the fact that the 0.002 inch tungsten-plated barrel shows practically no erosion up to 500 rounds and that the 0.004 inch tungsten-plated barrel shows almost no erosion up to 1500 rounds. It can be expected that heavier tungsten plating will retard erosion even further.

The feasibility of plating of gun barrel bores has been demonstrated. The test results show a substantial reduction of erosion rates, especially with increasing tungsten thicknesses. The program is only in its beginning and many improvements are possible. The optimum physical and mechanical properties of tungsten from the viewpoint of erosion resistance as dependent upon the deposition parameters should be determined to obtain the maximum erosion resistance possible. The process is expected to be adapted to larger calibers in the near future. Work has started to automate the tungsten plating

process by using timers, programmers, temperature and gas flow controllers, etc. Some basic research needs to be done to determine the influence of hydrogen embrittlement, diffusion bonding, etc., on the strength of the bond and the plating and to determine some mechanical and physical properties of the vapor deposited tungsten.

3.3 DISCUSSION:

D. P. Perrin: Has comparative heat input data been measured with tungsten plated barrels vs chrome plate or unplated steel?

Karl Meyer: Yes, it is included in the complete paper to be published in the proceedings.

J. K. Mayer: In the vapor deposition of W, what dew points must be established and maintained to ensure satisfactory coatings?

Karl Meyer: Deposition of tungsten was carried out at a substrate temperature of 1300°F. The WF_6 bottle and transfer lines were maintained at 110°F to obtain the required positive pressure and to prevent condensation of WF_6 in the lines.

V. P. Greco: 1. What was the thickness of Cr as compared with tungsten?

2. Wouldn't a comparison between equal thicknesses be more appropriate.

Karl Meyer: 1. 0.0005 in.

2. Correct. Larger chrome thicknesses will be tested in the near future.

3.3 DISCUSSION:

Steve. C. Fishmal: I notice you have shown no micrographs of the fired W plated gun barrels. Did you have any trouble with cracking or separation of the W coating?

Karl Wever: Cracking takes place after a much larger number of rounds in comparison to unplated barrels.

STUDIES OF EROSION RESISTANT COATINGS AT WATERVLIET ARSENAL

Iqbal Ahmad
V. Peter Greco
William Baldauf

Benet R&E Laboratories
Physical Chemistry Lab
Watervliet Arsenal
Watervliet, New York

Until recently, in spite of its well known inherent weaknesses (e.g., brittleness in presence of microcracks), chrome plating has been the only preventative measure adopted against erosion in cannon tubes at the Watervliet Arsenal. The introduction of wear-reducing additives (TiO_2-wax jacket) has increased the wear life of the tubes considerably to the point where they fail by fatigue rather than wear. In the meantime, successful application of the autofrettage process to cannon tubes including 105mm and 175mm enhanced their fatigue life by an order of magnitude, whereby these tubes are now wear limited. Therefore, R&D efforts are in progress at the Watervliet Arsenal to develop erosion resistant coatings superior to chrome. Alloys, including Cr-Re, Ni-Re, and Co-Re, and dispersion-hardened refractory metals are being applied by electroplating. As a parallel effort, plasma spray technique is being developed for the application of Mo, Cr, and other refractory alloys. To evaluate them, two types of erosion gages have been developed and will be described. The results obtained, so far, on the evaluation of some of the above coatings will be discussed.

INTRODUCTION

One of the primary missions of the Watervliet Arsenal is the improvement of the service life of gun tubes. To achieve this objective, the Arsenal R&E efforts are directed to:

1. Improve the design and performance of the gun tubes.

2. Enhance the fatigue life by physico-mechanical treatment of the steel.

5. Develop coatings or liners to protect the bore surface from the erosive powder gases which subsequently reduce the effective life of the gun tubes.

It is the purpose of this paper to review the Arsenal's activities in the development of the erosion resistant coatings.

HISTORICAL BACKGROUND

It has already been stated in previous papers, that bore erosion has been recognized as a major artillery problem for more than half a century, and that the most exhaustive studies were made during 1941-45, under the sponsorship of NDRC[1], the results of which were summarized in the well known report entitled "Hypervelocity Guns and the Control of Gun Erosion." This work resulted in gaining deeper insights into the various aspects of erosion, bringing into focus a number of materials, which, if successfully applied as a coating or a liner, could enhance the life of the tube. Yet no final solution to this malady was obtained. For example, Stellite 21 was found to be an excellent material for the liner of machine gun barrels, and was adopted for 0.50 caliber aircraft barrels. However, it was reported to have too low a melting point and therefore was unsuitable when a double base propellant was used.[2] Molybdenum, especially alloyed with 0.1% Co, was found to be among the best erosion resistant materials, but the techniques of its application either as a liner or as a coating were not adequately developed. When vapor deposited, molybdenum coatings were found to spall or have poor adhesion during firing.[3,4,5] Also, the difference in the coefficient of thermal

expansion and modulus of elasticity of Mo, as compared with steel, created serious problems when Mo was used as a liner. The development of molybdenum as an erosion resistant material has been reported by Harwood[6], Palmer[7] and Warden[8].

Vapor deposited coatings of tungsten and tantalum[9,10] were also reported to be unsuccessful due to brittleness and poor adhesion. The performance of numerous other coatings were evaluated in erosion vents and gun bores. Some of these were cermets[11], flame sprayed Mo[12], chromizing[13,14], diffused tantalum[14], and electrodeposited coatings of pure metals such as Ni, Co, Cu, Cr,[15,16] electrodeposited alloys such as Ni-S, and Co-W[17,18], Fe-Cr[19,20,21] and a series of duplex electrodeposited structures such as Cr on Co, Cr on Cu[22,23]. The general results from these investigations conducted under hypervelocity conditions, showed low melting point coatings to fail by rapid erosion and high melting point coatings to fail by spalling and flaking due to brittleness and poor adhesion. It is not to be construed from the latter that further attempts to apply the above coatings would continue to result in failure, since advancements in the technology of application over the span of the last two decades may provide coatings with improved properties which will be discussed later.

However, at the completion of the above studies, among all of the coatings evaluated, chromium performed comparatively well as a bore coating and could be economically applied (i.e., by electrodeposition).

Lamb and Young[24] have reported that the electrodeposition of coatings in gun bores was attempted as early as 1921 by de Sveshnikoff

and Haring of NBS, in which they deposited Ni, Cu and Fe. Between 1926 and 1928 some caliber .30 machine gun barrels were chromium plated at the Frankford Arsenal, and, since 1928, Naval gun bores were chrome plated.) However, these coatings were thin (1 mil or less) and did not demonstrate the usefulness of chromium as an erosion retardant. The extensive studies conducted from 1943 on, through NDRC, in which techniques were developed to deposit thick coatings (5 mils or greater) of chromium in gun bores, indicated the significant gains which could be achieved. Chrome plated bores (such as the caliber .30 barrel) have been reported by Lamb and Young[25] to increase barrel life by a factor of two to five times, while Hammond[26] reported life increases of eight to ten times with small arms. Therefore, it was widely accepted as the leading choice to retard erosion in high velocity production weapons by U. S. and foreign countries[1,3,6]. However, much was left to be desired as new weapon requirements increased.

The major shortcoming of chromium was (and still is) its brittleness and inherent crack pattern often making it susceptible to shearing and flaking during early stages of firing and subsequent undermining erosion of the base metal.[27,28]

With the conclusions of World War II and the Korean conflict, the interest in the control of erosion was diminished. The last major efforts were reported in two symposiums[2,4] published in 1950 and 1952, with the general conclusion that a complete solution to the problem of gun bore erosion is still a distance away. In the absence

of a better coating, chromium continued to be the only protective barrier in a number of cannon tubes.

During the last ten years, two important developments occurred. First, it was shown that addition of a TiO_2 which was impregnated in a wax cloth around the propellant charge significantly increased the wear life of the gun tube[29,30,31]. For example, a conventionally chrome plated 175mm M113 would reach the condemnation point of 0.2" wear after 300 EFC rounds. With the M1 propellant charge combined with wear reducing additive, 800 rounds could be fired before reaching this limit. However, the fatigue limit was reached at 400 EFC rounds. Similarly, an order of magnitude of increase in life was obtained in other guns, e.g., 105mm and 152mm. During this time the problem of wear was considered as non-existent. Then the second and very recent development occurred. At the Watervliet Arsenal, Davidson and Rummel[32] successfully applied the autofrettage process to large gun tubes, extending their fatigue life considerably. For example, the fatigue life of 175mm M113A1 was increased from 400 to 2550 EFC rounds. However, the 0.2" wear limit reached at 700 rounds, which again, brought back the problem of erosion into focus. This further proves that the problem of fatigue and erosion go hand in hand and remain equally important.

A review of the erosion characteristics in various weapon systems, some of which are given in Table I, shows that regardless of whether gun tubes are condemned by wear or by fatigue, even minor erosion effects such as at bore evacuator or detent holes, can adversely affect the service life of the tubes. Also, primary erosion can

TABLE I EROSION CHARACTERISTICS AND CONDEMNATION CRITERIA OF SOME CURRENT WEAPON SYSTEMS

WEAPON	EROSION RETARDANT	SERVICE LIFE	CONDEMNATION CRITERIA	UNUSUAL EROSION CHARACTERISTICS LEADING TO CONDEMNATION
105mm M68 Gun	TiO_2 Additive	4500 ADPS 1500 Heat or .075" Wear	Fatigue	-
175mm M113E1 Gun	TiO_2 Additive	1200 EFC Rds. .200" Wear	Fatigue	-
155mm M126E1 Howitzer		7500 EFC Rds. or 6.180 Dia.	Fatigue	Bore evacuator holes erode and form cracks radially
90mm M41 Gun	Chromeplate TiO_2 Additive	3000 Rds Wear	Fatigue	-
155mm M46 Gun	Chrome	700 Rds. Wear	Wear	-
152mm M81E1		600 Rds.	Fatigue	DETENT Hole erodes & cracks
152mm X162		800 Rds.	Fatigue	DETENT Hole erodes & cracks
120mm M58	Chromeplate	250 Rds. Wear	Wear	RAPID EROSION OF ORIGIN
106mm Recoilless		1200 Rds. for Vents 2400 Rds. for Wear	Wear	Gas Wash of Vents General Erosion of other Holes and Bore
20mm M24A1	Chromeplate	3000 Rds. .026" Wear	Wear	-

contribute to the reduction in the fatigue life of the tube. Excessive thermal checking and undermining erosion in chambers of howitzers sometimes results in condemnable longitudinal cracks[33]. The elimination of even such minor erosion effects can improve the life of the tube.

In recognizing this continuing problem of erosion, particularly in hypervelocity weapons, R&D activities in erosion control at the Watervliet Arsenal have steadily grown for the last few years, with the main objective of developing erosion resistant coatings superior to chrome plate.

REQUIREMENT FOR A SUCCESSFUL EROSION RESISTANT COATING

The requirements for a suitable material to withstand the environment of hypervelocity firing have been summarized by Schairer[34] and Hobstetter[35]. They include high melting point (>1500°C) chemical inertness to powder gases, high thermal conductivity and specific heat, high mechanical strengths and hot hardness, reasonable ductility and fracture toughness to withstand mechanical shock, fabricability and availability in economic quantities. For coatings and liners, good adhesion, and thermal and mechanical compatibility with the gun steel are additional requirements. The final selection of a material, however, will depend upon the performance for which the weapon has been designed.

Unprotected gun steel can be considered reasonably acceptable for weapons involving low temperature propellants and low muzzle velocities, such as in the case of some howitzers. As muzzle velocities and propellant flame temperature increase, Stellite 21 or other oxidation resistant Co-Ni alloys are found satisfactory. For more severe

conditions where double and triple base propellants are employed, it will be necessary to use relatively high melting point metals such as Mo, Ta, W, Cr, Re, Cb and their alloys.

In order to understand what is required to improve the performance of chromium as an erosion retardant, an understanding of its behavior in gun bores is important. Spalling or flaking usually occurs within the brittle chrome coating itself[36] which is accentuated by the inherent stress crack pattern which also leads to undermining erosion. This behavior rules out non-adhesion as the primary cause of failure as sometimes reported. Evidence of cracks and spalling of chrome in a fired gun tube is shown in Figure 1.

The limits in which a candidate coating will be considered to outperform chromium deposits onto gun steel during firing is shown in Figure 2, which shows the general form of wear vs. round curves for unprotected gun steel[1] and chrome plated gun steel[2]. Chromium exhibits zero or very little wear during the initial stage of tube life. As the chromium breaks down and flakes away, the base metal is quickly attacked and a sudden rise takes place in the slope of the curve. According to the shaded area, a candidate material could have a lower erosion resistance than chromium but better characteristics of adhesion and ductility and then outperform chromium by increasing the round life.

For the application of a material in a cannon tube, consideration has not only to be given to the necessary physical, chemical and mechanical properties mentioned earlier, but also to the methods of

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FIGURE 1. METALLOGRAPHIC STUDY OF A TEST FIRED 90 M/M T208 CHROMEPLATED GUN BORE

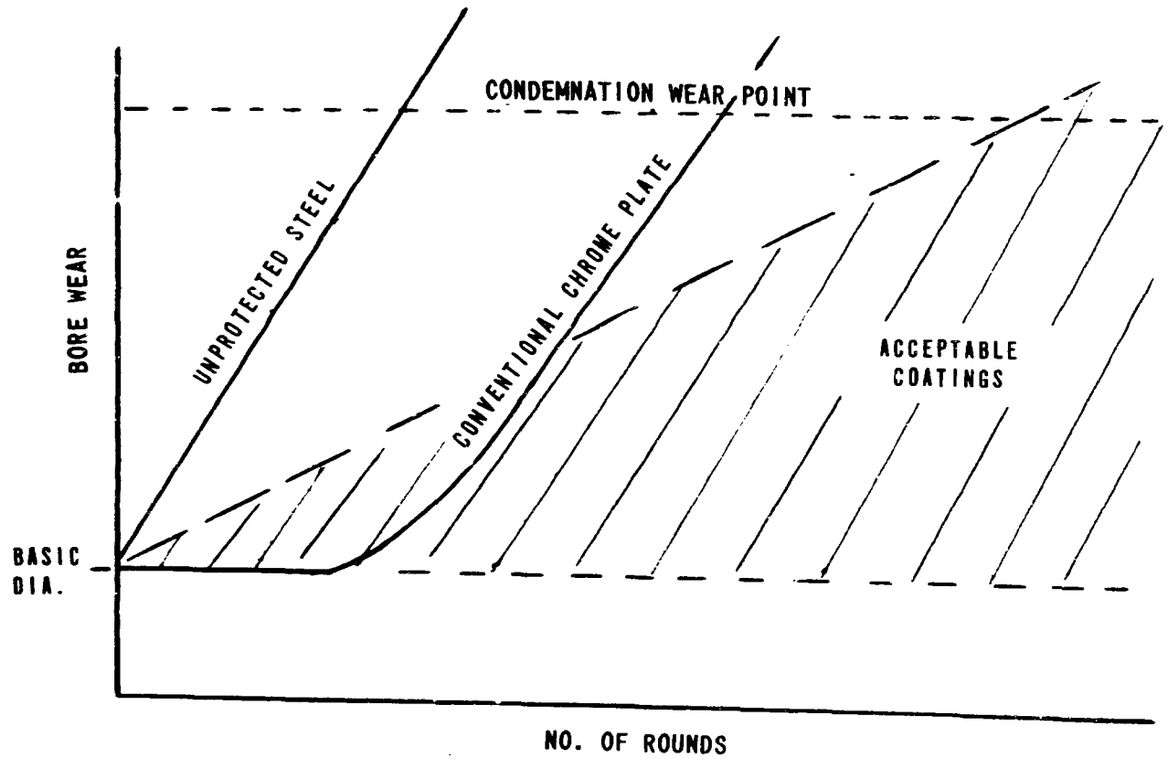

FIGURE 2. ACCEPTANCE PLOT FOR EROSION RESISTANT COATINGS
(CURVES SHOWN FOR GUN STEEL AND CHROME ARE APPROXIMATED FROM TYPICAL BEHAVIORS REPORTED IN THE LITERATURE WITH ACTUAL GUN TUBE LIFE INCREASE RANGING FROM 2-5 FACTORS).

its application. The most desirable technique has to be such that (1) the tube is not to be heated above 600°C, (2) the applied coating is uniform and has a good bond onto the substrate, and (3) the application process is economically feasible.

Scanning the present day technology of coatings which include electroplating, chemical conversion coatings (e.g., anodizing), diffusion coatings (carbiding, chromizing, nitriding and metalliding), flame spray coatings (D.C. ARC plasma, oxyacetylene and detonation), hot dip coatings, and vapor deposited coatings (such as vacuum evaporation, ion plating, sputtering, chemical vapor plating and glow discharge), indicate that the following four techniques can meet the requirements of coating in a gun tube: (1) electroplating, (2) flame spray, (3) sputtering, (4) CVD (chemical vapor deposition).

Of these, electroplating is the easiest and is being economically used on a large scale. With this technique, materials such as Cr, Co, Ni, Re and their alloys can be applied. However, other promising refractory materials such as pure Mo, W, Ta cannot be electrodeposited. Mo and W can be electrodeposited as alloying elements with Ni, Co and Fe but further experimentation must be undertaken to produce sound, and adherent deposits. Flame spraying (especially D.C. ARC flame spray) can be used to coat any material in a tube provided the diameter is large enough to accommodate the torch unit. Sputtering gives excellent coating-substrate bond and does not require heating the substrate. However, it gives coating of a limited thickness (generaly one mil). With large cannon, the thickness of more than

five mils is required. It is also not economically feasible for large tubes. In chemical vapor deposition, to achieve a good bond it is necessary to heat the substrate to a temperature which might adversely affect the mechanical properties of the tube.

Therefore, in this study we have selected electrodeposition and plasma spray techniques to apply candidate coatings to gun bores. To evaluate these coatings two types of erosion gages have also been developed which will be described later in this paper.

ELECTRODEPOSITED COATINGS

Efforts on electroplated coatings at this Arsenal can be divided into two categories.

1. Improvement of the chromium coating, by either providing an intermediate coating, or by alloying with other elements.

2. Development of coatings other than chromium.

In the initial stages Dashnaw,[37] formerly of the Watervliet Arsenal, investigated the possibility of improving conventional chromium plate by introducing an intermediate deposit of ductile metals such as Ni, Co, and Cr. Induction heating for a period of three to five hours was used to effect diffusion bonding. The results were not encouraging. It was also revealed that the formation of a brittle phase of chromium carbide at the interface was one of the causes of the flaking off of chrome plate from the bore surface.

Cr-Re - Small amount of Re[38] alloyed with chromium has been reported to increase its ductility. Also, as shown in the phase diagram (Figure 3), Cr-Re alloy has an m.p. higher than Cr, an

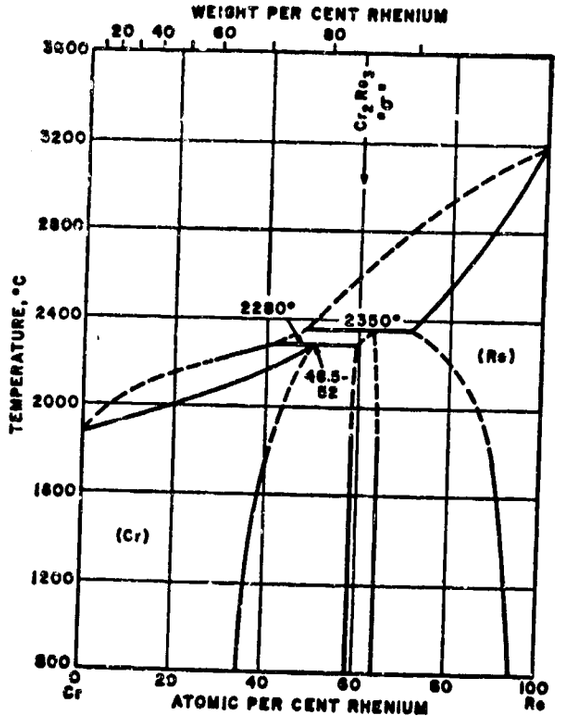

FIGURE 3. CONSTITUTION DIAGRAM FOR THE CHROMIUM-RHENIUM SYSTEM

important property for a desirable coating. Therefore, chromium-rhenium alloy coatings were attempted under various plating conditions. The electrolytic bath approximated the composition used in the limited studies reported by Kvokova and Lainer[39]. The microstructure of Cr (1%) Re deposits are shown in Figure 4 with and without stress cracks. The hardness of the deposits was found to be 1400 Kn as compared with 900 Kn for pure electrolytic chromium. In various degrees, the deposits exhibited stress cracks similar to Cr. One of the apparent influencing factors was the pH of the solution. Also, this alloy could not be coated beyond a certain thickness. Further studies are required to determine the cause of the formation of cracks and what limits the thickness of the coating.

Ni-Re and Co-Re Alloys - Because of the difficulties encountered with the Cr-Re system, coatings of Ni-Re and Co-Re were investigated. Re forms a solid solution both with Ni and Co and can therefore affect solution strengthening of these metals. According to the phase diagrams of these two systems (Figure 5), the melting points of the two alloys do not decrease at all with increasing percent of Re which is an encouraging feature of the systems.

Aqueous citric acid (and/or boric acid) nickel bath formulations mixed with potassium perrhenate, in accordance with the early work of Hetherton and Holt[40], were used to plate Ni-Re alloys. Ni-Re alloys were also deposited using new bath formulations consisting of a mixture of sulphamate and perrphenate electrolytes. Co-Re alloy deposits were obtained by introducing various amounts of potassium

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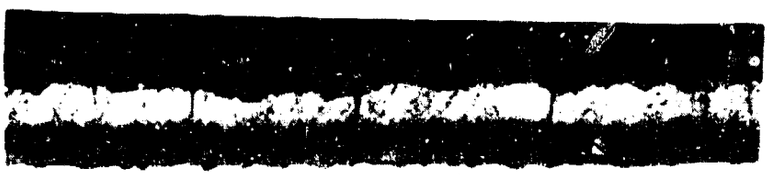
(a)



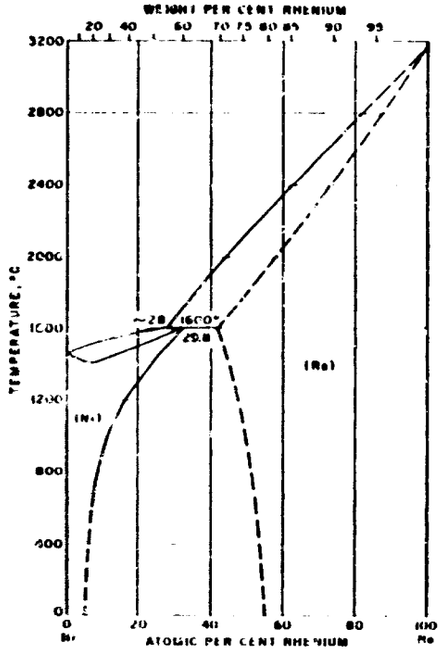
ETCHED .0005 in. THICK X1000

(b)

FIGURE 4 MICROSTRUCTURE OF CHROMIUM-RHENIUM ELECTRODEPOSITED ALLOY

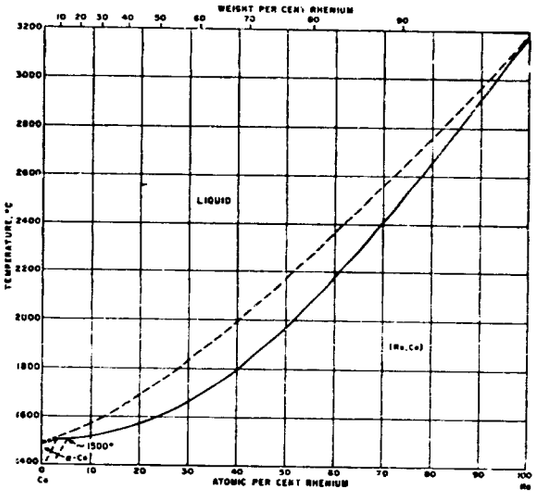
a) AREA FREE OF STRESS CRACKS

b) AREA WITH HIGH CONCENTRATION OF STRESS CRACKS



Ni-Re

1. E. M. Savitskii and M. A. Tylkina, *Zh. Neorgan. Khim.*, 3, 1958, 820–837.



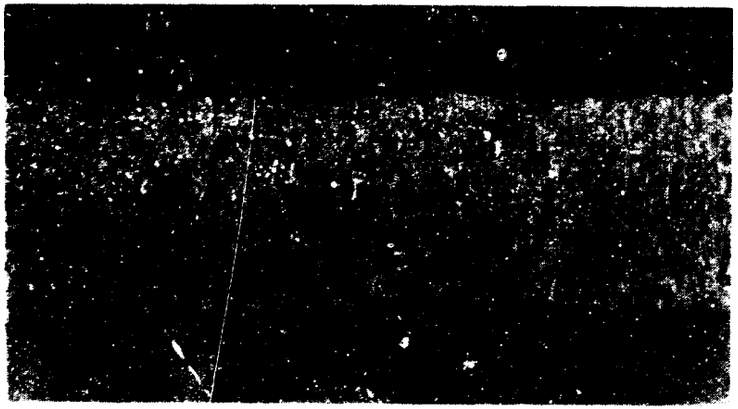
Co-Re

FIGURE 5. CONSTITUTION DIAGRAM FOR THE NICKEL-RHENIUM AND COBALT-RHENIUM SYSTEM

perrhenate into aqueous sulphamate solution. The microstructures of Ni-Re and Co-Re deposits and some of their properties are shown in Figures 6 and 7. The coatings were smooth and free of cracks and voids. Both columnar and laminar structures are observed. Observations under polarized lighting showed the laminar structure to be superimposed over the columnar structure. The exact composition of these coatings has not yet been determined. The Re concentrations indicated in the figures are those expected from the bath composition.

DISPERSION STRENGTHENED COATINGS

Dispersion strengthened alloys possess high hot-hardness, an important property required in materials for guns, especially those subjected to a rapid rate of fire. These coatings can further be strengthened by solution hardening of the matrix. Sauter et al[41,42] at the Watervliet Arsenal have demonstrated the feasibility of dispersion strengthening electroformed Ni, Co, and Ni-Co alloys with alpha Al_2O_3 particles. It was, therefore, decided to evaluate some of these coatings in this program. As an initial step, alloy systems of Ni-Al_2O_3, Ni-TiO_2, and Co-TiO_2 were coated on steel coupons and nozzles. The details of the experimental work have been reported elsewhere[43]. The microstructure of one of these coatings is shown in Figure 8. As will be discussed later, because of the low m.p. of the matrix, their performance was marginal with the use of triple base propellants; yet they have attractive possibilities as underlays for top coatings with a high melting point.

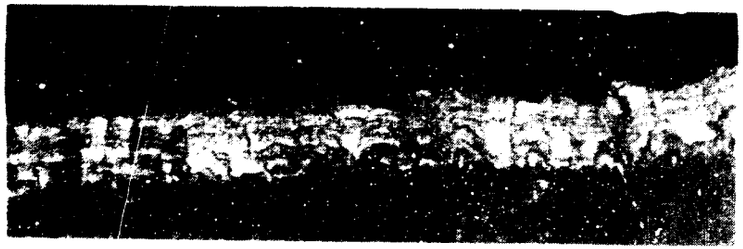


Alloy - Ni-Re (16%)
Current Density - 3.2 A ft^2 (1 A dm^2)
Thickness - 1.25 mils
Micro-Hardness - 550 knoop
Appearance - smooth and semi bright gray surface; sound deposit; crack-free; void free; very fine columnar structure (or fribrous structure)

3.4-17

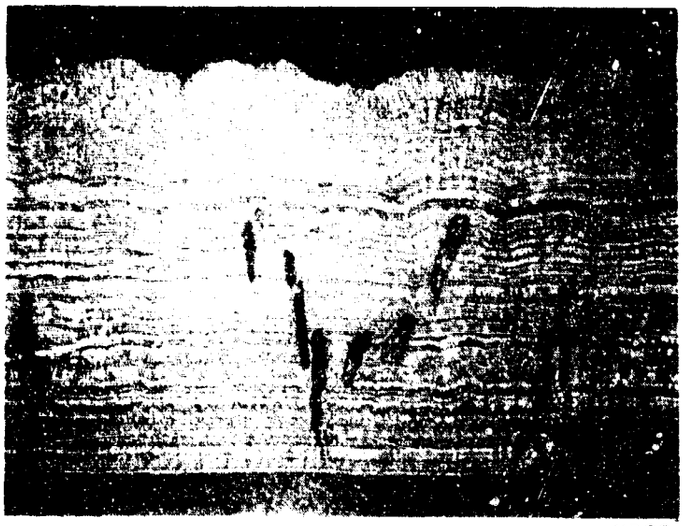
ETCHED

X1000



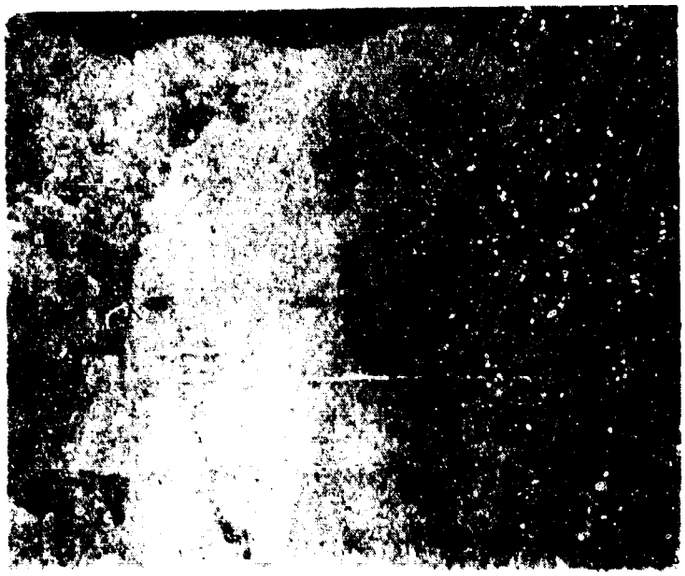
Alloy - Ni-Re (49%)
Current Density - 28 A ft^2 (3 A dm^2)
Thickness - .5 mils
Micro-Hardness - 470 knoop
Appearance - Surface is smooth and shiny resembling silver in color; sound deposit; crack-free and void free; fine laminar structure.

FIGURE 6. MICROSTRUCTURE AND PROPERTIES OF Ni-Re ALLOY DEPOSITS



X500

Alloy - Ni-Re (2%)
Current Density - 100 A/ft^2 (11 A/dm^2)
Thickness - 5 mils
Micro-Hardness - 525 knoop
Appearance - surface is not gray sound, free of stress cracks and voids. Laminar structure.



X500

Alloy - Co-Re (2%)
Current Density - 100 A/ft^2 (11 A/dm^2)
Thickness - 8 mils
Micro-Hardness - 510 knoop
Appearance - surface is dull dark gray; sound deposit; free of stress cracks and voids; void free; columnar structure.

FIGURE 7 MICROSTRUCTURE AND PROPERTIES OF Ni-Re AND Co-Re ALLOY DEPOSITS (FROM SULPHAMATE BATH)

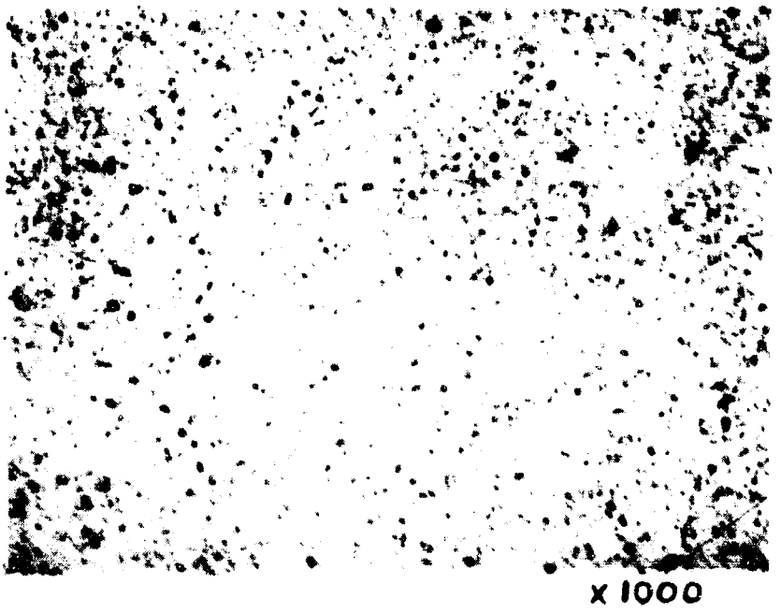


FIGURE 8. MICROSTRUCTURE OF Ni-$al_2 0_3$ DISPERSION HARDENED ALLOY

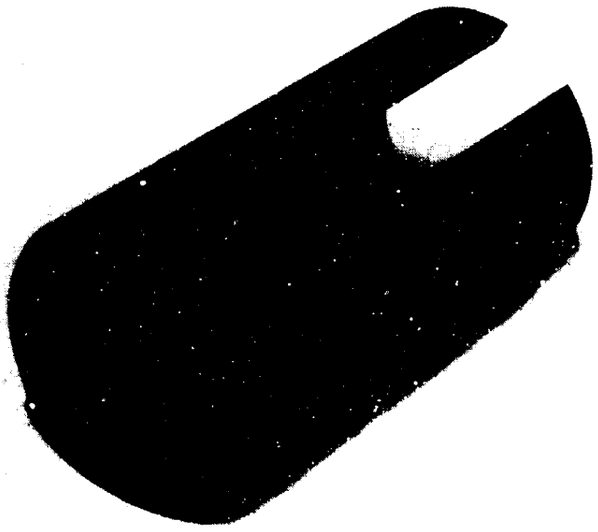


FIGURE 9. PLASMA SPRAYED Mo IN THE BORE CUT OF A 90MM CYLINDER

Reed[44] and other workers at Bendix by the addition of 2% MgO reported to have consistently obtained high level of room temperature ductility in chromium and Cr base alloys. Presently, we are developing techniques for the electrodeposition of Cr-MgO coatings, which will be subsequently evaluated with our erosion gages.

PLASMA SPRAYED MOLYBDENUM AND CHROMIUM COATINGS

As has been mentioned earlier, one of the reasons why molybdenum could not be successfully adopted as an erosion resistant material in spite of its excellent properties, was the fact that the technology of its application in tubes was not sufficiently developed. During the last few years, flame spray techniques have made considerable progress. Of special interest is the D.C. ARC flame spray technique. Because of the inert atmosphere used, it is a good technique to apply coatings of candidate materials such as Mo, Cr or other refractory metals. As a result of preliminary exploration, we have demonstrated that molybdenum can be coated in a section of a 90mm tube as shown in Figure 9. (A longitudinal section has been removed after coating for metallographic studies.) This accomplishment was very important, because it opened up great possibilities of applying coatings of a wide range of materials in cannon tubes. In fact, torches which can be used in as small as 2" diameter tubes are being developed but are not on the market yet. When available, it will be possible to coat even 60mm tubes.

Presently, we are optimizing parameters for applying molybdenum and chromium coatings. Data on the structure and bond strength with steel substrate is scant. It is therefore necessary to study the

properties of these coatings before they can be evaluated for application in cannon tubes. Figure 10 shows the microstructure of molybdenum coatings. The inclusions observed at the interface are residual sand particles from initial sand blasting of the substrate. The microstructure of chromium (Figure 11) shows crack-free deposit with inclusion of oxide because the specimen was not protected from the atmosphere during coating. Arrangements have now been made to provide an inert gas envelope around the specimen at all times during spraying. It is hoped that this will give inclusion free coatings of chromium. A 3M Metco Plasma Spray unit was used to apply these coatings for which the process conditions are summarized in Table II.

EROSION GAGES

To evaluate the erosion behavior of candidate coatings, two types of erosion gages have been developed.

155mm Stub Gun - This is essentially a breech end assembly of a 155mm Howitzer which was initially designed to evaluate metal seals but has now been adopted as an erosion gage. The seal, which is essentially a conical vent as shown in Figure 13, forms the substrate for the coatings to be evaluated. A schematic of the apparatus is shown in Figure 12. The chamber has a volume of 150 cubic inches and is provided with a crusher gage to record chamber pressures. A pressure-time curve for this system obtained with two pounds of T36 propellant is shown in Figure 13. The peak corresponds to a pressure of 48 kpsi. Both cool propellants and high temperature propellants have been used in our studies with firing conducted at 35,000 and 50,000 psi chamber pressures. The extent of erosion is determined

AS-POLISHED X200

ETCHED X1000

Deposit - Mo
Particle Size - (-170 to -325 Mesh)
Thickness - 13 mils
Micro-Hardness - 310 knoop
Appearance - mat gray surface resembling a sandblasted finish; sound layered deposit with columnar structure within the layers. A few stress cracks with layers but no through cracks. Relatively few voids and few areas consisting of separate phases of oxides.

FIGURE 10 MICROSTRUCTURE AND PROPERTIES OF PLASMA SPRAYED MOLYBDENUM

AS-POLISHED X200

Deposit - Cr
Particle size - (-170 to -325 Mesh)
Thickness - 11 mils
Micro-Hardness - 270 knoop
Appearance - mat gray surface resembling sandblasted finish; sound and relatively void free deposit; crack free; several large areas consisting of phases of chromium oxide.

ETCHED X1000

FIGURE 11. MICROSTRUCTURE AND PROPERTIES OF PLASMA SPRAYED CHROMIUM

TABLE II

PROCESS CONDITIONS FOR APPLYING PLASMA SPRAYED COATINGS ONTO STEEL

PROCESS PARAMETERS	Mo	Cr
Impinging Particle VEL.	150-250 ft/sec	150-250 ft/sec
Nozzle to Surface Distance	3 - 5 in	5 - 6 in
Specimen Surface Temp. Rise	350°F	350°F
Temp. of Plasma Material	20,000-30,000°F	20,000-30,000°F
Rotation of Test Nozzle During Spraying	400 rpms	400 rpms
Power Applied for Producing Plasms (Micro-Sec. Exposure)	500 AMPS	500 AMPS
Specified Bond Strength on Steel by Most Users	650 psi	650 psi

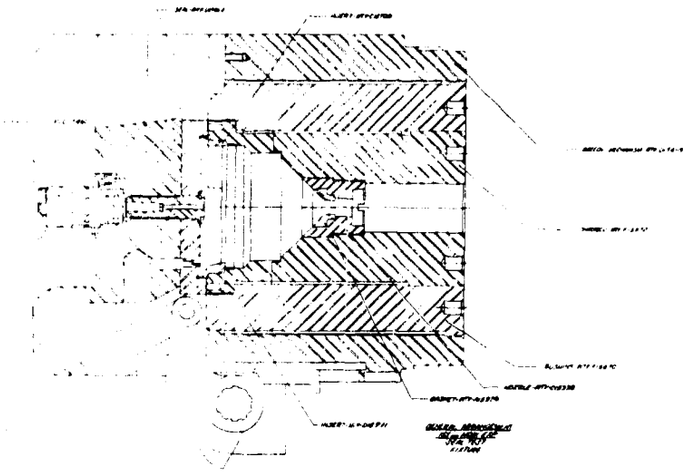


FIGURE 12. SCHEMATIC OF THE 155MM STUB GUN EROSION GAGE

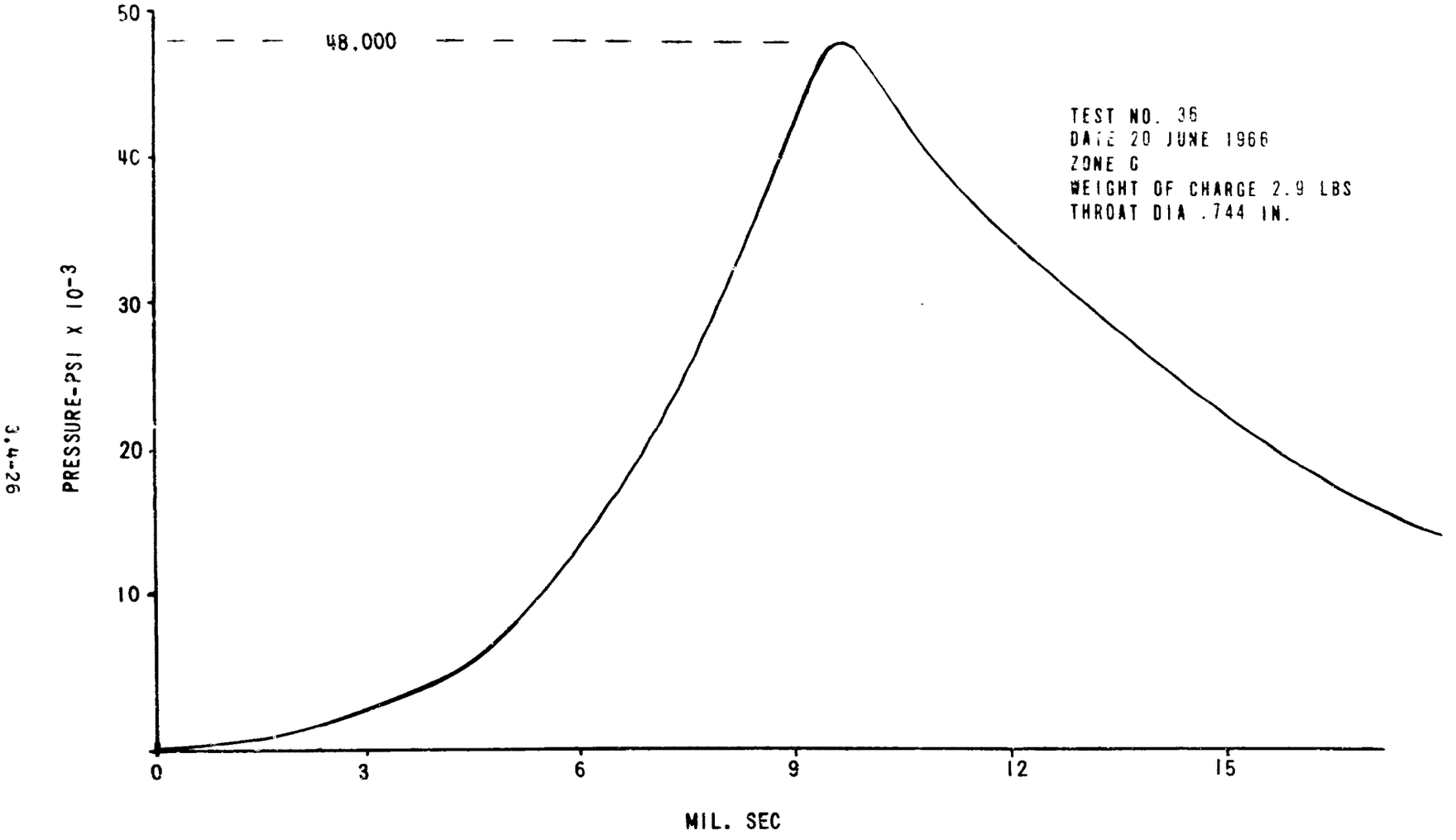


FIGURE 13. PRESSURE-TIME CURVE OF 3/4" CONICAL EROSION VENT

by nozzle weight loss measurements and by bore or throat enlargement. A reasonable correlation between the enlargement of the bore and the number of rounds using single and triple base propellants at two pressure levels was obtained. The use of M30 propellant at a pressure of 50 kpsi results in a very severe environment for a nozzle material. Figure 14 compares the view of a new nozzle and one that has been fired 13 rounds with the latter propellant. In our studies, therefore, for preliminary acceptance of a material, candidate coatings are first subjected to a lower pressure of 35 kpsi using a single base (M1) propellant.

M14 Rifle - To provide a simple method for in-house evaluation, an erosion gage utilizing the M14 rifle tube has recently been developed. A photo and drawing are shown in Figure 15. The design of the nozzle is such that the surface on which the test coating is applied can be easily examined by usual optical and metallurgical methods after firing. Test coatings are applied on the flat surface exposed at the bore. The coating extends part way into the nozzle hole. Figure 16 shows a cross-section of a gun steel nozzle after 820 rounds. The typical erosion characteristics, especially the white layer, are evident. The average wear vs. number of rounds of gun steel nozzles, using standard ball propellant, is given in Figure 17.

PERFORMANCE OF SOME OF THE COATINGS TRIED IN 155MM STUB GUN

Some of the coatings described above were applied in the conical nozzle of the 155mm stub gun and test fired. As references, some

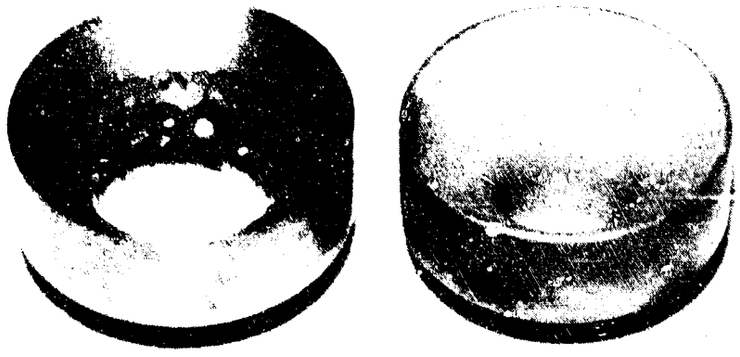


FIGURE 14 COMPARISON OF A NEW AND ERODED 3/4" NOZZLE

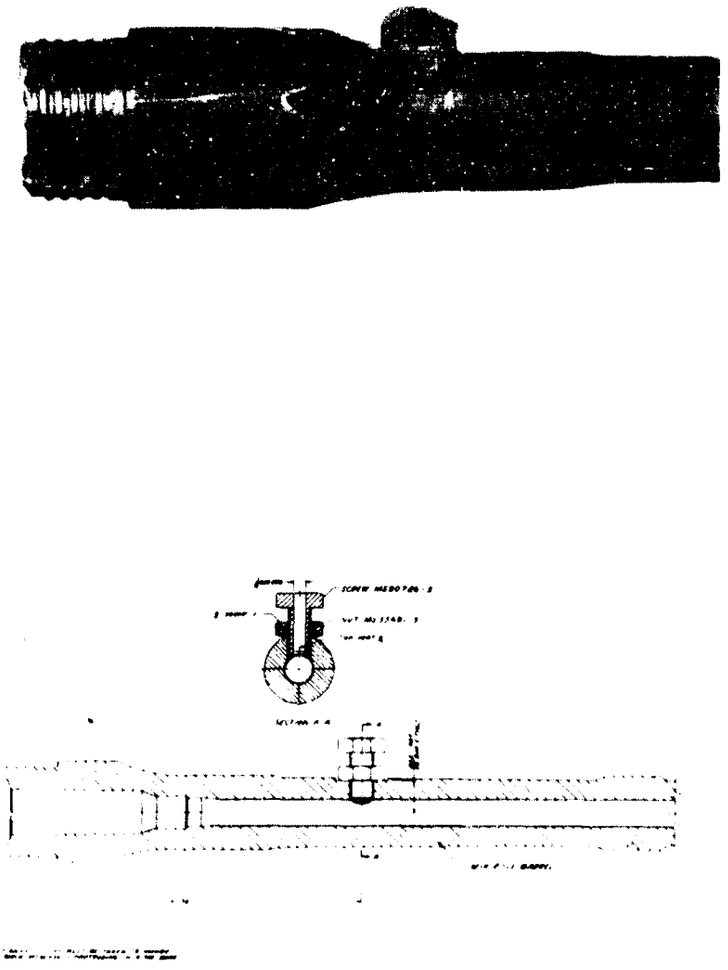


FIGURE 15. PHOTO AND SCHEMATIC OF THE M14 EROSION GAGE

NITAL ETCH X1000

FIGURE 16 ERODED GUN STEEL SURFACE AT ORIGIN OF 1.8" NOZZLE FIRED 820 RDS IN M14 RIFLE

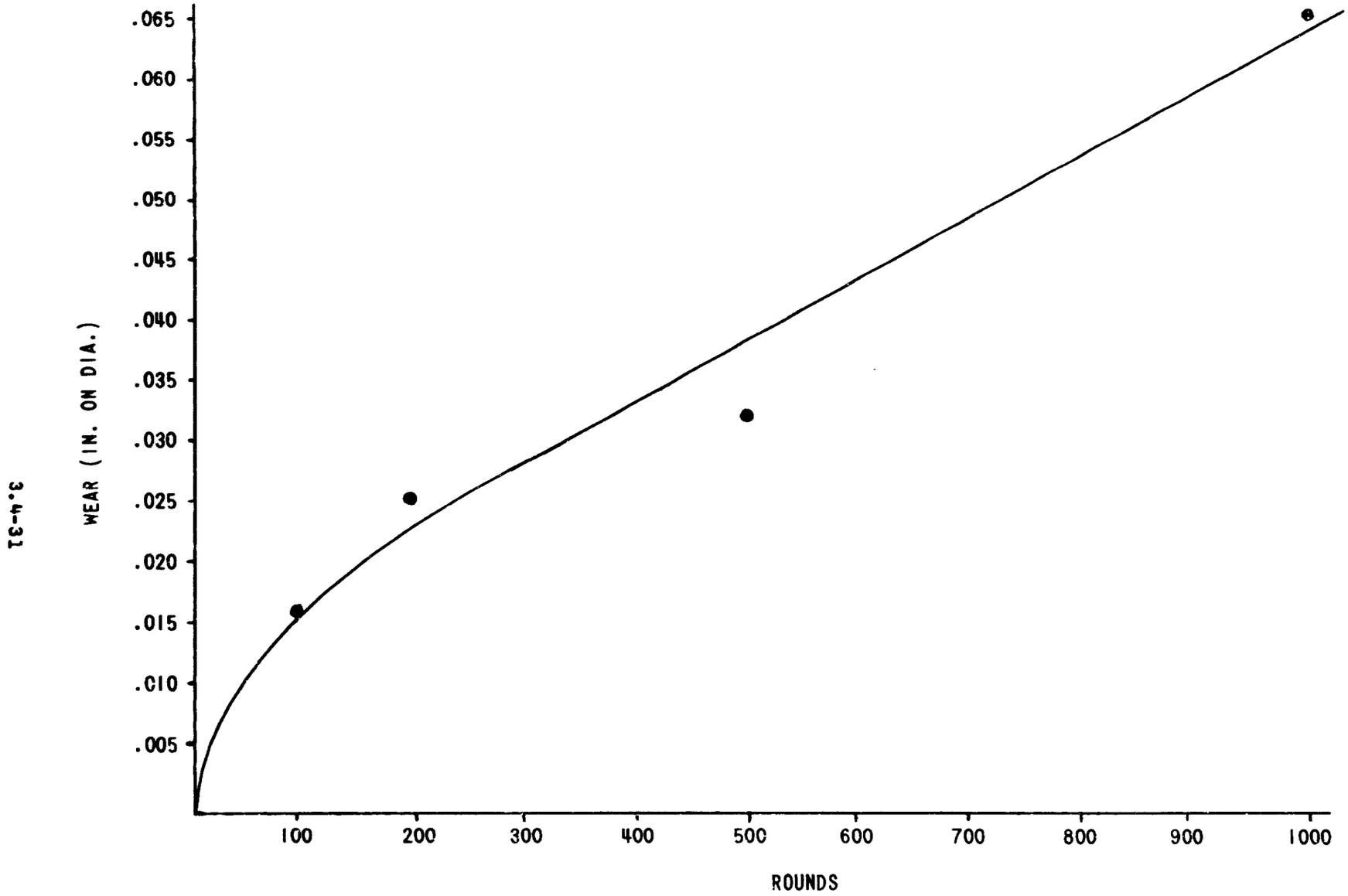


FIGURE 17. WEAR vs ROUND PLOT OF M14 NOZZLES

nozzles were also coated with pure electrolytic nickel and cobalt. Cast nickel and cast cobalt nozzles were also evaluated. The data obtained to date is summarized in Table III. At this stage the study must be considered preliminary and non-conclusive. It does, however, show that out of the bulk materials tested with triple based propellant, the performance is in the order written: cast Ni, cast Co, steel. Among the coatings, chrome and Ni-TiO_2 (600 g/l) and Co-W-Al_2O_3 showed negligible erosion, at lower pressures, and Co faired better than nickel, and iron was the poorest.

As a matter of interest, it is mentioned here that another approach to obtain increased life of gun tubes under hypervelocity and rapid rate of fire conditions is to use a completely new concept of material design for the tube. One of the concepts which we are exploring is to select a liner of a refractory metal which has a very high melting point and other erosion resistance characteristics and back it with a filament reinforced metal matrix composite jacket. This is illustrated by Figure 18, which is a picture of a 20mm thick refractory alloy liner with a 0.0005" tungsten filament (tensile strength 500,000 psi) reinforced nickel matrix jacket. The composite with 33 vol. percent of the filament is estimated to have a tensile strength of 200,000 psi[45]. The smooth section demonstrates the machinability of the composite. The inset shows the cross-section of the composite. Tubes designed from such high strength, high temperature refractory material may prove successful in withstanding the condition of very high muzzle velocity (like that expected in kinetic energy rounds) and rapid rate of fire anticipated in future weaponry.

TABLE III. EROSION RESISTANCE OF COATINGS IN 3/4" NOZZLE

Enlargement of the Nozzle Diameter in Mils, per Round

	MTL	M1 35Ksi	M30 35Ksi	M1 50Ksi	M30 50Ksi
BULK MATERIALS	Gun Steel	1.90	6.38	4.4	10.8
	4340	1.42	4.56	-	-
	Cast Nickel (depolarized)	-	2.5	-	-
	Cast Cobalt	-	3.3	-	-
COATINGS	Chromium	NIL	NIL	NIL	WASH OUT (2 Rds.)*
	Iron	1.08	-	-	-
	Nickel	0.25			
	Cobalt	0.195	3.0		
	Ni-TiO_2(200 g/l)		1.25		
	Ni-TiO_2(400 g/l)		NIL		
	Co-Wp-al_2O_3	NIL			
	Ni-Re(18%)				
	Ni-Re(25%)				
	Ni-Re(48%)				
	Ni-Re(>80%)				
	Co-Re				

*WASH OUT - is defined as complete removal of coating on throat area with simultaneous removal of some substrate after one round. Cause of coating removal under these circumstances may be either poor adhesion or rapid erosion.

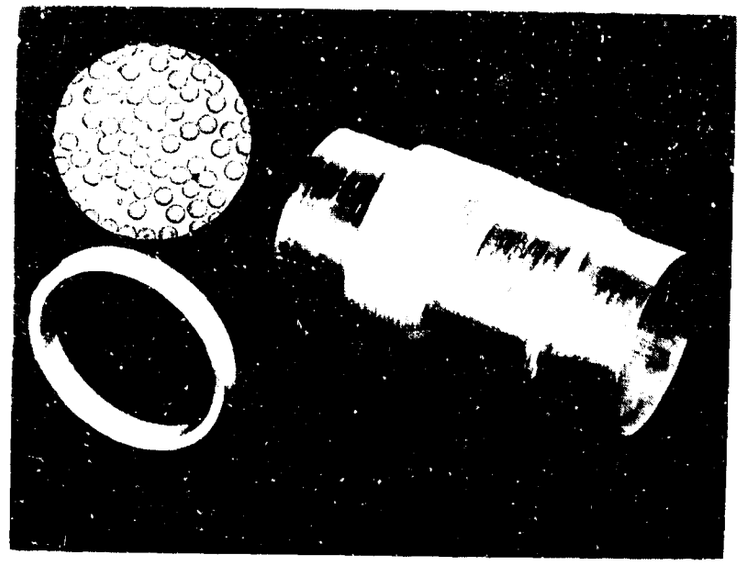


FIGURE [illegible] A TUNGSTEN FILAMENT REINFORCED NICKEL
[illegible] ON A 20 MIL COLUMBIUM ALLOY LINER

CONCLUSIONS AND FUTURE PLANS

The work reported above is still in its preliminary stages and is in effect exploratory; the main reason being that it was supported by M&T funds, which do not provide for research and development efforts. Their requirements dictate a quick exploration of the technology followed by its application to the solution of a specific problem or producing a hardware. It is heartening that recently we have given some responsibility to undertake R&E work on the erosion control in small arms which will complement this M&T work, and thus enable us to have a balanced program on erosion control. Our future plans include:

1. Further develop the electrodeposition technique to obtain improved chrome or chrome alloy and other refractory coatings.

2. Evaluate dispersion strengthened coatings both as underlays and as primary coatings.

3. Further develop the plasma spray technique, and investigate the mechanical and metallurgical properties and erosion behavior of promising coatings.

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AERONUTRONIC ADVANCED GUN BARREL DEVELOPMENT PROGRAM

R. A. Harlow
R. C. Kimball
Aeronutronic Division
Philco-Ford Corporation
Newport Beach, California

Aeronutronic is conducting a program for fabrication development and testing of advanced gun barrel concepts for high cyclic rate weapons. A 7.62 mm MG3 machine gun capable of firing 1100-1200 rpm is being used as the test weapon. Homogeneous and bimetal barrels are being fabricated from high strength steels, superalloys, and refractory alloys and tested to destruction such that comparative data for each class of materials are generated. Preliminary data on various alloys have shown very significant improvements in burst length capability and erosion life compared to conventional gun barrel steels.

Introduction

Present and future advanced high cyclic rate weapon designs, such as the XM-140, XM-129, HIPAC, VRFWS, and the AX Cannon, have created a need for improved barrel materials and processing technology. Requirements for increased firing rates, muzzle velocities, flame temperatures, burst lengths, barrel lives, and strength to weight ratios have made state-of-the-art materials obsolete for various advanced designs. Barrels for high cyclic rate weapons must endure firing rates of up to 1200 rpm/barrel or greater which result in very high bore temperatures. Burst lengths must be limited to several seconds in order to avoid severe erosion and/or bowing and catastrophic failure of the barrel. This limits even present-day guns to very short time on target capability, (3 to 5 seconds).[1] Barrel life is limited primarily by erosion from hot oxidizing gases (~5000°F) and from the projectiles. Added problems include galling between the barrel and rotating band. Advanced weapons such as Aeronutronic's caseless HIPAC and CAW-T require barrels to withstand bore temperatures of approximately 2000°F due to the high firing rates and relatively long burst lengths involved. These

temperatures would severely limit the life of barrels fabricated from conventional materials. Aircraft mounted weapons such as the HIPAC involve an added requirement of high strength to weight ratio.

The problem of barrel erosion is not new, and several techniques involving electrolytic Cr plating of the bore or employing cast Stellite 21 (cobalt base) inserts have been used with reasonable success for short burst lengths with intermediate cool-down cycles.[1-3] However, the need for further improved gun barrel materials and fabrication processes is very significant, particularly with the inception of more advanced gun designs.

Although much of the gun barrel development work of recent years is not well documented, a literature survey supplemented by discussions with Government agencies and by Aeronutronic experience served as a basis for initiating an advanced barrel fabrication and testing program. The survey indicated that an extensive, well organized testing program, wherein various materials were tested identically to generate comparative data, has not been conducted (or reported). Therefore, even though some duplication of previous data may result, a screening approach was selected for this program in order to generate comparative erosion data on the most promising classes of materials for homogeneous and bimetal (lined) barrels. The program involves fabricating barrels and life testing on a high cyclic rate (1100 to 1200 rpm) single barrel 7.62 mm machine gun. The classes of barrel materials are rated with respect to barrel life/burst length capability. This program is being given supplemental support by Rock Island Arsenal (QDRI) under Contract DAAF 01-69-M-6556, "Gun Barrel Development." This contract has supplied Aeronutronic with ammunition and two machine guns for use in the test program. The program is outlined as follows:

Barrel Test Facility

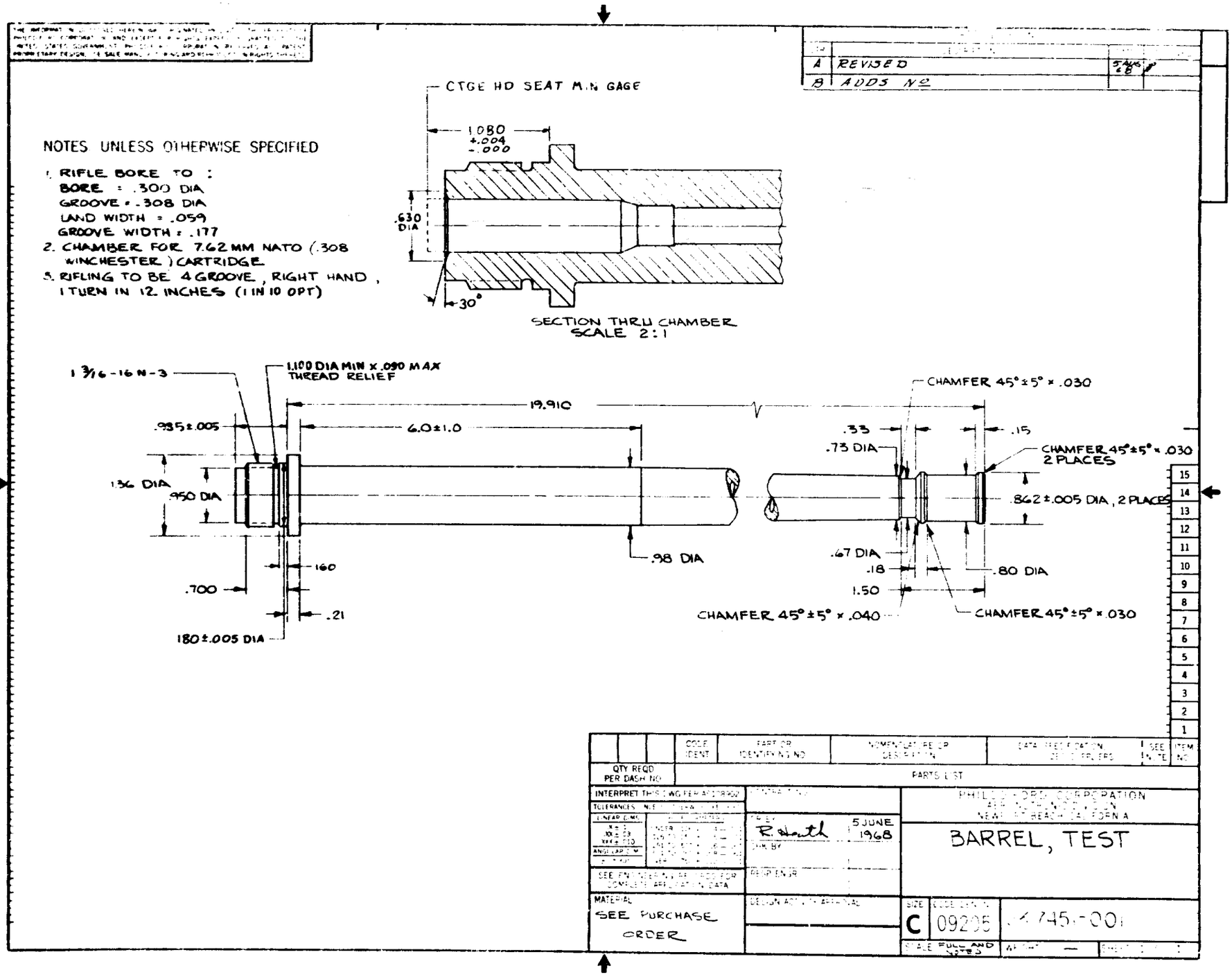
A 7.62 mm NATO MG1(42/59) single barrel machine gun was originally purchased for barrel testing. This gun has advantages of very high firing rates 1100-1200 rpm, a quick interchange barrel, and low cost ammunition. The small size of the barrel (1 in. diameter by 21 in. long) provides a relatively inexpensive configuration for test barrels. A sketch of the barrel is shown in Figure 1. Late in 1969 a new MG3 which is a later version of the MG1 was purchased. This gun shows little change from the MG1 which is of World War II vintage except that it will accept the standard 7.62 mm disintegrating link.

The test gun is set up at the El Toro test facility. It is equipped with a remote fire control, Franklin/Lumiline system for measuring muzzle velocity, a six channel temperature recorder, and a rapidly moving chart paper device to record accuracy of each projectile. Barrel erosion is measured after each burst by a silicone rubber replica technique.

Two supplemental 7.62 mm test guns designated as XM-161 with firing rates of 900 rpm supplied by Rock Island Arsenal were held in reserve as backup for the purchased MG1(42/59).

Candidate Materials Selection

The materials selected for evaluation are listed in Table I. Several classes of materials are represented in the list of candidates for homogeneous barrels and/or liners, i.e., (1) nickel and cobalt base production superalloys, (2) a developmental high strength stainless steel, (3) a tantalum base refractory alloy, and (4) a conventional "gun barrel steel." The screening approach used in testing enables a comparative rating of each class of materials for various burst length and barrel life requirements of present-day and advanced high cyclic rate weapons.



3.5-3

FIGURE 1. TEST BARREL

TABLE I

BARRELS INCLUDED IN THE TEST PROGRAM

Homogeneous Barrels

Alloy	Description and Nominal Composition
Cold Worked L-605	Cobalt Base Superalloy (Co - 10Ni - 20Cr - 15W - 3Fe max - .10C - 1.5Mn)
Rene 41	Nickel Base Superalloy (Ni - 19Cr - 5Fe max - .10C - 11Co - 3Ti - 10Mo - 1.5Al)
Pyromet X-15	High Strength Stainless Steel Used for CAW-T Barrel (Fe - .03C - 15Cr - 20Co - 2.9Mo - .2Ni max, .01S max, .10Mn max, .10Si max)
"Gun Barrel Steel"	Purchased German-made Barrels, ~4150 Steel (Fe - .55C - 1.03Cr - .19Mo - .60Mn - .36Ni)

Bimetal Barrels

Shell	Liner	Fabrication Method
4340 Steel*	L-605**	Coextrude
4340 Steel*	Ta-10W	Coextrude

---

*(Fe - .42C - .8Cr - .33Mo - .78Mn - 1.79Ni)

**Composition listed above

As mentioned previously, the primary failure mode of a barrel is believed to be erosion from the hot gases and projectiles which occurs over a relatively short period of time. For this reason, a material with good hot erosion resistance is preferred which does not necessarily imply a requirement for oxidation or corrosion resistance due to the short periods of time involved. There is no satisfactory method of predicting hot gas and projectile erosion resistance with a complex environment such as a gun barrel which results in the necessity for testing barrels rather than performing a simple laboratory test. This situation is further compounded by galling between the copper rotating band and the barrel and related problems such as softening of the barrel in localized areas. Criteria used for selection of potential barrel or barrel liner materials include (1) hot hardness, (2) high elevated temperature strength, (3) high melting point, (4) strength to weight ratio, (5) fabricability, (6) cost and availability, and (7) existing barrel development data. Oxidation resistance is also considered desirable but to a lesser degree as discussed previously.

Barrel Fabrication

Although many materials appear promising as candidates for high temperature gun barrels, their marginal fabricability would preclude their ultimate use on a production basis. For this reason this program and those following will necessarily explore fabrication techniques concurrently with evaluation of advanced materials. It is anticipated that the screening test approach may isolate materials that perform well but that require further fabrication development work before high volume usage would become practical.

The homogeneous 7.62 mm test barrels were fabricated by conventional gun drilling and rifling techniques by a local gun component machine shop. A sketch of this barrel is shown in Figure 1. As anticipated the Rene 41 barrel was somewhat

difficult to machine but with the use of carbide tooling resulted in an excellent quality barrel. The cold worked L-605 was considerably easier to machine, and the Pyromet X-15 was machined with no difficulty. The more difficult alloys to machine make the process of rifling by swaging appear very attractive, particularly if these materials are used only as a liner.

Bimetal barrels are being fabricated from lined tubing produced by coextrusion. It is believed that metallurgical bonding between the shell and liner is desirable for optimum heat transfer. For this reason coextrusion of bimetal tubing appears very attractive. Two material combinations were initially selected for coextrusion, i.e., a Ta-10W liner with a 4340 steel shell and an L-605 liner with a 4340 steel shell. An extrusion vendor with previously reported experience in this field[4] was utilized. Tubing dimensions were specified to allow finish machining to a nominal liner thickness of 0.025 in. The L-605 lined tubing produced was of good quality, and the tubing was honed to size and rifled by conventional methods. The Ta-10W lined tubing was inadequate dimensionally and with respect to bond quality between shell and liner. The extruded liner was hexagonal in cross section rather than cylindrical and was too far out of tolerance to clean up to barrel dimensional requirements. The bonding between shell and liner was of poor quality and revealed brittle intermetallics. Typical photomicrographs of both material combinations are shown in Figure 2. Comparative notch fracture tests were conducted on the L-605 and Ta-10W lined coextruded tubes which, as shown in Figures 3-A and B, confirmed the good and poor bond qualities, respectively. The test consists of cutting nearly through the shell (or jacket) material on sections of the extrusion. Testing these samples on a tensile machine then reveals the strength of the bond relative to the parent material. Fracture through the liner rather than along the bond line is considered a criterion for acceptable bond quality. Additional efforts are being made to secure acceptable coextruded tubing.

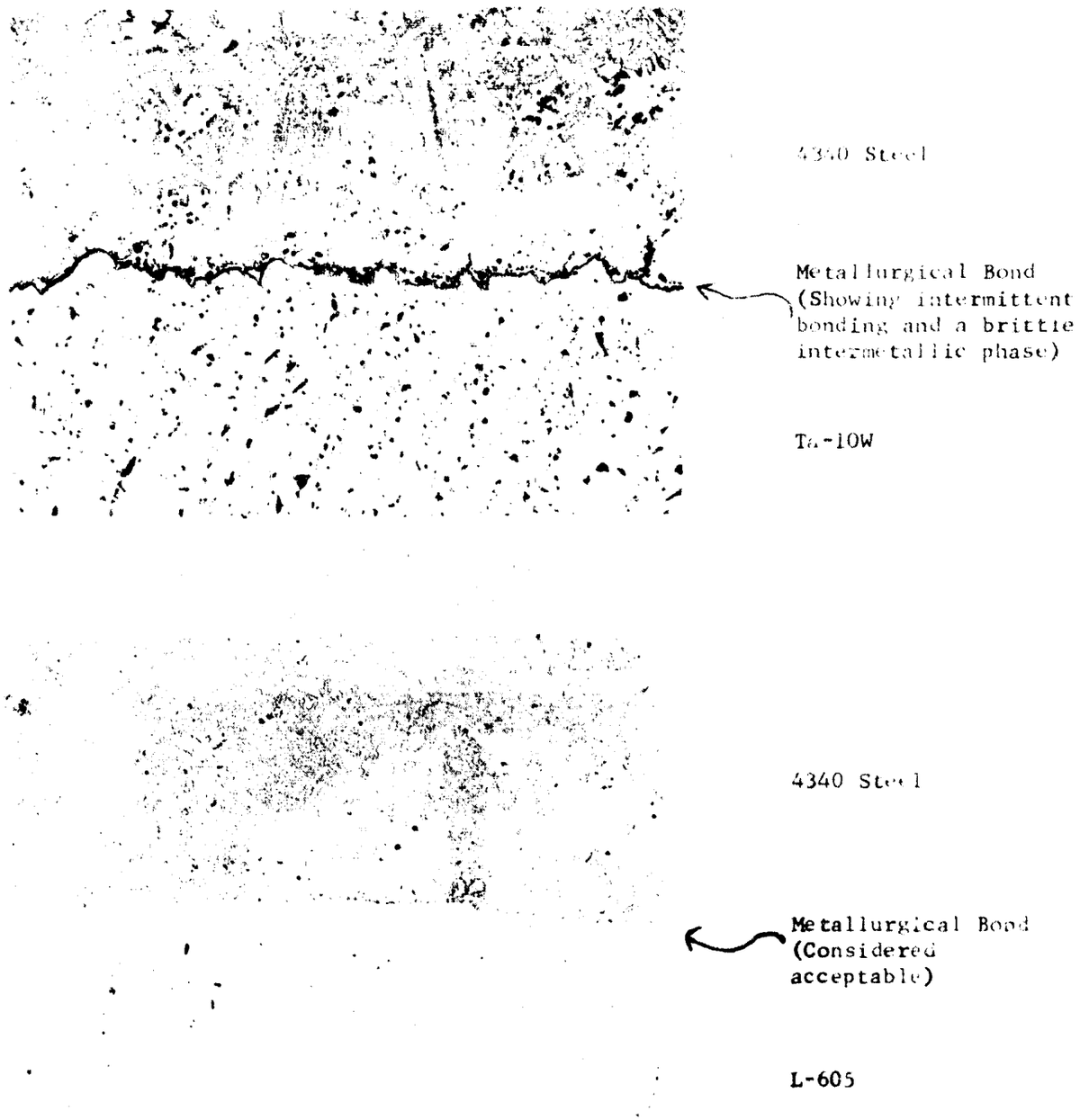
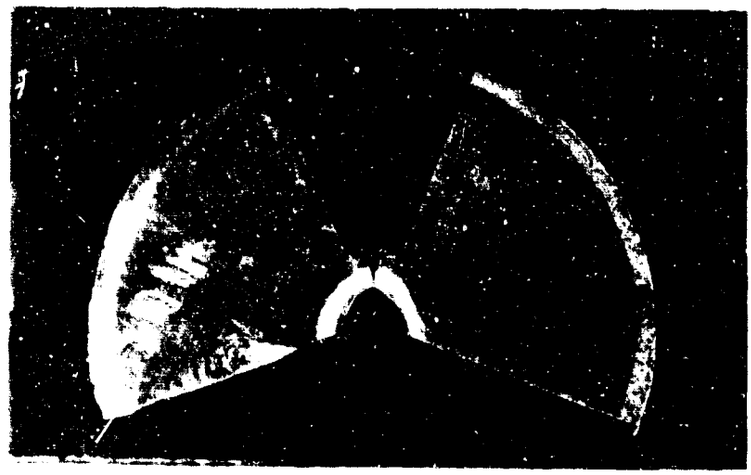
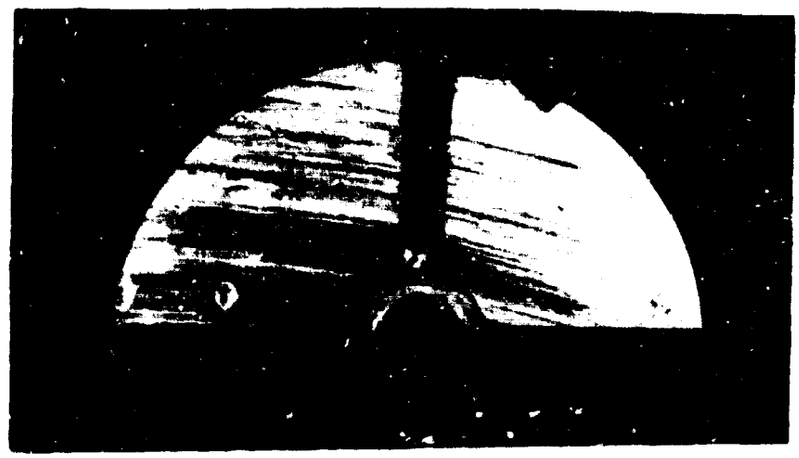


FIGURE 2. DIFFUSION BONDS IN COEXTRUDED 4340/Ta-10W AND 4340/L-605 TUBES



2.5X

A. 4340/L-605 Sample Showing Acceptable Bond Quality. Note: The photo shows remnants of the sacrificial steel core adjacent to the L-605 liner on the ID



2.5X

B. 4340/Ta-10W Sample Showing Unacceptable Bond Quality. Note: The photo shows remnants of the sacrificial steel core adjacent to the Ta-10W liner at the ID

FIGURE 3. TESTED NOTCH FRACTURE SAMPLES OF COEXTRUDED TUBING

Preliminary Results

The fabrication and testing of barrels is nearing completion. The Ta-10W lined 4340 barrels have been temporarily delayed because of coextrusion difficulties as previously mentioned.

The test data are summarized graphically in Figure 4. The burst length versus nominal bore temperature plot was based on thermocouple measurements taken at five locations on the OD of the barrel. An Aeronutronic TLOG computer program was developed for converting OD temperature to bore temperature. As can be seen, burst lengths in the 600 to 800°F range result in nominal bore temperatures of 1800 to 2000°F (each time starting with a cold barrel). These data refer to a maximum temperature measured approximately 2 in. from the chamber (throat) area.

As can be seen from the graph, very severe testing parameters were selected. A cursory stress analysis was performed in conjunction with preliminary firing trials to establish a maximum burst length that would not cause structural failure. Empirically, a maximum burst length of 400 rounds was established for the steels and high strength stainless steels. This empirical approach was necessary in order to utilize thermal data from the initial firings for the TLOG computer program. Similarly, a burst length of 600 rounds was established for the superalloys, indicating their much higher temperature capability. The bar chart (Figure 4) plots the entire barrel testing history versus erosion (and ultimate failure). The shorter bursts resulting from preliminary trials and occasional stoppages of the gun are considered relatively unimportant with respect to erosion, in comparison with the longer bursts, i.e., ~300 rounds. The bar chart shows that the gun barrel steel eroded significantly after a single 400 round burst and failed shortly after a total of three 400 round bursts. By comparison, the Rene 41 and L-605 barrels showed no erosion after five 600 round

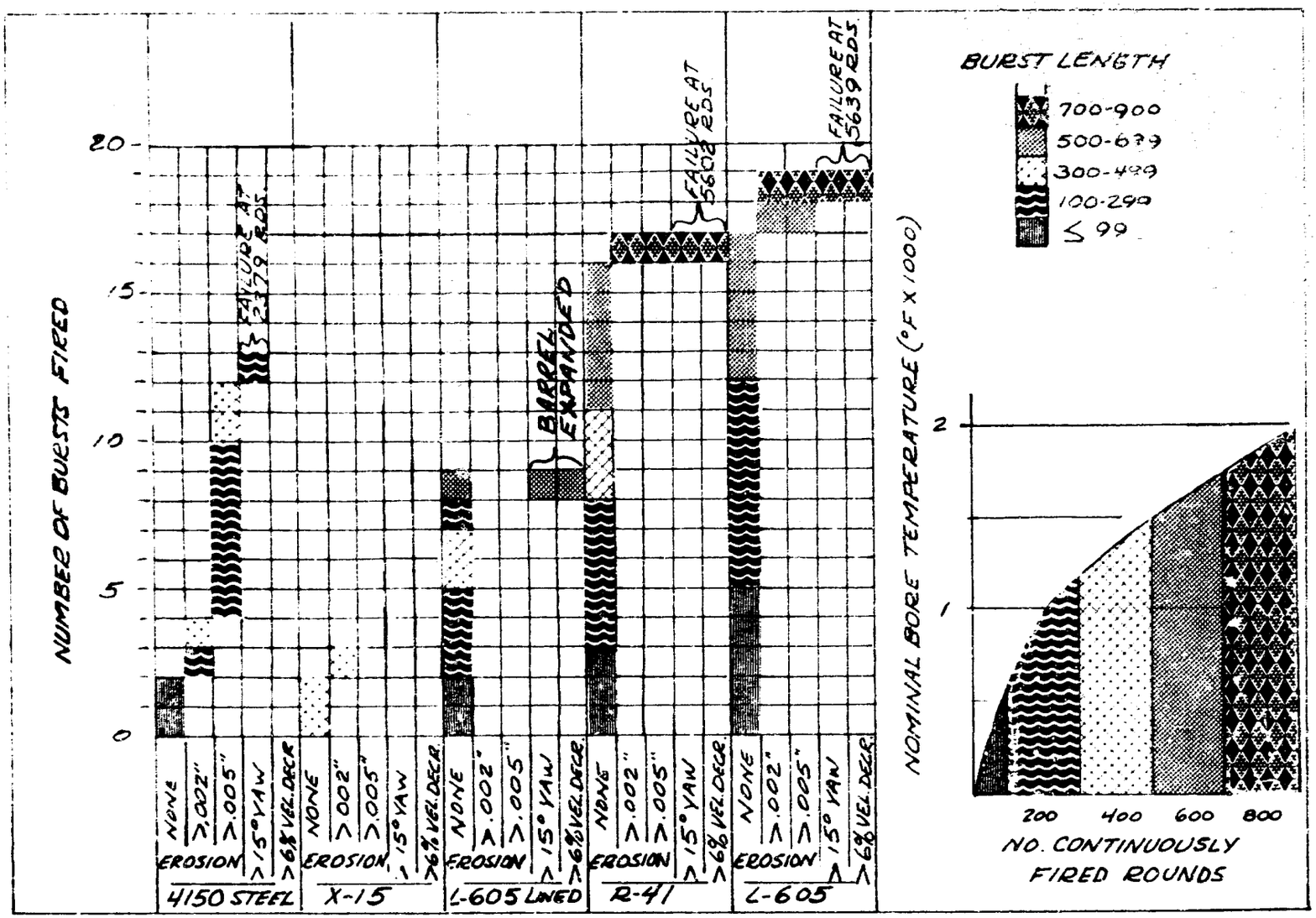


FIGURE 4. GUN BARREL EROSION DATA

bursts Failure of these barrels occurred only during an exploratory 700 or 800 round burst. This is considered to be a very significant improvement in burst length and barrel life capability. Data on the Pyromet X-15 showed somewhat better erosion resistance than steel but less than the superalloys. Data on the 4340/L-605 bimetal barrel showed a capability of many 400 round bursts with no erosion. However, the barrel failed structurally by bulging during the initial 600 round burst. More work would be necessary to design a bimetal barrel for structural integrity to meet specific high temperature requirements, considering the jacket to liner thickness ratios and outer jacket material choice. The lined 4340 barrel design that was tested showed improved erosion life but very little increase in burst length capability.

A photograph of the eroded area in the Rene 41 barrel (sectioned longitudinally) is shown in Figure 5. The erosion appeared most severe in the hottest portion of the barrel as expected, although very little rifling was left over the entire length. A metallography sample was taken from the severely eroded area and as shown in Figure 6 proved significant with respect to determining mechanism of failure. The copper from the projectile jackets alloyed with the barrel alloy, effectively lowering its melting point. The incipient melting that resulted allowed the bore surface to be literally "wiped away." This phenomenon might also be expected in steels. Further work is recommended to supplement existing data on non-copper (e.g., Fe) rotating bands to achieve prolonged burst lengths and barrel life.

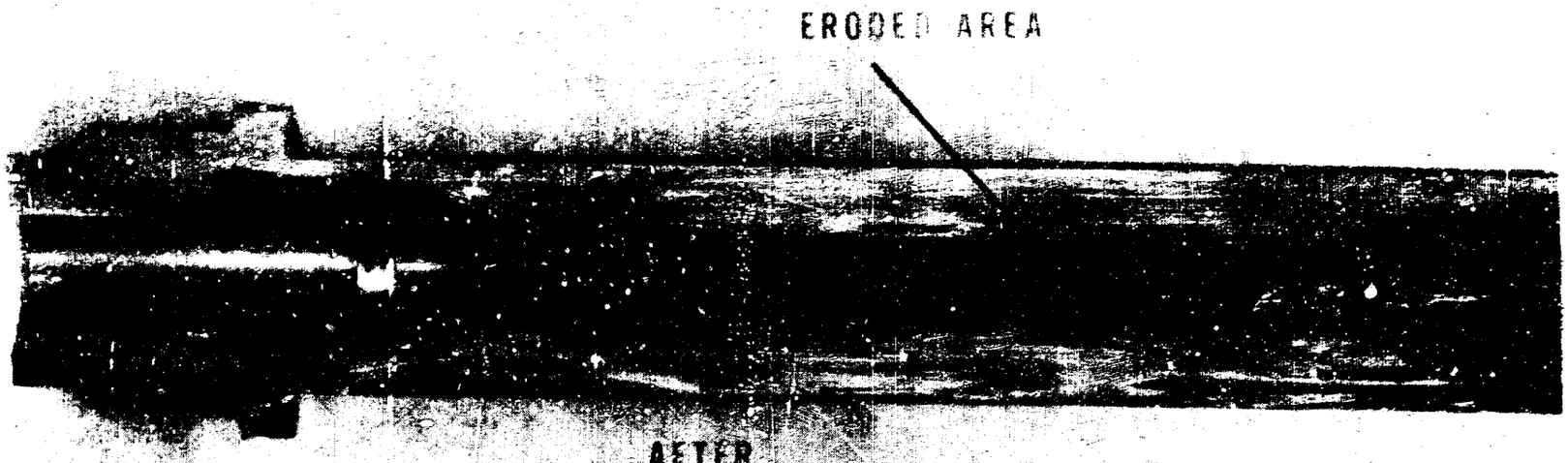


FIGURE 5. RENE 41 TEST BARREL

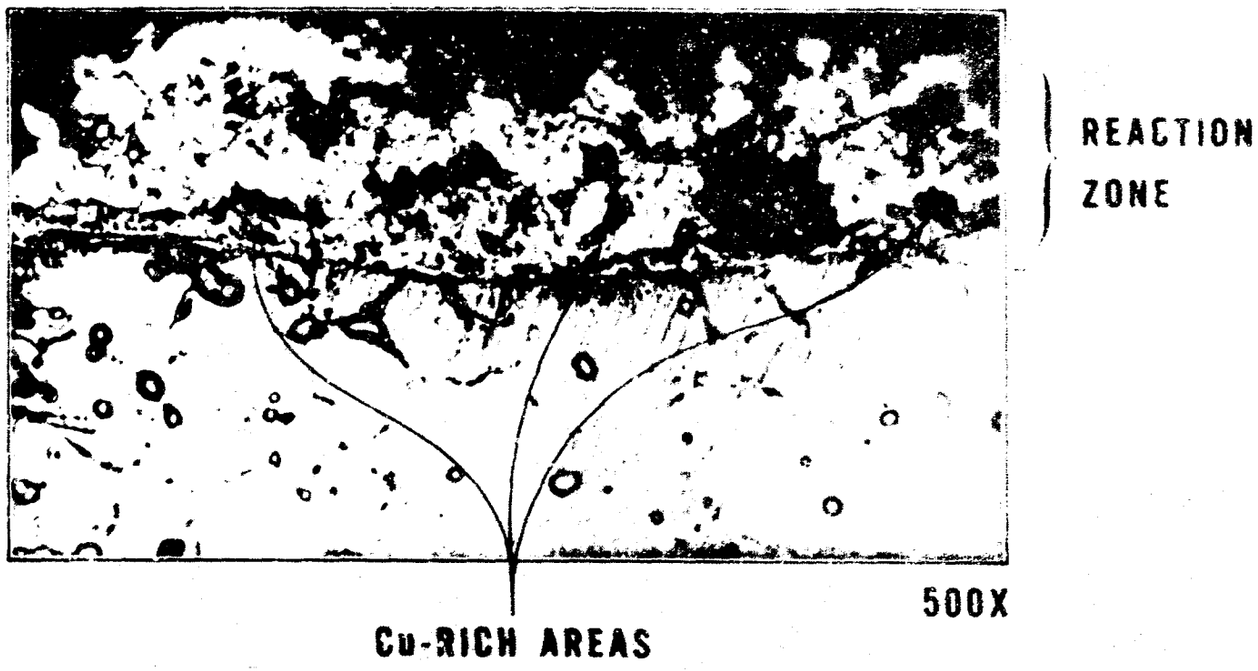


FIGURE 6. RENE 41 BARREL - CROSS SECTION OF EROSION ZONE

Conclusions

(1) Typical gun barrel steels will fail by erosion in less than 2000 rounds at nominal peak bore temperatures of 1250°F, based on test results from a single barrel.

(2) High strength stainless steels such as Pyromet X-15 will exceed the erosion life of gun barrel steels by 1000-2000 rounds at nominal peak bore temperatures of 1250°F, based on extrapolated data.

(3) Rene 41 and L-605 exceed the erosion life of gun barrel steel by at least an order of magnitude when tested at nominal peak bore temperatures of 1250°F based on extrapolated data. In addition, these alloys reveal no evidence of erosion after 3000 rounds at nominal peak bore temperatures of 1700°F.

(4) The erosion life of gun barrel steels can be increased by at least an order of magnitude utilizing an L-605 liner. The barrel is still temperature-stress limited and must be designed accordingly.

(5) Alloying of copper with nickel or iron base alloys during extended bursts is a serious performance limiting factor. Alternate rotating band materials could greatly improve barrel (and weapon) performance.

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EXPLOSION LINING OF GUN BARRELS

by

James F. Kowalick, Frankford Arsenal
Harry J. Addison, Jr., Frankford Arsenal
Winston W. Cavell, U.S. Army Munitions Command

Abstract. This paper is a progress report on a study to determine the applicability of the explosives bonding process to lining a 20mm gain-twist rifled, Mann test barrel. Low carbon steel and 304 stainless steel tubing were employed as liner materials and the base material was a 20mm gun barrel segment. Results are presented on the quality of the bonded joint, surface smoothness of the welded liner, formability limits of the liner material and the ratio of the explosive mass to combined liner and buffer material mass. The theory behind the bonding mechanism is discussed. The work accomplished thus far indicates that explosive bonding holds considerable potential for cladding the interior of rifled 20mm gun barrels.

Introduction. Explosive bonding is a relatively new joining process that is being used to bond metals and alloys in various combinations and geometries. With this process, bonding results when appropriately positioned materials are thrust together within a particular range of velocities by the force from an explosive charge.

The process has been developed to the extent where it is now being employed or considered for a number of specialized applications, including the lining of gun barrels. It appears to be especially suitable for this purpose due to its ability to bond materials that may otherwise be difficult to join by fusion welding. Explosives bonding in its simplest form consists of explosively impelling a flat flyer plate against a backer, or parent plate. The setup before detonation of the charge is shown in Figure 1.

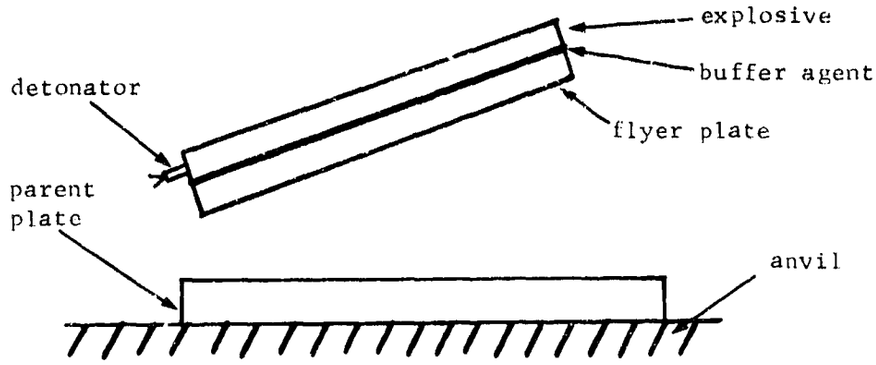

FIGURE 1. EXPLOSION BONDING ARRANGEMENT

The buffer agent serves to minimize gouging of the flyer plate by the explosive products and to control the impacting velocity of the flyer plate. The anvil supports the test arrangement and absorbs excessive stresses that may be generated during the bonding operation.

When the flyer plate strikes the backer plate within a certain range of the dynamic angle of collision γ and impacting velocity v_p as shown in Figure 2, a jet is formed which consists of the surface contaminants (oxides, etc.) between the two components to be bonded. The force of the explosion brings the clean surfaces into such close contact that a bond is established through interatomic forces.

The impacting velocity v_p and dynamic bend angle β of the flyer plate (See Fig. 2) are influenced by the ratio of the explosive to flyer and buffer plate mass L/m, the velocity of detonation of the explosive charge v_d, and the initial angle of inclination α between the plates. When the flyer and parent plates are initially parallel,

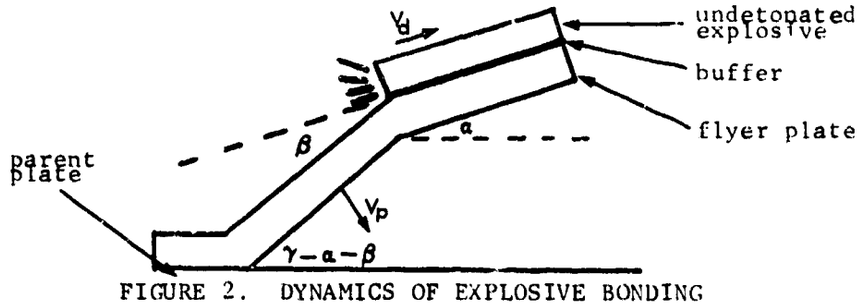

FIGURE 2. DYNAMICS OF EXPLOSIVE BONDING

$\alpha = 0$, and the dynamic angle of collision γ equals the dynamic bend angle β. A more quantitative understanding of the interdependencies among the dynamic variables can be deduced with the aid of the vectorial sketch in Fig. 3., from which the following equations have been rationalized:

$$v_p = 2\, v_d \,\mathrm{Sin}\,(\beta/2) \qquad (1)$$

$$v_c = v_d \,\mathrm{Sin}\,\beta/\mathrm{Sin}\,(\alpha+\beta) \qquad (2)$$

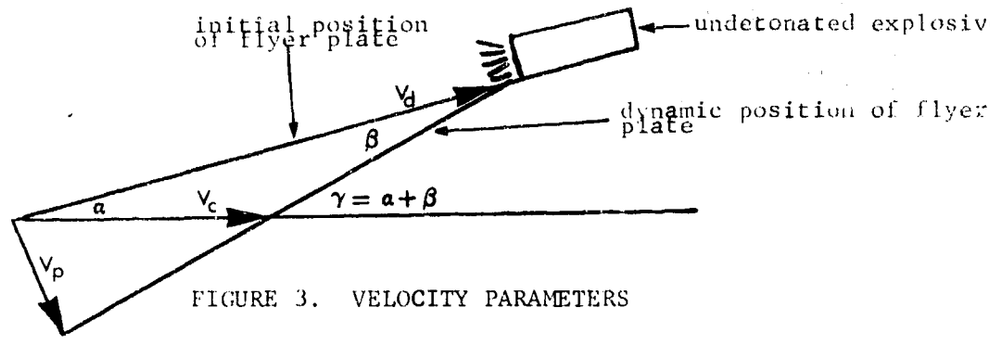

FIGURE 3. VELOCITY PARAMETERS

Here v_c is the velocity of the collision point in a direction tangent to the parent plate. Although Eqs. 1 and 2 were derived for flat plates, they are generally applicable to curved geometries.

Other investigators[1] have reported that a jet will be formed and permit a metallurgical bond to be accomplished if (1) the magnitude of v_c ranges from approximately 1200 meters per second to the sonic speed in the members being joined and (2) the magnitude of v_p exceeds a critical value required to produce stresses sufficient to overcome the elastic strength in at least one of the members.

Experimental Procedure. The current explosive bonding study reported here involves the lining of gain-twist rifled, 20mm Mann barrel segments with tri-helical rifled liners. The barrel sections were 4 inches in length, had a chemical composition in accordance with MIL-S-11595D (MR) and were [illegible] tempered to a Brinell hardness of approximately 325. Relatively inexpensive, low carbon and type 304 stainless steels were used

as liner materials instead of the more expensive refractory alloys. It was the intention that, after the feasibility of the process was demonstrated, refractory liners would be employed in subsequent work. The explosive employed throughout this work was nitroguanidine, a powdered substance which can be conveniently loaded in the density range from approximately 0.2 to 1.0 g/cc, corresponding to a velocity of detonation of approximately 2250 to 5460 meters per second. Based on past experience, the nitroguanidine charge was employed at density levels between 0.2 and 0.4 g/cc (Table 1). Thus, the calculated detonation velocity and consequently the collision point velocity of the charge was equal to or less than 3050 meters per second, which is considerably less than the sonic velocity of steel (5130 meters/second). The subsonic range of these velocities fulfills one of the two primary requirements for a bond to be accomplished as discussed previously.

A schematic drawing of the experimental setup is shown in Figure 4. The drawing shows the relative orientation of the explosive, buffer, liner and gun barrel.

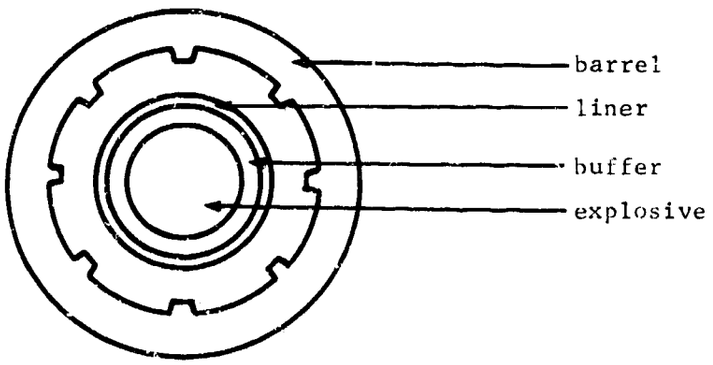

FIGURE 4. EXPLOSIVE LINING CONFIGURATION (CROSS-SECTIONAL VIEW)

The explosive was handloaded into the buffer tube, either before or after the buffer tube was slipped into the liner. The liner and interior barrel surfaces were then degreased prior to positioning the liner inside the barrel.

TABLE I

EXPLOSIVE LINING DATA

Gun Barrel - 20mm Mann Test Barrel
Hardness = B301-344
Composition = Cr/Mo/V Steel
Rifling: ID Lands = 0.787 Inch
ID Grooves = 0.817 Inch
Length = 4 Inches

Explosive - Nitroguanidine
Density = 0.2 - 0.4 g/cc
Deta. Velocity ∿ 3400 m/sec

Liners: 304 Stainless Steel or 1008 Steel
Wall Thickness: 5, 10, 20 mils
OD: 0.5625, 0.625, 0.675, 0.750 inch
L/m = 0.2 - 0.4

Buffers: Glass Tubing
Tygon Tubing
Teflon Tubing

Environmental Medium - Air or Vacuum

The gap or distance between the liner and barrel was maintained through the use of spacers placed at either end of the barrel. Finally, the explosive initiation train was placed against the main nitroguanidine charge at one end of the barrel. No anvil was required as the test barrel was massive enough to absorb and attenuate shock waves that may have prevented or minimized bonding. Process data and the ranges of variables studied in the present work are listed in Table I. Bonded samples were visually and metallographically examined and peel or chisel-tested.

Discussion. Several conclusions may be drawn from the results of the experimentation conducted thus far on the explosive lining of 20mm gain-twist rifled Mann test barrels. These conclusions tend to narrow the range of interest of the gross process parameters, and consequently, set limitations on the range of variation of these parameters for a successful lining operation. While the conclusions only strictly hold for the materials and combinations used in the present day study, it may be possible to extend them to other systems, e.g., other combinations of materials and larger or smaller calibers.

Weld quality and surface finish of liner - Studies to date indicate that the most difficult section of the rifling to overlay is that portion around the steps. The most promising welding conditions thus far from the standpoint of the liners being bonded essentially around the interior of the barrel were obtained with a 0.750 inch OD low carbon steel tube having a 0.010 inch wall thickness, glass tubing as a buffer material and a L/m value of 0.3. Photomicrographs of two locations within the welded joint transverse to the direction of welding are shown in Figure 5. The liner was well bonded and could not be separated by peel or chisel testing. Although the interior surface of the liner was pitted by the glass buffer

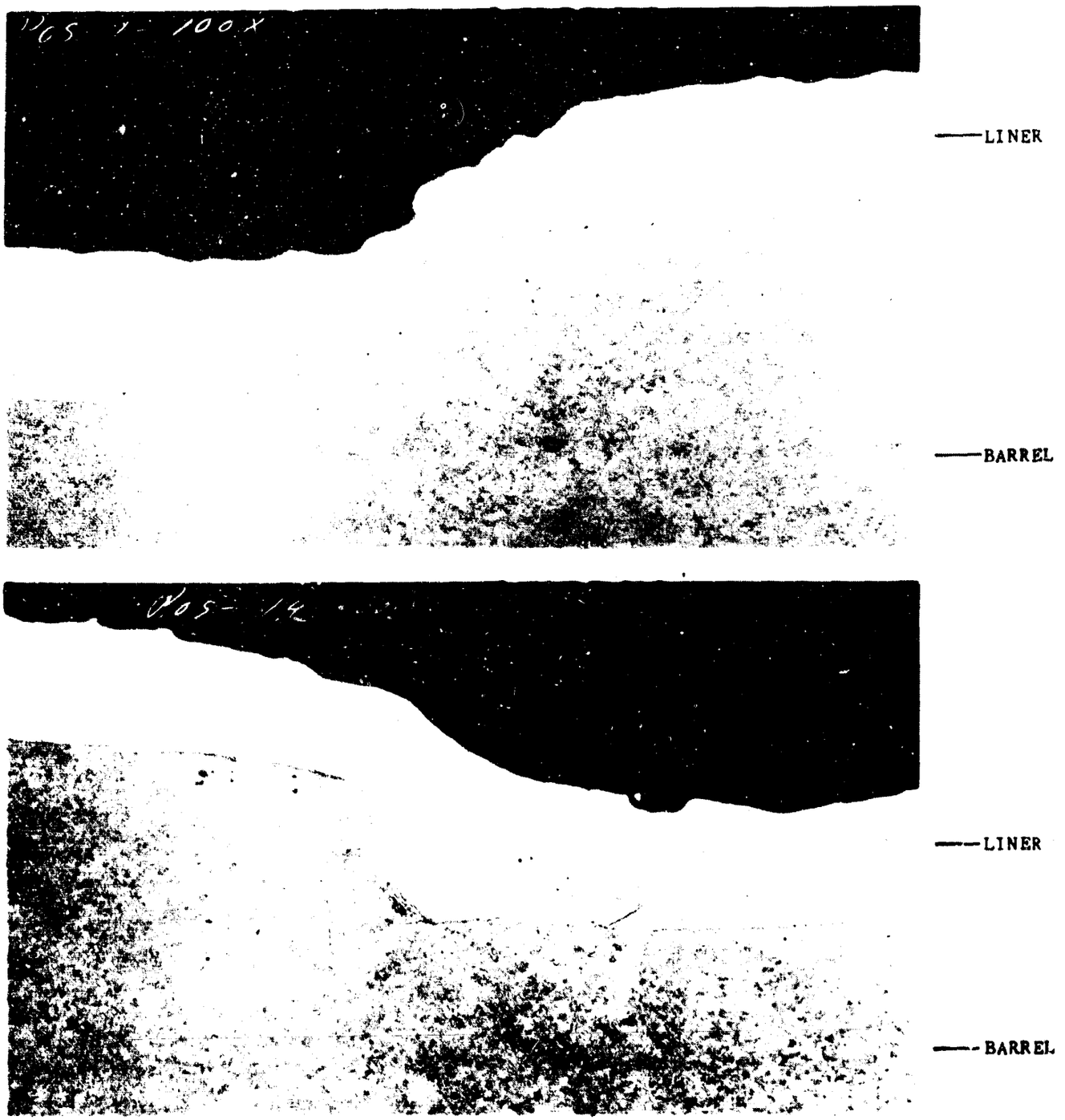

Figure 5. Bond Interface Between 10-mil Thick 1008 Steel Liner Clad to Region Around Steps in Chrome-Moly-Vanadium Steel Barrel, Using a Glass Buffer and L/M - 0.3. Magnification - 500X Etchant - Picral.

during welding, the sand blast effect of the glass was not considered critical in this test because emphasis was placed on the quality and extent of bonding rather than the surface finish of the liner.

With respect to the surface finish of liners, photomicrographs of other assemblies showed that glass buffers consistently produced marred surfaces, whereas teflon or tygon liners produced relatively smooth surface interiors. Glass and tygon tubing, initially, were used as buffer materials because of their ready availability and their densities, which permitted desirable L/m ratios to be obtained in the geometries of interest. Despite the pitting generated by glass tubing, tygon buffers were believed less desirable because the wall thickness of the commercially available tygon tubing was inconsistent and consequently produced a range of impacting velocities, which in turn, probably promoted intermittent non-bonded regions between the liner and barrel surfaces. Subsequent testing has indicated that extruded teflon tubing apparently is superior to glass and tygon, in that it does not pit the liner surface and has a relatively uniform wall thickness (see Figure 6). It was of interest to note that, even at the present state of development, the surface finish of explosively lined barrels made with teflon buffers are smoother than those observed previously with some plated barrels.

Formability Limits - Constancy of volume during expansion of the liner into the barrel is satisfied by the approximate equation

$$W_1 R_1 = W_2 R_2 \qquad (1)$$

where the W's are average wall thicknesses, the R's are average liner radii, and the subscripts refer to initial and final conditions. The fractional decrease in wall thickness, $F = (W_1 - W_2)/W_1$, becomes by Eq. 1,

$$F = (R_2 - R_1)/R_2. \qquad (2)$$

F can vary from zero (for $R_2 = R_1$) to nearly one (for $R_2 > R_1$).

Figure 6. Bond Interface Between 10-mil Thick 304 Stainless Steel Liner Clad to Region Around Steps in Chrome-Moly-Vanadium Steel Barrel, Using a Teflon Buffer and L/M = 0.3. Magnification - 500X Etchant - Picral.

Each of the contemplated liner materials has a ductility limit which, even under the high energy rate conditions of impulsive loading, results in a critical value F_c as a formability limit, above which a fracture process is initiated in the material. While this limit is unknown for the liner materials used in this work, conditions resulting in high F-values are known. These conditions include large gaps (separation distances between outside liner and inside barrel surfaces) which correspond to large values of $R_2 - R_1$. In the current program, relatively high F-values result from the use of 0.5625 and 0.625-inch OD liners which, when expanded into the barrel (0.787 - 0.817 inch ID), have fractional decreases in wall thickness ranging from approximately 0.20 to 0.31. The remaining liners having OD's of 0.675 and 0.750 inches are less likely to nucleate and propagate cracks during expansion. For this reason the 0.675 and 0.750 inch OD liners are being emphasized.

Cutting - Metal cutting occurs when a sharp surface strikes or is struck by a metal surface in a relatively high velocity collision. In the present work, the possibility of this occurring is good, as the corners on the rifling act as cutting edges. There are two conditions favorable to explosive cutting which have been observed in this work, one of which concerns high ratios of the explosive charge mass to combined liner and buffer mass. Results to date have indicated that successful bonding can be obtained when this ratio (L/m) lies in the range of 0.2 to 0.4. Higher values result not only in severe cutting but also in the formation of undesirable melt zones at the bonded interface. Secondly, thin liners are more prone to cutting than thicker ones. Of the three wall thicknesses employed in this investigation the five-mil liners are particularly susceptible to either very extensive stretching or cutting

at the rifle corners. Metallographic surveys have shown this cutting/stretching action to occur with five-mil liners around the step region even with relatively low charge-to-mass ratios.

Cutting of the five-mil liners by the rifled corners, however, did not occur in a symmetric fashion around the barrel which is indicative of the close tolerances required on gross process parameters to avoid cutting with liners having extremely thin wall thicknesses. For example, small eccentricities between liner and barrel or zones of high density in the charge could result in localized cutting action, with the lined (finished) barrel showing regions of good bonding and regions of unclad, rifled corners.

Charge-to-Mass Ratio - The acceptable range of the charge-to-mass ratio has been established in these studies as 0.2 to 0.4. This ratio, more than any other parameter, determines the velocity of impact of the liner material on the interior surface of the barrel. Significantly lower values than 0.3 usually resulted in non-bonding, while significantly higher values resulted in excessive melt formation, non-bonding, cutting or combinations of these. In order to achieve the 0.2 to 0.4 L/m range for a liner material of fixed density, thickness, and size, the amount of explosive which must fill the available space inside the liner is also fixed. Consequently, the required mass of explosive was not enough to fill the available space inside the liner material. In order to rectify this situation, a buffer material - glass or plastic tubing - was inserted into the liner to reduce the available volume for the explosive. Teflon was found to be more suitable as a buffer, chiefly because of the tendency of glass to shatter and "sandblast" the liner surface as discussed previously.

Liner-Tube Alignment - An internal spacer has been employed at the barrel edges during the present work, which results in a consistent gap distance between liner and barrel. One disadvantage of this method, however, is that conditions at both ends of the barrel specimen are undesirable, as the spacer lowers the impact velocity of the liner and prevents welding at the ends. For this reason, all sections examined and analyzed were taken from the central portion of the specimens.

Conclusions. The studies accomplished to date indicate that explosion bonding holds considerable potential for the lining of 20mm gain twist rifled, Mann test barrels. The most promising welding conditions employ nitroguanidine, with charge to mass ratios ranging from 0.2 to 0.4, steel liners ranging from 0.675 to 0.750 inches in OD, with 10 to 20 mil thick walls, and a buffer material of extruded teflon tubing. Further work, however, is needed to refine present welding techniques - particularly to enable the liner to follow the rifled contour of the barrel more closely. Nevertheless, even at the present state of development, the surface smoothness of the liner is superior to that observed in some conventionally plated barrels.

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A HIGH PERFORMANCE AUTOMATIC AIRCRAFT CANNON BARREL

Frederick R. Gruner
Science and Technology Laboratory
Headquarters, U. S. Army Weapons Command
Rock Island, Illinois

Design parameters and materials are described to obtain an optimum barrel design for the 30mm XM140 Automatic Aircraft Cannon. The optimum design was based on the actual dynamic properties of the barrel material at elevated temperatures. Barrel temperatures on the outside diameter approaching 2000°F during long bursts made conventional design practice unusable. Stresses at elevated temperatures approach the dynamic yield point. Wall ratios down to 1.25 near the muzzle were required to meet space and weight limitations. Comparative data taken during the actual firing tests are shown for an iron-nickel base alloy, a chromium-molybdenum-vanadium low-alloy gun steel and a typical nonferrous superalloy. A metallurgical method is described for the determination of the actual maximum barrel temperatures within 50°F. Effects on the bore of superalloy barrels after continuous bursts of 400 to 600 rounds are shown in photographs.

Introduction

The severe firing schedules demanded by the United States Army Combat Developments Command make necessary the use of high-temperature, high strength materials for gun barrels. A case in point is that of the performance requirements of the 30MM, XM140 Aircraft Cannon Barrel. A cannon tube of gun steel (MIL-S-46047) failed after a continuous burst of 266 rounds. The maximum temperature of 1480°F was reached at the thinned-down muzzle section. These results precipitated an intensive investigation of suitable materials for the high temperatures reached in the gun tube during long bursts. Conventional design parameters were reviewed and more information sought on the dynamic properties of gun barrel materials at high temperatures. This investigation and the results obtained are only a beginning in the design of high-performance gun barrels. The lack of information on the dynamic properties of materials at elevated temperatures is still a major handicap in the

obtaining of optimum gun tube designs. Much research remains to be done in this field of metallurgy to aid the designer in obtaining the most efficient gun barrel configurations.

Objective

The objective of this study was to develop an optimum design gun barrel for the XM140 Automatic Aircraft Cannon. This gun barrel design is to meet the specifications of the CDC firing schedule and, in addition, to permit extremely long bursts without damage.

Discussion

The ideal gun tube materials for the type of high-performance weapon being considered would have high strength, low coefficient of thermal expansion, high-impact resistance, and insensitivity to notches and stress raisers over a temperature range of -65°F to 2000°F. In addition, the material should have reasonable machinability, especially with regard to drilling the bore and broaching the rifling. Other requirements are uniformity of physical properties, good weldability, dimensional stability over wide temperature ranges, availability, reasonable cost, and last but not least, exceptionally good resistance to wear and erosion. The additional life obtained from an alloy gun barrel should justify the extra cost over conventional gun tube materials.

Many materials were investigated. The static yield strengths of a few of these are shown in Figure 1. The time frame for this gun design required a high probability of success for material selection. After the many factors involved in choosing a gun barrel material were weighed, two materials were selected. These were Crucible Steel Company High Temperature Alloy CG27 which is an iron-nickel base alloy and René 41 being a nickel-chromium-cobalt alloy. The chemical composition of these two materials is shown in Table I. The physical properties are shown in Table II. Included in these tables are the properties of Cr-Mo-V gun steel (MIL-S-46047) for comparison. A comprehensive

summary of the chemical and physical properties of many high-temperature, high-strength materials can be found in the literature cited.[1,2,3,4] Very little significant data are available on the dynamic strengths of these materials at high strain rates and at elevated temperatures in the range of 1500°F to 2000°F. The strain rates to be considered are in the range of 5 to 20 inches per inch per second.

The best available data on the dynamic strengths of the CG27 and the Inconel 718 alloys at elevated temperatures are shown in Figure 2. Most of the high-temperature, high-strength alloys now available were developed for gas turbine applications where long-time rupture strength and creep resistance were primary requirements. The life of a machine gun or a small bore cannon, however, can be in the range of 5 to 30 minutes of actual firing time.

Unfortunately, no single alloy embodies the optimum combination of all mechanical, physical, and chemical properties; therefore, a compromise is usually required.

This XM140 gun tube is reciprocated by a cylindrical cam actuated by an electric motor; clearances in the sliding parts are affected by thermal expansion of mating parts. The thermal expansion coefficient of most of the high-temperature alloys is significantly greater than that of steel. Readjustment of the operating clearances in many of the sliding and the rotating fits to increased values was necessary to permit long bursts of 200 to 500 rounds. Temperature coefficients of expansion of various metals are shown in Table III. The results of the stress analysis of the optimum barrel design are shown in Figure 3, which include the effects of pressure, temperature, and external forces. An equilibrium temperature of 1600°F was used in the calculations. This value was based on firing data from previously designed barrels and from the results of heat-transfer studies. These data are shown in Figure 5 and are the

result of firing tests by the Aeronutronics Division of the Philco-Ford Corporation.

The detailed procedure for the determination of the maximum barrel temperatures by measurement of the grain growth is described in the appendix.

A temperature difference of 50°F was assumed across the barrel wall. This does not include the skin temperature at the bore that is very high (2000°F to 2500°F). A dynamic ultimate strength at 1600°F of 76,000 pounds per square inch was used for design calculations. At high temperatures, the dynamic yield strength and the ultimate strength are very nearly identical. The total equivalent stress is based on the "von Mises-Hencky Equation" following the strain energy theory of failure. Equations for the stress calculations are discussed in detail in the literature cited. Stress concentration and shock effects of external forces were not considered in the calculations. A modulus of elasticity of 10,000,000 pounds per square inch was used which corresponds to an equilibrium temperature of 1600°F. The results of a series of tensile tests at elevated temperatures on samples of alloy CG27 are shown in Table IV.

The external forces on the gun barrel and the corresponding bending moments are shown in Figure 4.

The important point to be emphasized in this design analysis is the use of the dynamic ultimate strength for the strain rate encountered in this gun barrel, at the specific maximum equilibrium operating temperature of the barrel material.

Results

Three gun barrels, each of a different material, were subjected to firing tests by the Philco-Ford Aeronutronics Division at Long Beach, California. These materials were the widely used Cr-Mo-V gun steel, MIL-S-46047; René 41, nickel-chromium-cobalt alloy; and CG27, iron-nickel alloy. The gun barrels

were subjected to various firing schedules, and finally were subjected to a continuous burst for as long as the barrel or the entire gun could function properly. The results are shown in Table VI.

The Cr-Mo-V gun steel barrel withstood a continuous burst of 266 rounds of standard XM639 ammunition and then failed by a fracture of the barrel at the muzzle end. The maximum temperature was 1480°F at the muzzle end.

The René 41 barrel performance was disappointing. At 460 rounds of a continuous burst of XM639 ammunition, the muzzle velocity dropped from 2180 feet per second at the beginning of the test to 1851 feet per second at 460 rounds. The permanent bulge in the barrel, 8½ inches from the breech end, and the condition of the rifling after the gun stopped at 560 rounds are shown in Figure 25. A total of 1000 rounds were fired in this barrel. The René 41 barrel material significantly had the lowest impact strength of the three materials tested.

The CG27 barrel gave the best performance of the three barrels tested. This barrel was not of the optimum design as shown in Figures 3 and 4. The optimum design was a strengthened barrel particularly in the area subjected to the external forces. The test results on this initial CG27 barrel led to the optimum design. A total of 4500 to 5000 rounds were fired in this initial CG27 barrel. The firing test that led to a bow in the barrel consisted of 660 rounds of ablative ammunition and 441 rounds of standard XM639 ammunition. The barrel was slightly bowed and fired off target, but grouped the shots in the required three mil accuracy pattern. This barrel was subjected to very severe tests during its life cycle of 4500 rounds. Four attempts were made to fire the XM140 gun with the initial CG27 barrel through the "Worst Case Firing Schedule" shown in Table VII. The first attempt continued until a stoppage occurred at 621 rounds. The second attempt continued until a stoppage occurred at 674 rounds. The third attempt continued until a stoppage

occurred at 551 rounds. The fourth attempt continued until stoppage occurred at 691 rounds. The CG27 barrel operated very satisfactorily in this high temperature environment. No evidence of keyholing was observed. No rotating bands were thrown from the projectiles. The only evidence of a potential problem was that of a very slight decrease in the muzzle velocity as the test progressed. This same CG27 barrel was subjected to the test shown in Figure 5 with continuous bursts of 660 rounds of ablative ammunition and 441 rounds of standard XM639 ammunition.

The condition of the bore of the initial CG27 barrel is shown in Figures 26 to 29. The evidence which exists of the balloting of the projectile is probably due to the expansion of the bore. The rifling lands were severely flattened, as shown in the photographs. Evidence of severe wear and erosion was noted. The condition of the bore of the René 41 barrel shown in Figure 25 is similar to that of the CG27 barrel, although only 1000 rounds were fired.

Both the CG27 barrel and the René 41 barrel were subjected to abnormally long continuous bursts lasting a minute to a minute and a half.

Conclusions

From this series of tests, it can be concluded that superalloy gun barrel materials are necessary to withstand long continuous bursts expected of the XM140 gun. Of the three materials tested, the Crucible Steel Company CG27 High-Temperature Alloy gave the best results and should meet the requirements of performance for the XM140 gun barrel. This metal is one of the lower cost superalloys and also one of the easier to machine and weld. No doubt other alloys are available that will give satisfactory performance, however, testing all other candidate materials is a long and expensive procedure. From the results of these tests, complete reliance cannot be placed on published physical and chemical properties of the materials, although this information is of assistance in screening materials for gun barrels. As a matter of fact,

better parameters are needed for the measurement of performance of materials for gun barrels. More research is required in the field of physical properties at elevated temperatures and high strain rates.

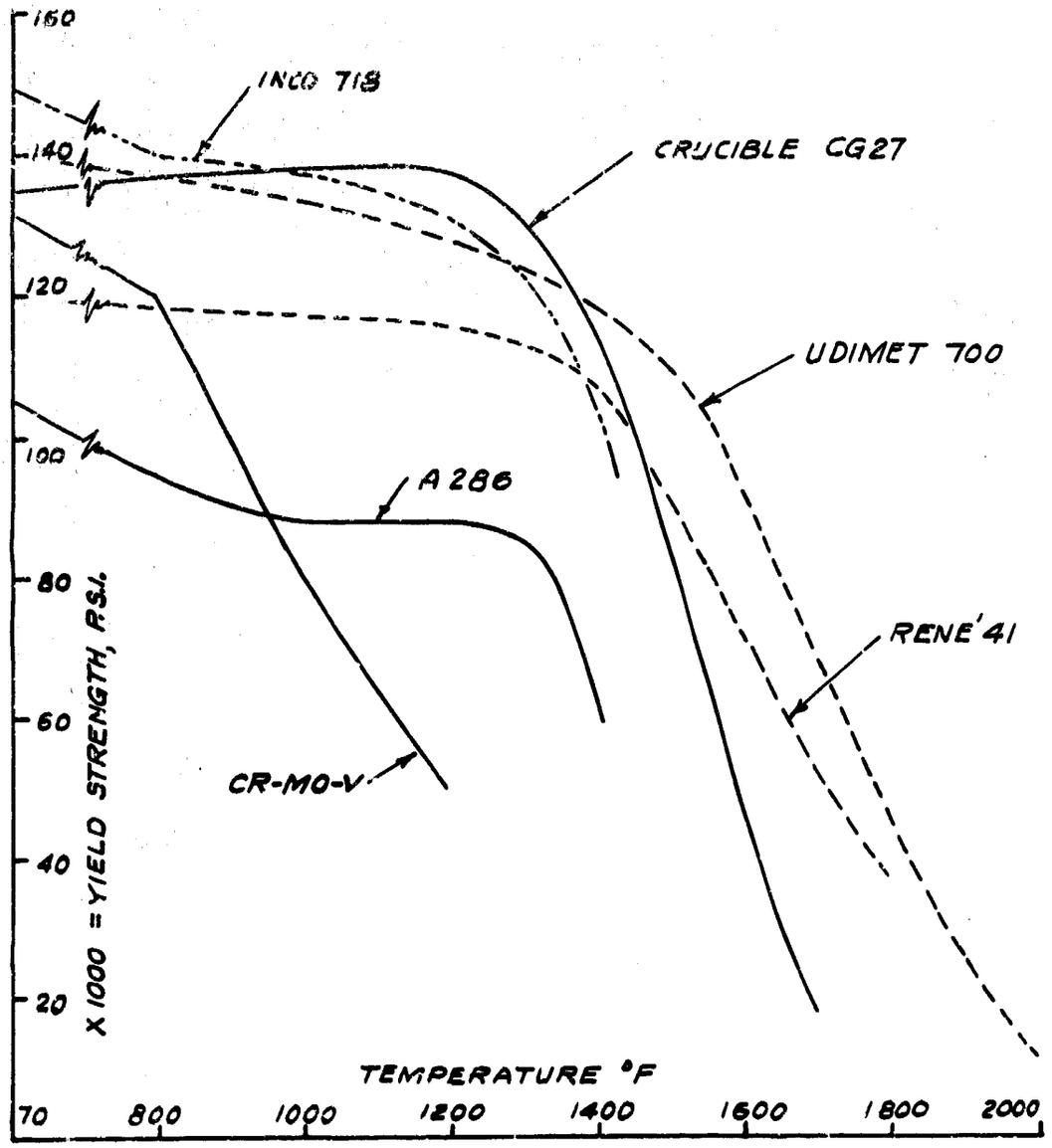


Figure 1. Effect of Temperature on Yield Strengths of Various Superalloys and Cr-Mo-V Gun Steel (MIL-S-46047)

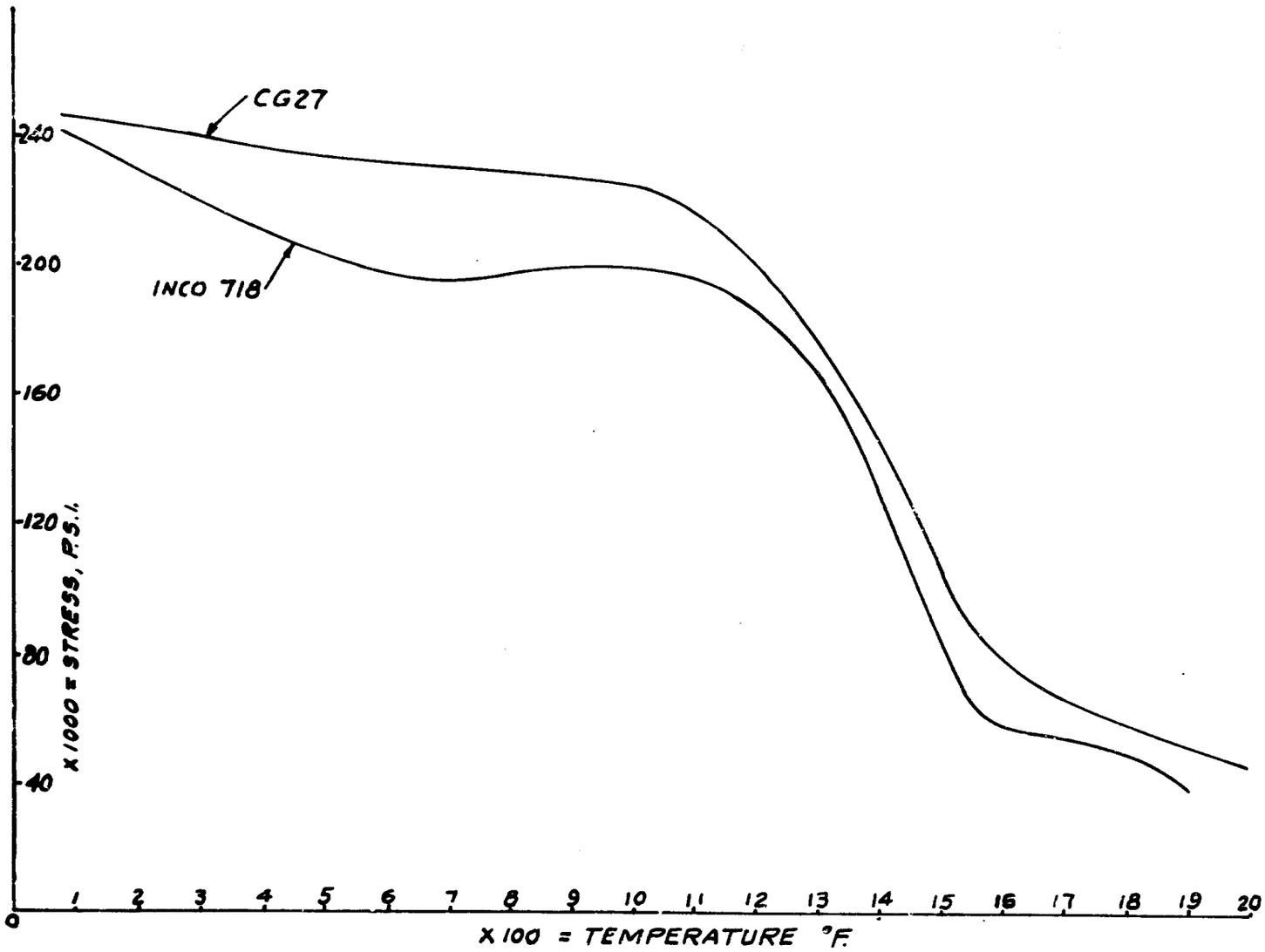


Figure 2. Effect of Temperature on the Dynamic Strength of High Temperature Alloys CG27 and Inco 718 at a Strain Rate of 12.5 in. per in. per sec.

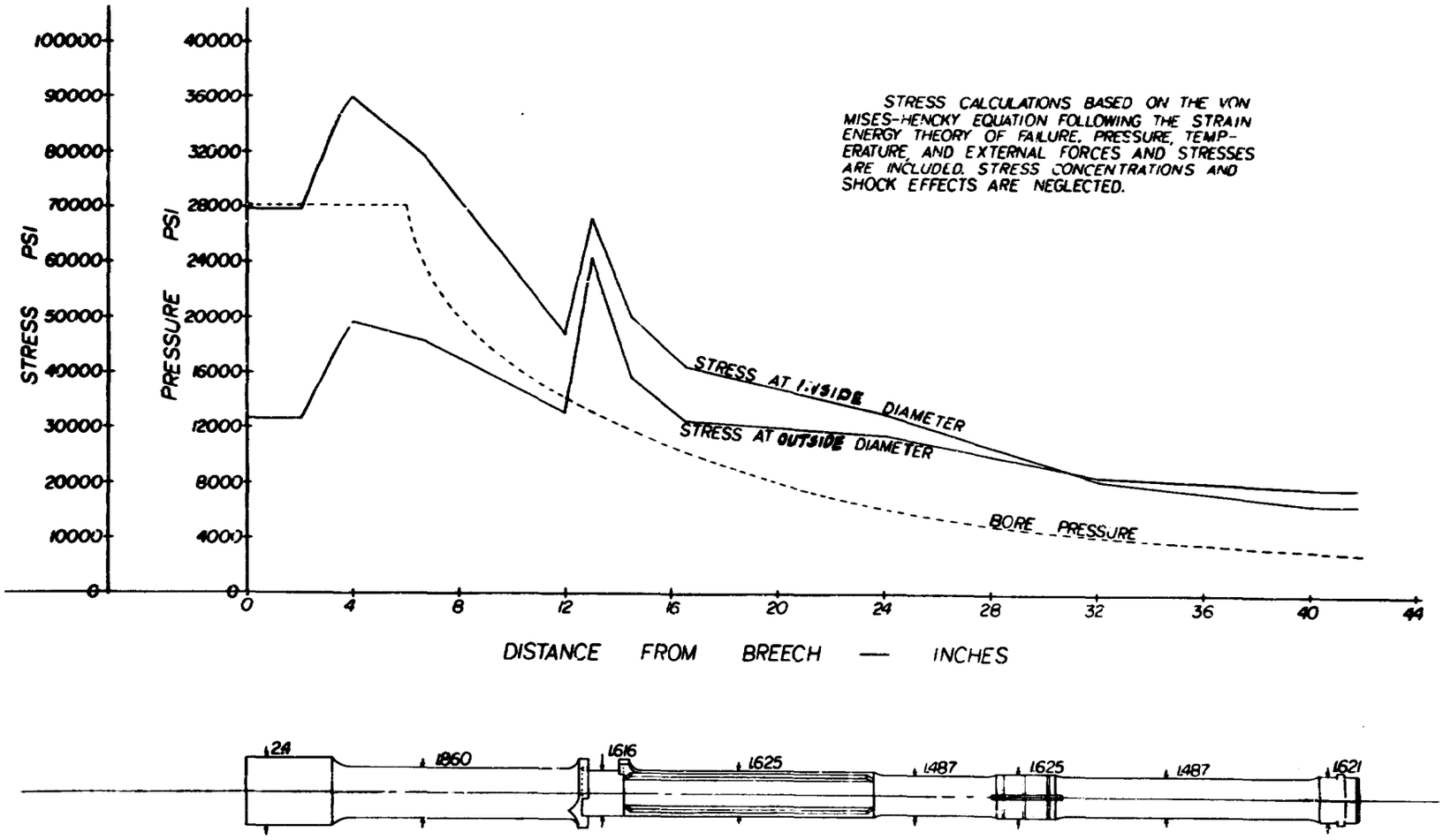


Figure 3. Stress Analysis of XM140 30MM Gun Barrel

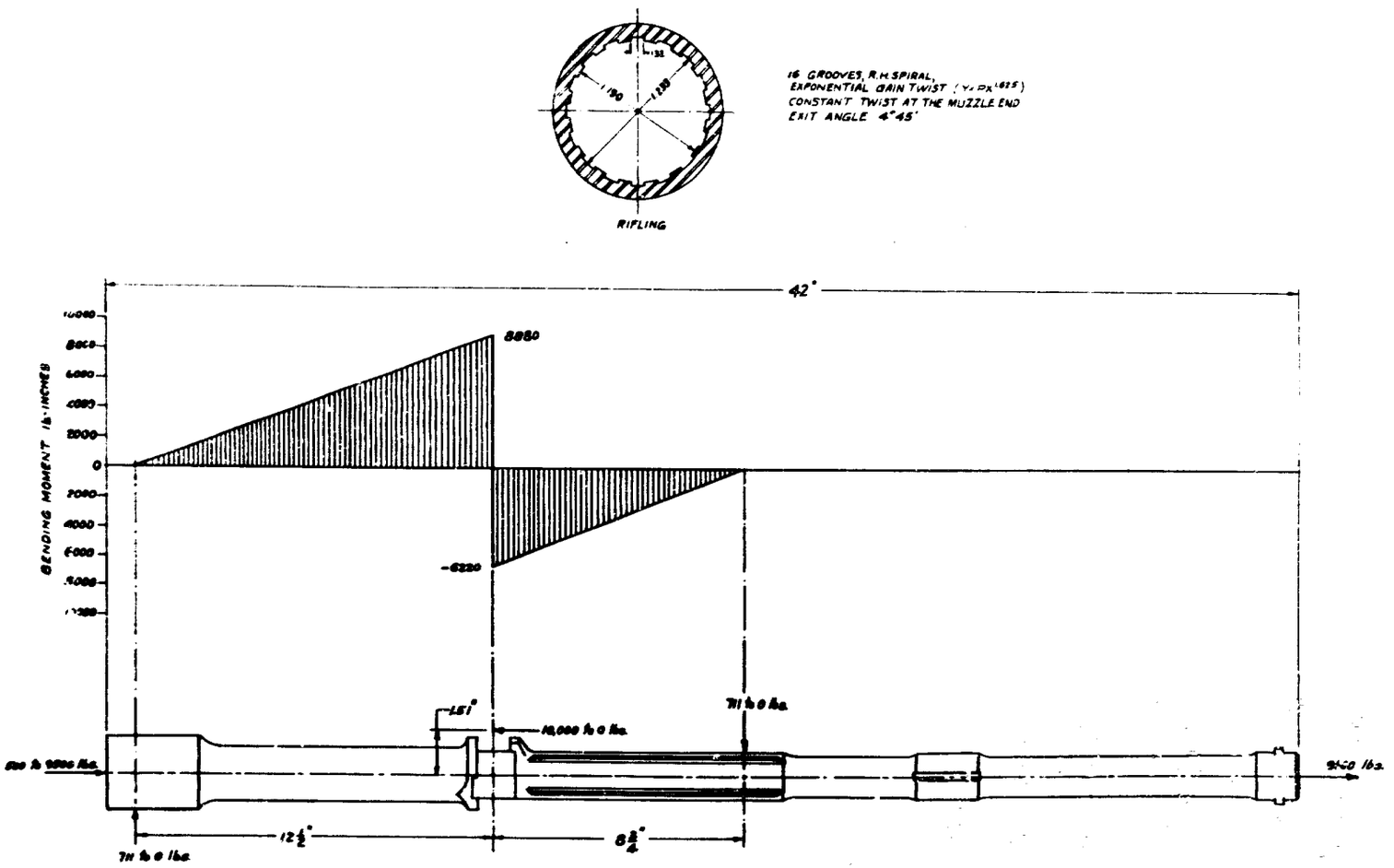


Figure 4. External Force and Bending Moment Diagram, XM130 Gun Barrel

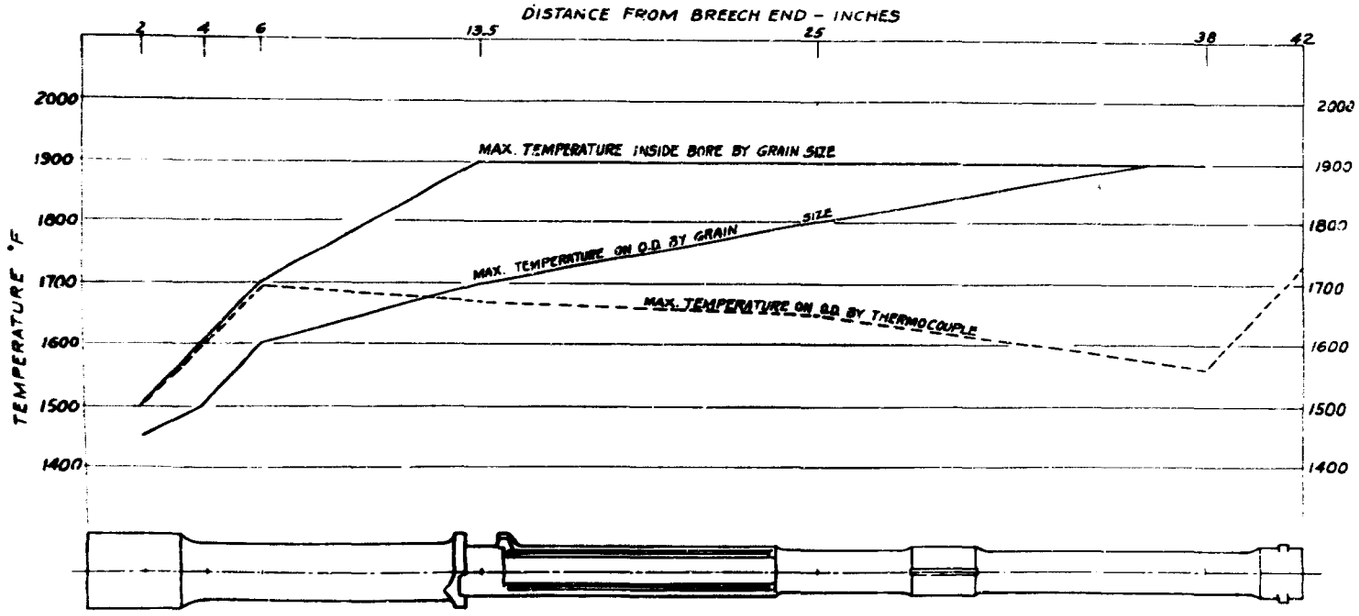


Figure 5. Effect of Long Bursts on Barrel Temperatures, XM140 Aircraft Cannon (CG27 Alloy)

SK RIA 140271
USARWECOM AMSWE-RET-ED
ROCK ISLAND, ILLINOIS
F.R. GRUNER 15 DEC 1969

9256

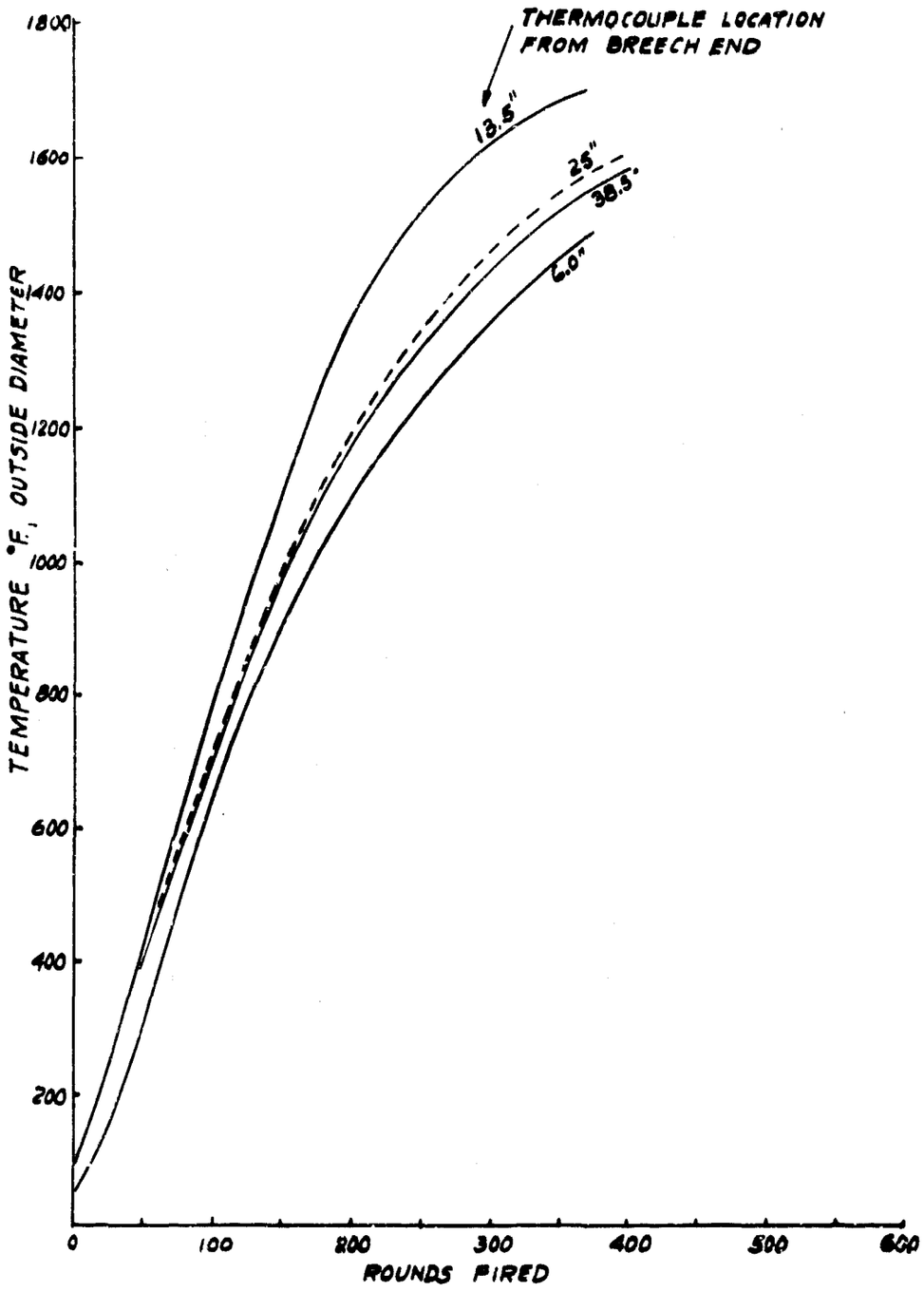


Figure 6. Thermal Performance Test XM140 30MM Aircraft Cannon CG27 Barrel Continuous Firing

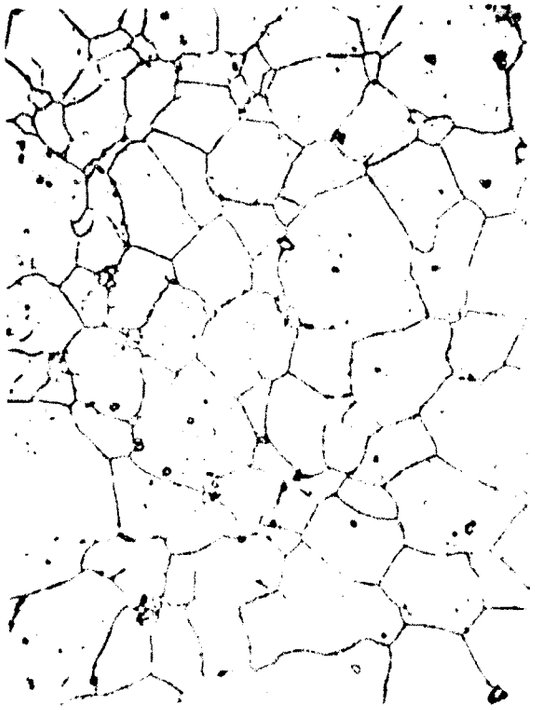


Figure 7 As-Heat Treated

Figure 8 As-Heat Treated Plus 1500 F for 15 Minutes

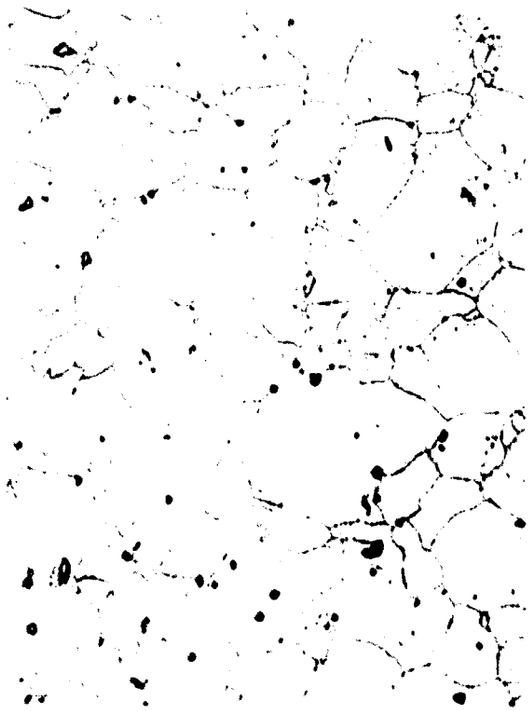


Figure 9 As-Heat Treated Plus 1550 F for 15 Minutes

Figure 10 As-Heat Treated Plus 1600 F for 15 Minutes

All specimens were etched in Marble's Solution. Magnification X250.

Figure 11 As-Heat Treated Plus 1650 F for 15 Minutes

Figure 12 As-Heat Treated Plus 1700 F for 15 Minutes

Figure 13 As-Heat Treated Plus 1750 F for 15 Minutes

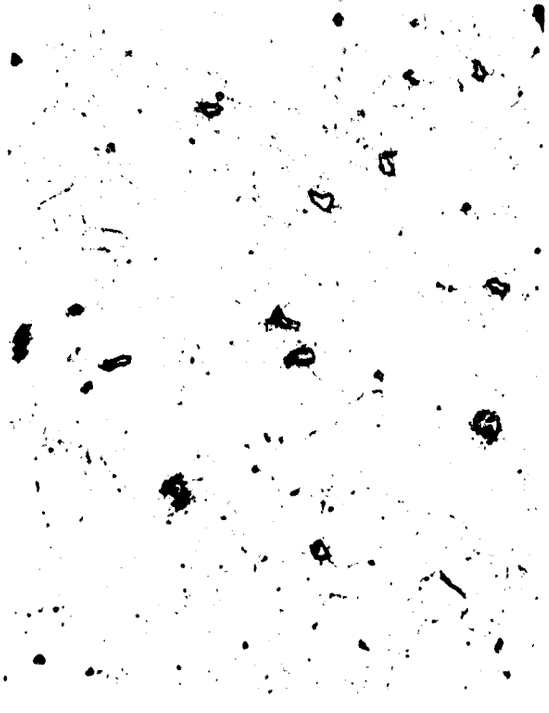


Figure 14 As-Heat Treated Plus 1800 F for 15 Minutes

All specimens were etched in Marble's Solution. Magnification X250.

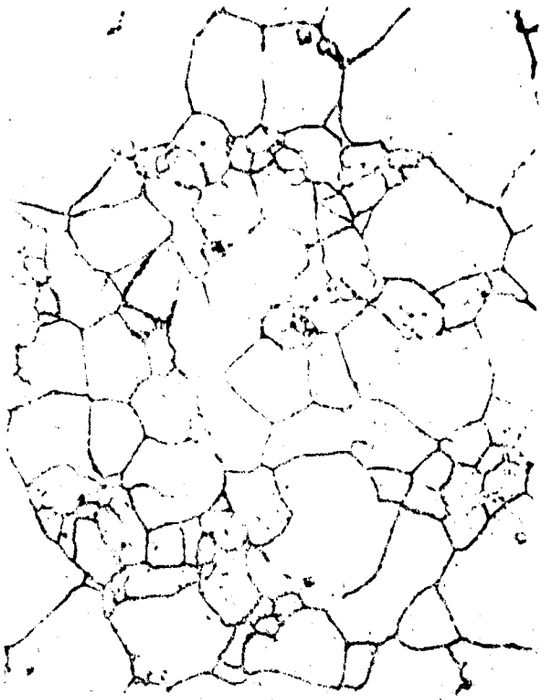


Figure 15 Sample Taken 2 Inches from Breech End

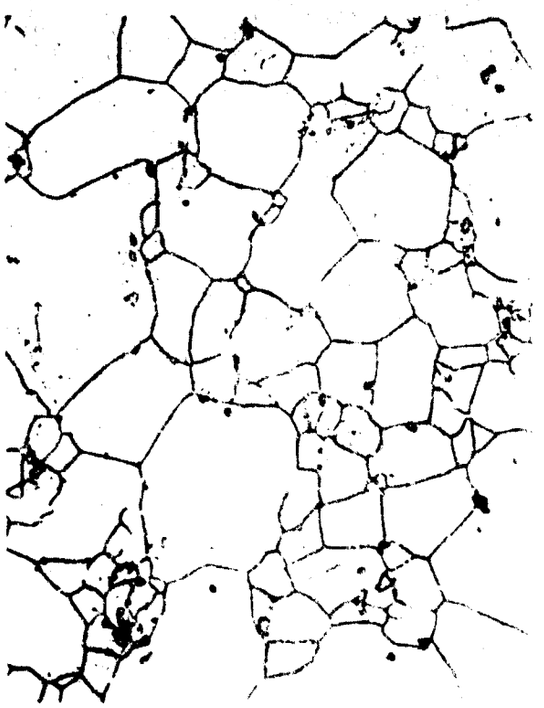


Figure 16 Sample Taken 4 Inches from Breech End

All specimens were etched in Marble's Solution. Magnification X250.

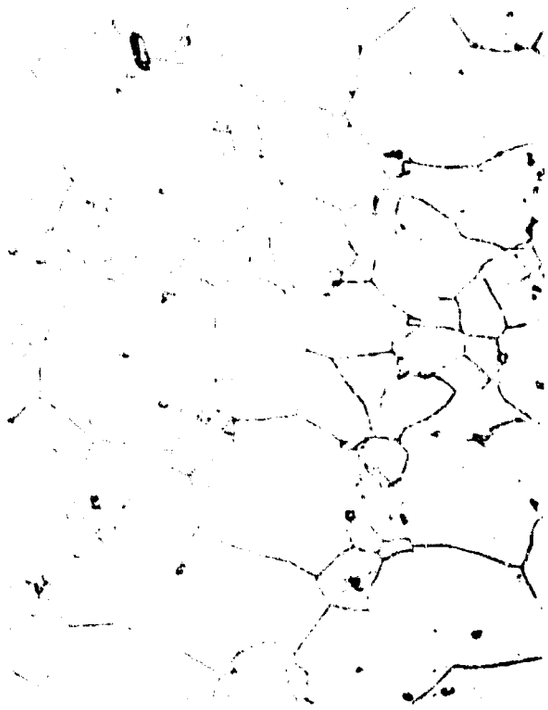


Figure 17 Sample Taken 6 Inches from Breech End (Outside surface)

Figure 18 Sample Taken 6 Inches from Breech End (Inside surface)

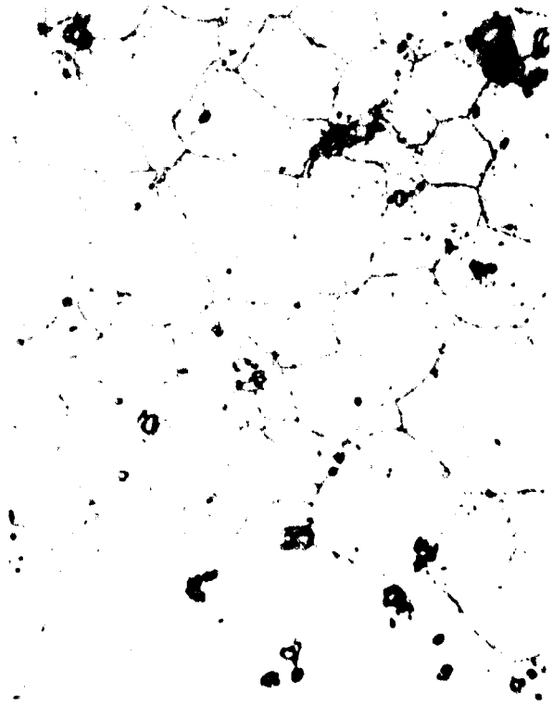


Figure 19 Sample Taken 13-1/2 Inches from Breech End (Outside surface)

Figure 20 Sample Taken 13-1/2 Inches from Breech End (Inside surface)

All specimens were etched in Marble's Solution. Magnification X250.

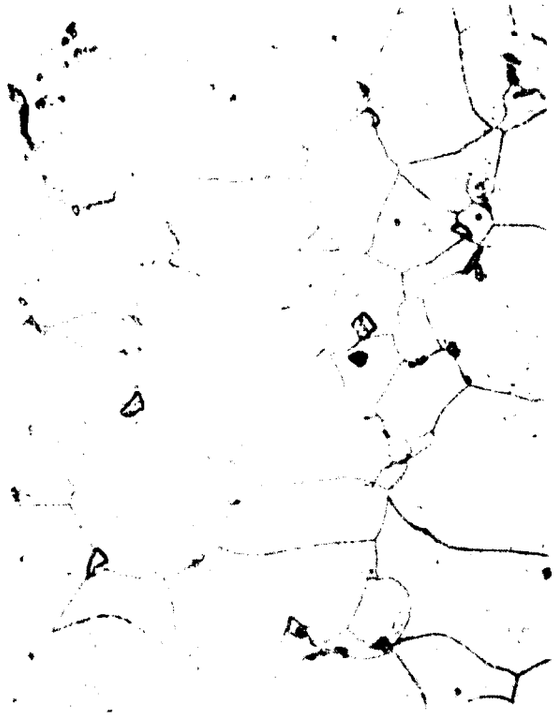


Figure 21 Sample Taken 25 Inches from Breech End (Outside surface)

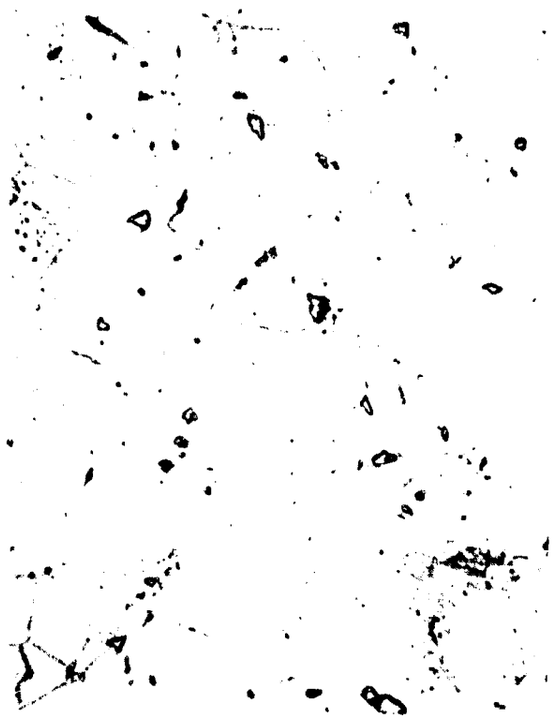


Figure 22 Sample Taken 25 Inches from Breech End (Inside surface)

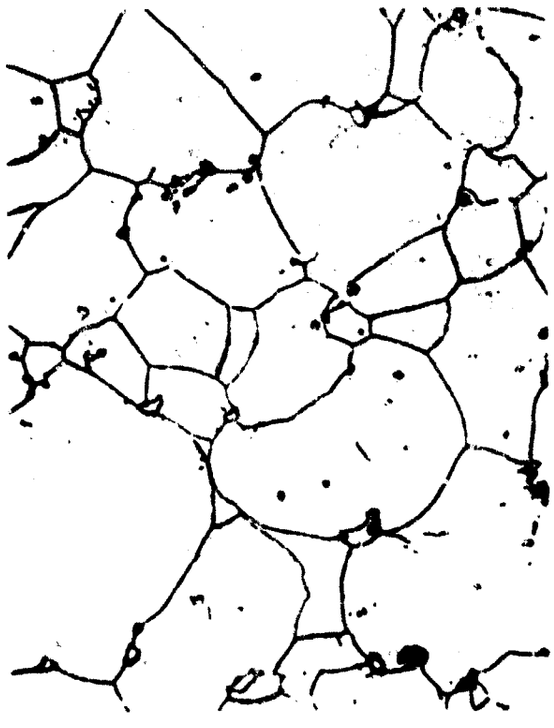


Figure 23 Sample Taken 38-1/2 Inches from Breech End (Outside surface)

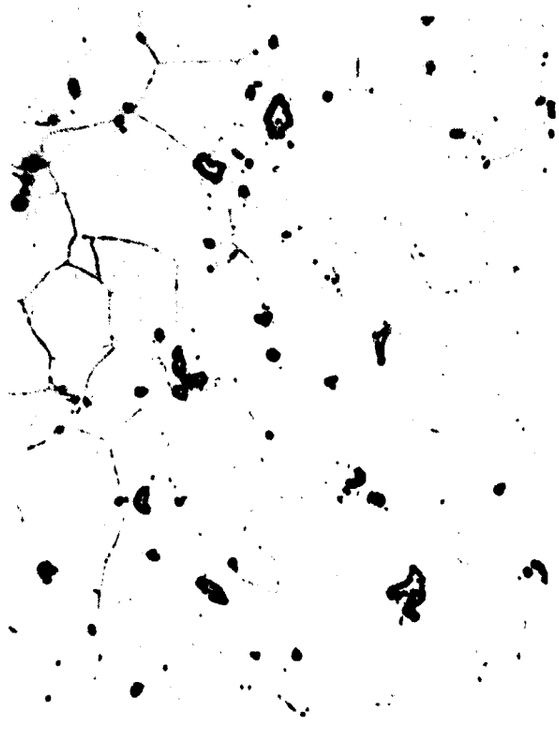
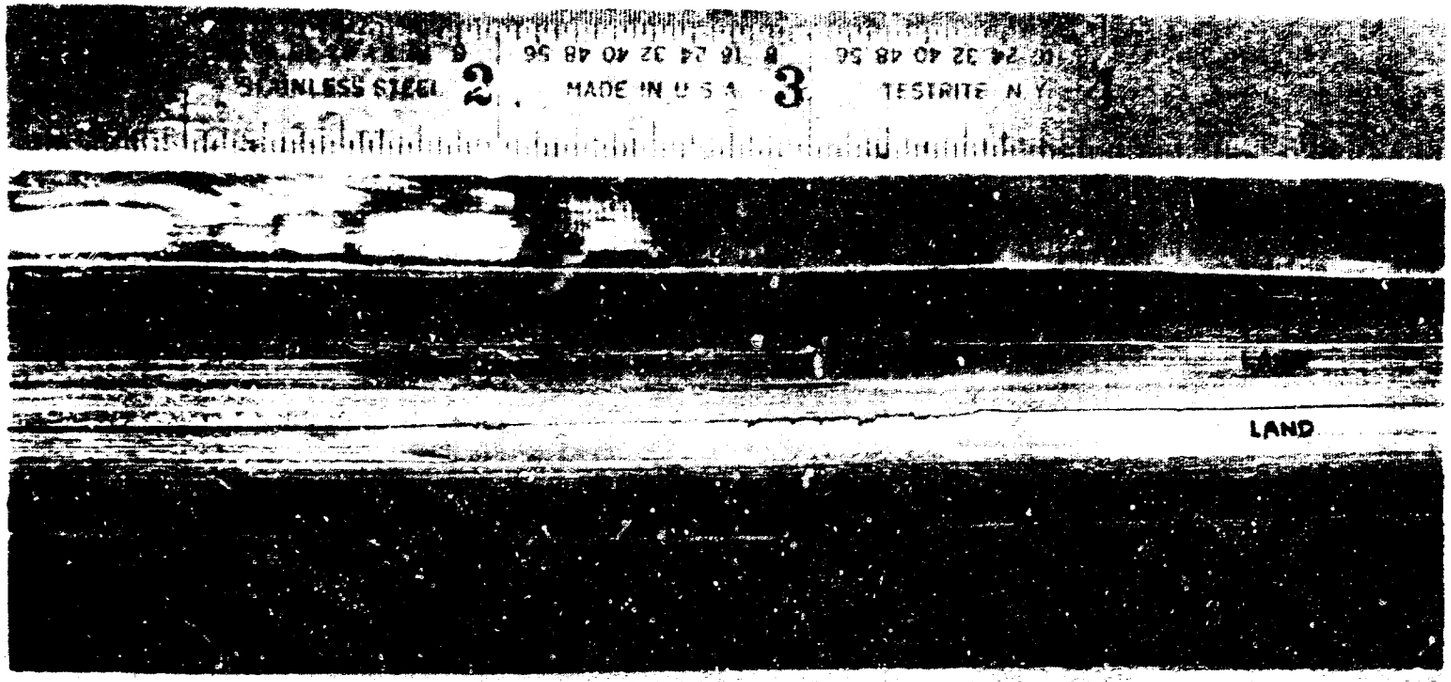


Figure 24 Sample Taken 38-1/2 Inches from Breech End (Inside surface)

All specimens were etched in Marble's Solution. Magnification X250.



5" From
Breech End

10-3/4 From
Breech End

Figure 25. Bore Photograph of a Section of the René 41 Barrel after a Long Burst of 560 Rounds and Total Rounds of 1000

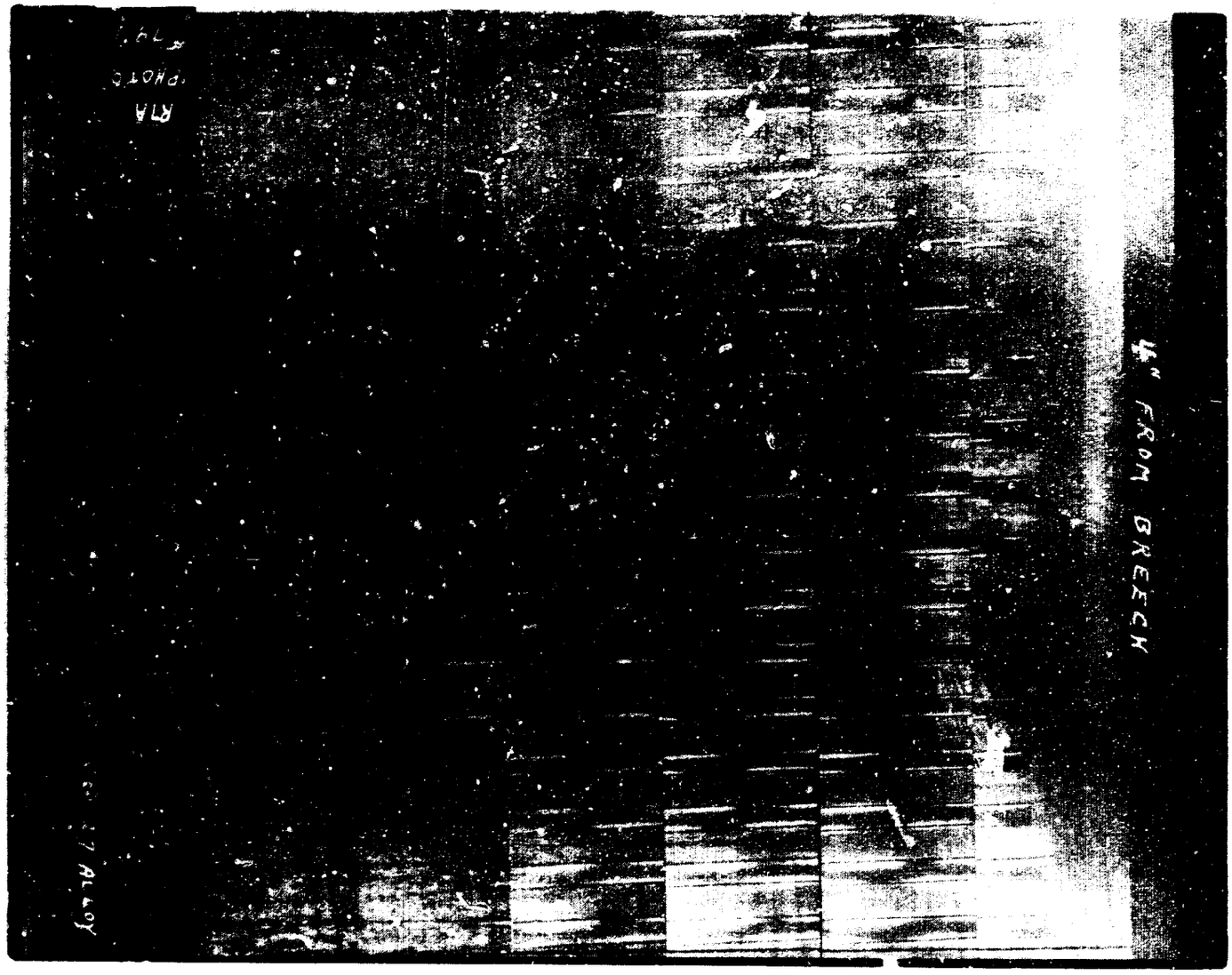


FIGURE 26
BORE PHOTOGRAPHS OF THE CG27 ALLOY BARREL
AFTER A TOTAL OF 4500 TO 5000 ROUNDS

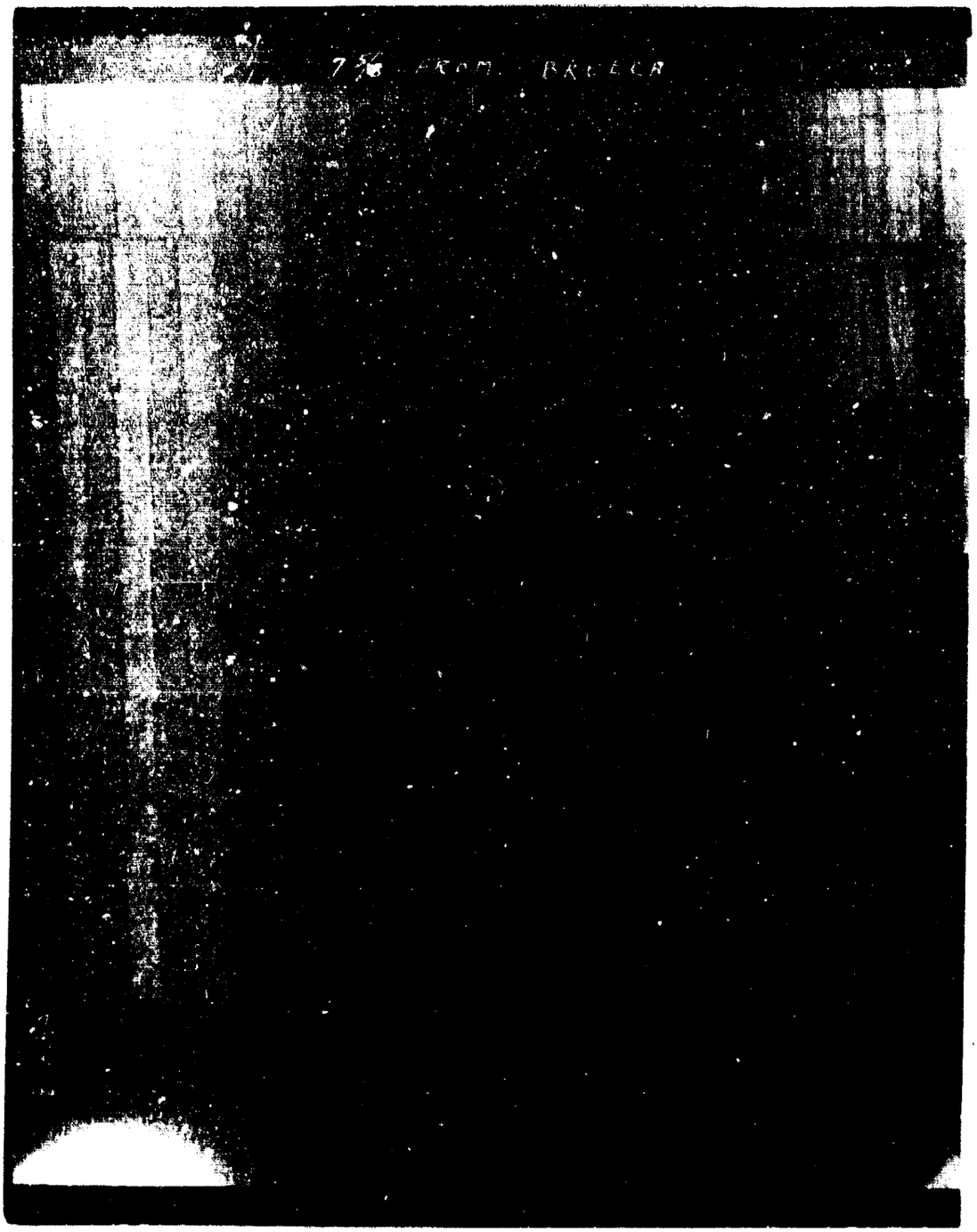


FIGURE 27
BORE PHOTOGRAPHS OF THE CG27 ALLOY BARREL
AFTER A TOTAL OF 4500 TO 5000 ROUNDS

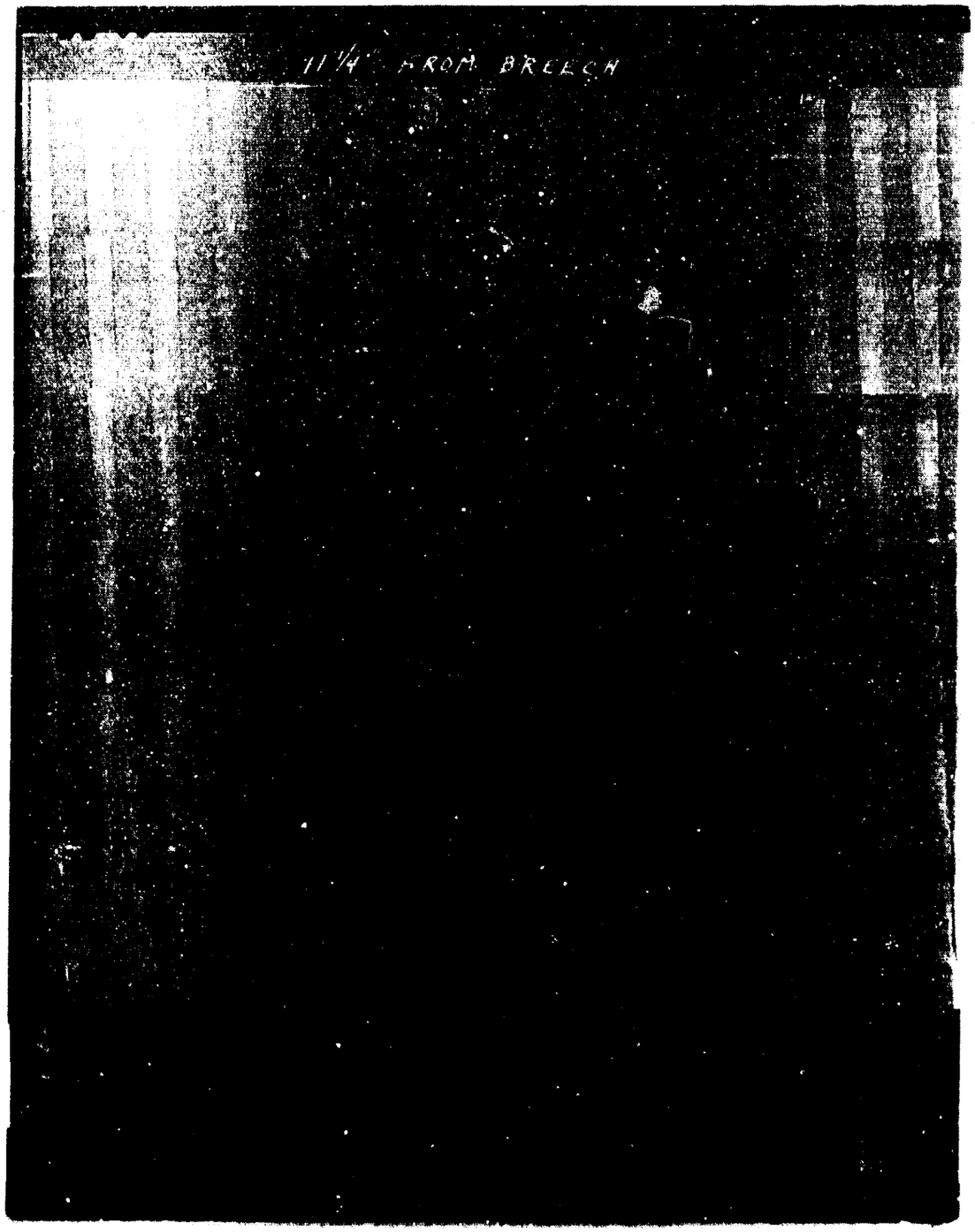


FIGURE 28
BORE PHOTOGRAPHS OF THE CG27 ALLOY BARREL
AFTER A TOTAL OF 4500 TO 5000 ROUNDS

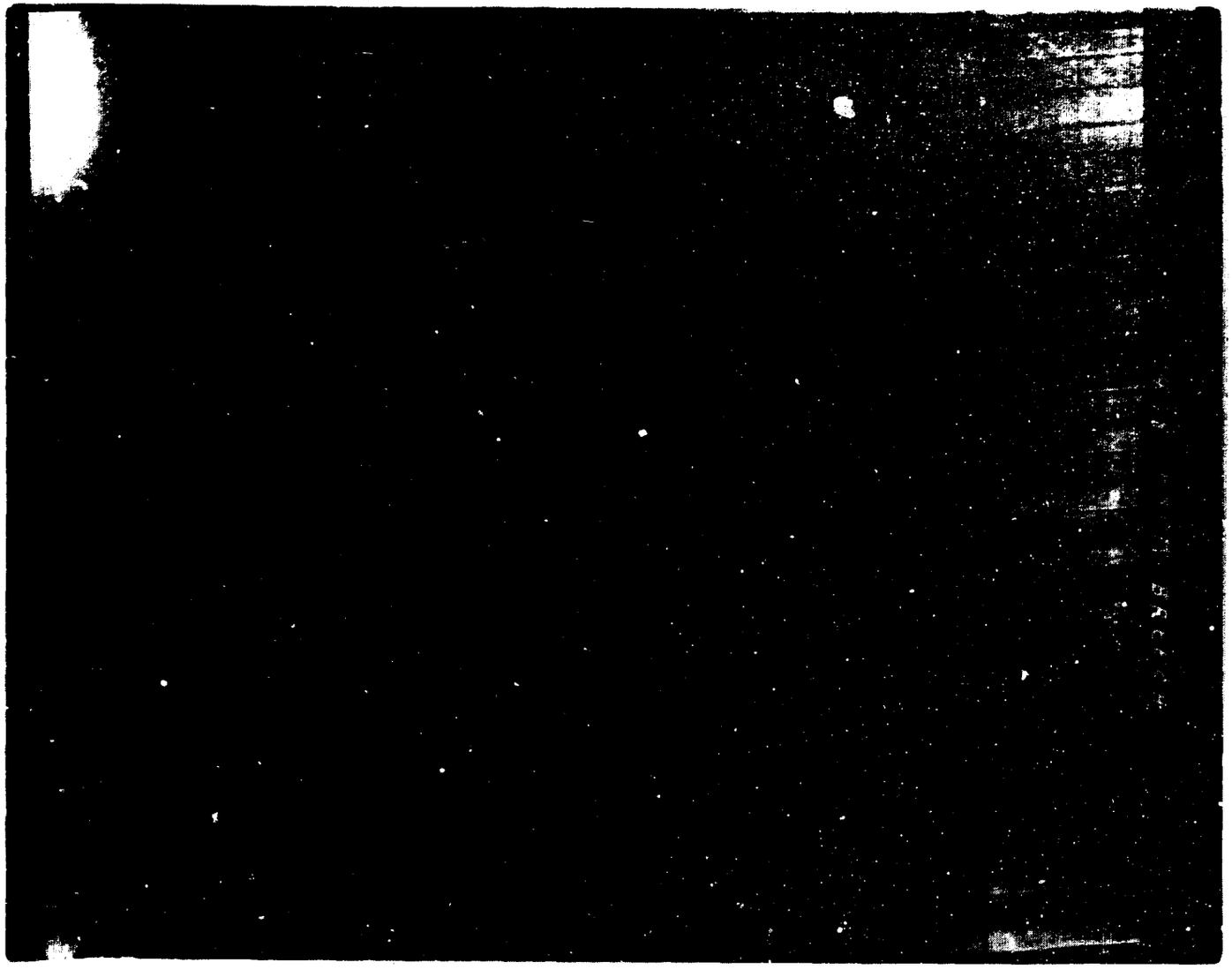


FIGURE 29
BORE PHOTOGRAPHS OF THE CG27 ALLOY BARREL
AFTER A TOTAL OF 4500 TO 5000 ROUNDS

TABLE I

APPROXIMATE CHEMICAL COMPOSITIONS OF ALLOYS (PERCENT)

	Alloying Elements													
Alloy	Ni	Co	Cr	Mo	V	Fe	C	B	Al	Ti	Cb	Si	Mn	Others
Crucible CG27	38.0	-	13.0	5.75	-	Bal.	0.05	0.01	1.6	2.5	0.7	-		
Haynes René 41	Bal.	11.0	19.0	10.0	-	5*	0.12*	0.007	1.5	3.2	-	-		
Cr-Mo-V Steel	-	-	0.95 to 1.25	.55 to .70	.20 to .30	-	0.38 to 0.45	-	-	-	-	.20 to .35	.75 to 1.00	Phos. 03* Sulf. 03*
Inco 718	Bal.	-	18.6	3.1	-	18.5	.04	-	0.4	0.9	5.0	0.3	0.2	
Udimet 700	Bal.	15 to 20	15	5	-	-	.05 to 0.10	0.03	4.4	3.4	-	-	-	
A 286	25	-	15	1.3	0.3	Bal.	.05	0.005	0.3	2.2	-	0.5	1.5	
901	43	-	12.5	5.7		Bal.	.05	0.015	0.2	2.8	-	0.1	0.1	

* Maximum

TABLE II

PHYSICAL PROPERTIES OF ALLOYS

Alloy		René 41	CG27
Density, lb./ cu. in.		0.298	0.290
Melting Range °F		2400-2500	2500-2600
	70°F	62	
	200	71	
	400	86	93
	600	102	108
Thermal Conductivity	800	115	123
BTU/sq. ft./hr./°F/in.	1000	125	138
	1200	136	154
	1400	148	169
	1600	160	
	1800	172	
	2000	183	
Mean Coefficient of Thermal Expansion (Table III)			
Hardness fully aged - Rockwell "C"		36-38	38-40

TABLE III

Mean Thermal Coefficients of Expansion, Various Metals
(in. per/in. per ^{o}F) x 10^{6}

Metal	70 to 200	70 to 400	70 to 600	70 to 800	70 to 1000	70 to 1200	70 to 1400	70 to 1500	70 to 1600	70 to 1800	70 to 2000
Steel 1030				7.8	8.0	8.3					
Steel 1040				7.8	8.0	8.3					
Steel (gun) Cr-Mo-V				7.7	7.8	7.9					
Steel 4140				7.0		8.3					
René 41	6.7	6.8	7.0	7.2	7.5	7.8	8.2	8.5	8.7	9.4	
CG27			8.1	8.3	8.5	8.7	9.1	9.5			
Haynes Stellite 25	6.8	7.2	7.6	7.8	8.0	8.2	8.6		9.1	9.4	9.8
Haynes Stellite 21			7.8	8.0	8.2	8.4		8.7			
Waspaloy	6.8	7.3	7.7					8.7		9.7	10.4
Udimet 500	6.3		6.7		7.3			8.4		9.8	
Udimet 700		7.5	7.5	7.6	7.7	8.0	8.4		9.0	9.7	10.3
W545	9.3		9.7			10.1		10.7	11.0		
Moly-0.5 Titanium	3.0									3.4	
Inconel 700	6.8		7.5		8.0		8.7		9.3		
Inco 718	7.1	7.5	7.7	7.9	8.0	8.4	8.9				
TRW VMS201	7.8	8.7	9.3	9.7	9.9	10.1	10.3		10.4		

TABLE IV

Tensile Tests of CG27 High-Temperature Alloy at Elevated Temperatures

Sample: .357 in. diameter, standard test sample with 3/4-in. x 10 thread

Heat Treatment:

a. Solution heat-treated at 1900°F for one hour, air-cooled
b. Aged at 1400°F for 16 hours, air-cooled
c. Hardness, Rc 40-42

Specimen	Test* Temp (°F)	Tensile Str (P.S.I.)	.2% Yield Str (P.S.I.)	.1% Yield Str (P.S.I.)	% Elong	% Reduction in Area
1	1600	52,000	48,600	45,240	23.6	66.0
2	1600	(Threads stripped from grip)				
3	1600	51,650	48,000	44,640	48.6	63.4
4	1700	21,950	17,900**	14,900**	81.5	96.4
2***	1700	21,035	17,050	16,000	50.0	82.3

* Tested after 15 minutes at temperature

** Estimated yield strength because extensometer rods slipped on the test bar

*** The retest on Specimen 2 showed very little degradation of the yield strength when the alloy was held for at least 15 minutes at 1600°F prior to the 1700°F (for 15 minutes) tensile test

TABLE V

Standard Charpy (V-Notch) Impact Strengths (Ft-Lb)

	Alloy (Rc 37-39)							
	Cr-Mo-V		Inco		Crucible		René	
	Mil S-46047		718		CG27		41	
Temp °F	Long.	Trans.	Long.	Trans.	Long.	Trans.	Long.	Trans.
70		16.0		18	9 - 12	5 - 6		3 - 4
-40		7.0 - 10.0		9 - 11	9 - 12	5 - 6		3
-65					8 - 10	5 - 6		
-320					6 - 7			

TABLE VI

Summary of Firing Data XM140, 30MM, Gun Barrel

Material	Total Rounds Fired	Length of Burst at Failure Rounds	Maximum Temperatures Observed by Thermocouple — Outside Diameter In. From Breech End						Maximum Temperatures Observed by Grain Size — Outside Diameter In. From Breech End					
			2	4	6	12-13½	25	38½	2	4	6	13½	25	38½
Cr-Mo-V	8,000-10,000 (100 rd. bursts 15 min. cooling)	266		950	1120		1300	1400						
René 41	1000	460			1680	1600	1700							
CG27	4500-5000	600 ablative am., air-cooled, followed by 441 Std XM639 am.			1700	1700	1650	1570	1450 to 1500	1600 to 1700	1600 to 1700	1800 to 1900	1800 to 1900	

Inside Diameter

2	4	6	13½	25	38½
		1700 to 1900	1700 to 1900	1800 to 1900	1800 to 1900

3.7-28

Remarks

Cr-Mo-V Barrel burst at muzzle end after a 266 round burst.

René 41 Barrel bulged 8½" from breech end. Rifling damaged.

CG27 Barrel bowed after cooling. Accuracy pattern OK, shooting low.

TABLE VII

"Worst Case" Firing Schedule

Section	Phase	Bursts	Rounds/ Burst	Fire Time (Min.)	Time Between Bursts (Min.)	Total Time (Min.)	Cum. Time (Min.)	Total Rounds	Cum. Rounds
I	A	1	50	.125	0	.125	.125	50	50
	B	0	0	0	.33	.33	.455	0	50
	C	20	10	.50	.05	1.45	1.905	200	250
	D	0	0	0	7.00	7.00	8.905	0	250
II	A	20	5	.25	.25	5.00	13.905	100	350
	B	0	0	0	.25	.25	14.55	0	350
III	A	6	50	.75	.167	1.585	15.740	300	650
	B	0	0	0	.167	.167	15.907	0	650
	C	8	25	.50	.167	1.669	17.576	200	850
	D	0	0	0	5.00	5.00	22.576	0	850
	E	40	10	1.00	.0825	4.2175	26.7935	400	1250
	F	0	0	0	.0825	.0825	26.8760	0	1250
	G	50	5	.625	.05	3.075	29.951	250	1500

APPENDIX

Introduction

The initial CG27 30mm gun barrel test fired by Philco-Ford Corporation (Newport Beach, California) had accumulated approximately 5000 rounds of firing. The gun barrel was returned to the U. S. Army Weapons Command, Research and Engineering Directorate, where it had been manufactured, for evaluation. Samples from various locations along the barrel were sent to the Crucible Steel Company for examination in an attempt to establish barrel temperatures achieved during firing.

Procedure

To obtain standards for comparison purposes, a sample of 5/8-inch CG27 bar stock was solution-treated at 1875°F for two hours, oil-quenched, aged at 1450°F for 16 hours, air-cooled, reheated to 1200°F for 16 hours, and air-cooled. Seven disks were cut from the bar and given thermal treatments ranging from 1500°F to 1800°F in 50°F intervals for 15 minutes followed by air cooling. One disk was retained in the as-heat-treated condition. Transverse microstructures were examined, and representative photomicrographs are shown in Figures 7 through 14.

The six samples from the 30mm gun barrel, submitted by U. S. Army Weapons Command, were prepared for microscopic examination in the transverse direction. The gun barrel, prior to test firing, was solution-treated at 1875°F for one hour, oil-quenched, and aged at 1450°F for 16 hours. The final age at 1200°F, normally used for gas-turbine applications, was eliminated in this instance since the service temperature of the gun barrel was expected to exceed 1500°F and the final age would have slight effect on barrel performance. Typical microstructures in the various samples examined are shown in Figures 15 through 24. Samples were identified as follows:

Sample	Distance from Breech End (in)
S1	2.0
S2	4.0
T1	6.0
T2	13.5
T3	25.0
T4	38.5

Results

The examination results of the CG27 gun-barrel samples indicate that no microstructural changes occurred at a point up to four inches from the breech end. Therefore, the temperature at this barrel location did not exceed 1450°F to 1500°F (Figures 15 and 16). Six to 13-1/2 inches from the breech end (Figures 17 through 20), the outer surface of the gun barrel reached temperatures of 1600°F to 1700°F, whereas the inside (bore) reached temperatures of 1700°F to 1900°F. At 13-1/2 inches to 38-1/2 inches from the breech end the barrel reached estimated temperatures of 1800°F to 1900°F across the entire thickness of the barrel (Figures 19 through 24).

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REFRACTORY COATING ON 7.62 MM MACHINE GUN BARRELS

G. F. Wakefield
J. A. Bloom
Texas Instruments Incorporated
Dallas, Texas 75222

In an attempt to develop improved performance gun barrels, preliminary work has been carried out in application and evaluation of refractory coating to the internal diameter of the 7.62 Mini-gun machine gun barrel. The performance, as measured by velocity, of the coated barrels was nominally equivalent to the standard chromium plated barrels. Post firing examination indicated that a number of improvements can possibly be made to improve performance in that the coating applied was considered to have been non-optimum in substrate preparation, in thickness of coating, and in size and shape of the rifling. Further evaluation of this approach will be conducted.

Introduction

Application and preliminary evaluation of a refractory hard coating to the internal diameter of a 7.62 mini-gun machine gun barrel was done in an attempt to improve lifetime and performance. These results are to be considered preliminary and are presented for information only. The performance as measured by bullet velocity, was found to be nominally equivalent to standard chromium plated barrels. Because of the recognized nonoptimized nature of these initial coated barrels the results were considered encouraging. Post firing examination indicates potential for improvements in the coating, and some significant differences between the refractory and chromium plated barrels.

Experimental Approach

This work is an attempt to utilize a refractory hard coating, which had previously been developed by Texas Instruments, to improve machine gun barrel life. The coating, TI KOTE®C, is of the refractory carbide type and is applied by chemical vapor deposition. This same coating has been evaluated for the improvement of life and performance of jet engine helicopter blades in sand erosion environment, on other government programs. The erosion resistance observed on coated blades indicates a very high potential for reducing particle erosion. Other Texas Instruments work which also suggests a potential for the gun barrel application has been an improved lifetime noted in dies used to cast molten metals, such as aluminum, where the coating provides chemical and thermal mechanical protection of the substrate die material.

Because of this potential for improved lifetime, a number of barrels were obtained and the coating applied to the internal diameter. The first experiments used barrels of standard dimensions with chromium plate over which the applied the thin hard coating. Coating thickness was small so that the final dimensions would not be changed beyond a testable degree. However, the presence of the chromium plate interfered with good adherent bonding to the substrate material, and introduced a possible weak link between the coating and the steel barrel. Additional barrels were obtained which did not have the chromium plating and the coating was applied at a thcikness level of approximately 0.4 mil to the bore of these barrels.

Adherence of the coating to the steel was fair.

Testing

Following an application of the coating to these barrels a number were submitted for test firing. Two barrels were test fired as part of a six barrel set under conditions considered to be relatively standard. The inclusion of the four standard production chromium plated barrels gave an internal calibration point to compare the performance of the barrels. The major criteria of performance was projectile velocity measured at the end of every 4,000 rounds. The barrel set fired for a total of 124,000 rounds.

A plot of the actual velocity data points from the test firing is given in Figure 1. The general consistent shape of the curves implies that velocity is a reliable parameter on which to base barrel lifetime. The constant velocity from 40,000 to 100,000 rounds indicates a stable barrel condition. Furthermore, a line drawn through the points of each of the curves past 100,000 rounds shows a relatively straight line drop in velocity for all of the barrels.

The slope of the straight lines does not differ greatly. Qualitatively this may indicate a similar failure mechanism for all of the barrels. The post firing metallographic examination also indicated similar failure modes. Examination of more failed barrels may indicate a different type of failure and could be compared to velocity versus rounds curve. A listing of the velocity data is given in Table I for the barrel set and the velocity change is given in Table II.

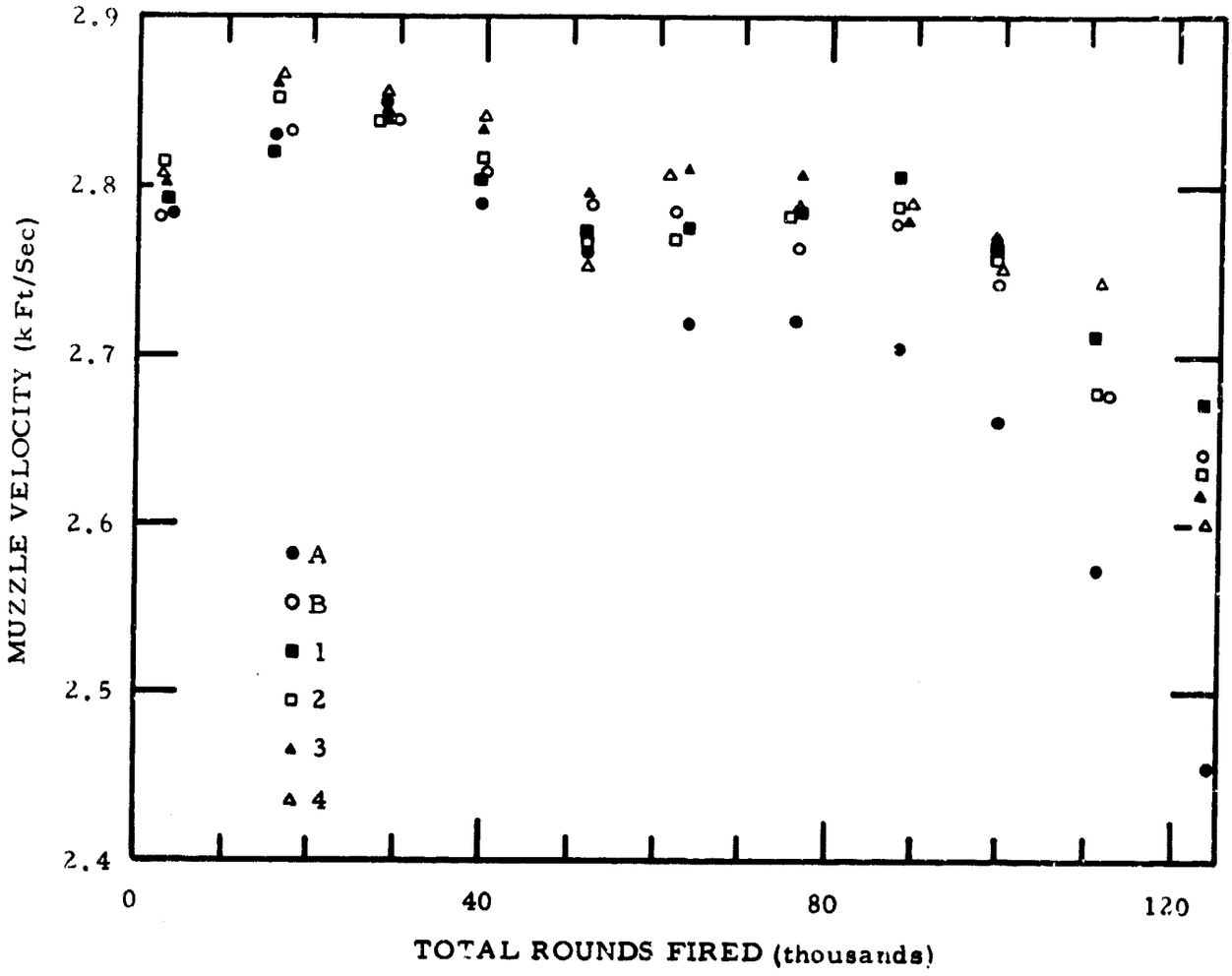


Figure 1. Velocity Vs Rounds for Barrels Tested

Table I

SUMMARY BARREL TEST DATA, VELOCITY

Barrel No.	I. D. Plating	Muzzle Velocity Ft/Sec					
		Rounds					
		Start	4K	100K	104K	116K	120K
A	TI-KOTE® C	2785	2787	2653	2571	2520	2456
B	TI-KOTE® C	2785	2848	2747	2677	2692	2631
1	Chromium	2789	2765	2751	2705		2672
2	Chromium	2818	2823	2740	2669		2627
3	Chromium	2804	2819	2749	2684		2623
4	Chromium	2813	2830	2734	2667		2605

Table II

SUMMARY BARREL TEST DATA, VELOCITY CHANGE

Barrel No.	I. D. Plating	Muzzle Velocity Ft/Sec					
		Rounds					
		Start	4K	100K	104K	116K	120K
A	TI-KOTE® C	-0-	+2	-132	-214	-265	-329
B	TI-KOTE® C	-0-	+63	-38	-108	-93	-154
1	Chromium	-0-	-24	-38	-86		-117
2	Chromium	-0-	+5	-78	-149		-191
3	Chromium	-0-	+15	-55	-120		-181
4	Chromium	-0-	+17	-79	-146		-192

Post Firing Examination

Following the test firing the barrels were returned to Texas Instruments for examination and comparative evaluation.

The interior bore surfaces were replicated by filling the barrel with an RTV silicone rubber fluid and a removal of the rubber after solidification. This method of replication served to show some significant differences in the interior surfaces of the barrels. The chamber surface of the chromium barrels showed to be a very rough surface in the grooves, which appeared to result from a galling type failure. The refractory coated barrels had more of the original surface area retained and a much smoother surface in the grooves, though, some areas of bare steel were also noted.

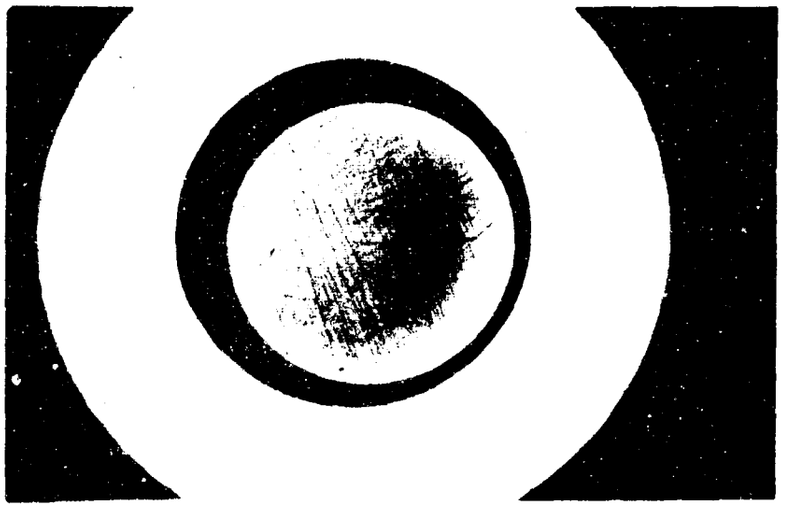
The same galling tendency of the chromium barrels was noted at the last 3-inches of the muzzle end, where again the groove areas were very rough and also contained chips of the gilding metal. For both barrel types, cracking at the base of the lands was very evident in the chamber section, but appeared to be more extensive in the chromium barrels.

Barrels 1, 3 and B were sectioned for metallurgical analysis; Number 1 because it was unusual in its velocity during test, Number 3 as being typical of the chromium barrels, and B because it was the better of the two refractory coated barrels. The appearance of the interior surface was similar to that expected from observation of the replication samples. That is, the chromium barrels showed very rough, undoubtedly high friction, areas at the muzzle end and at the chamber end. The refractory coated

barrel was smoother in the muzzle end and also appeared to have a better surface at the chamber section.

The chromium barrels appeared to show a more normal wear situation, that is, a thinning of the coating, whereas the harder coating appeared to have essentially the original coating where there was coating left, with no evidence for a thinning or normal wearing.

The most significant feature of the cross section analysis is evident in comparison of the cross sections of the three barrels shown in Figure 2. The muzzle end of each of the barrels lacked rifling. In the mid-sections there appears to be slightly more rifling left in barrel B, though both it and the barrels 1 and 3 show tendency for one side of the lands to be worn. The groove surfaces all appeared smooth at this section. The most significant differences were noted in the breech end of the three barrels in the amount and depth of cracking, due to the thermal and mechanical stresses exerted on the chamber The cracks are much larger with barrels 1 and 3 than with barrel B. Qualitatively, it appeared as though barrel B had retained more of the original shape of the I. D. than barrels 1 and 3. The nature of the cracks were different in that the cracks in barrels 1 and 3 and the extrusion of gilding metal back into both the cracks and voids left by pull out was very obvious. At higher magnification, gilding metal was seen extruded to the bottom of the cracks in barrels 1 and 3. This appeared less in barrel B. Whether this factor influences crack propagation, or the reason for the difference in amount of extrusion into the cracks of the chromium barrels compared to the B barrel, is not known.

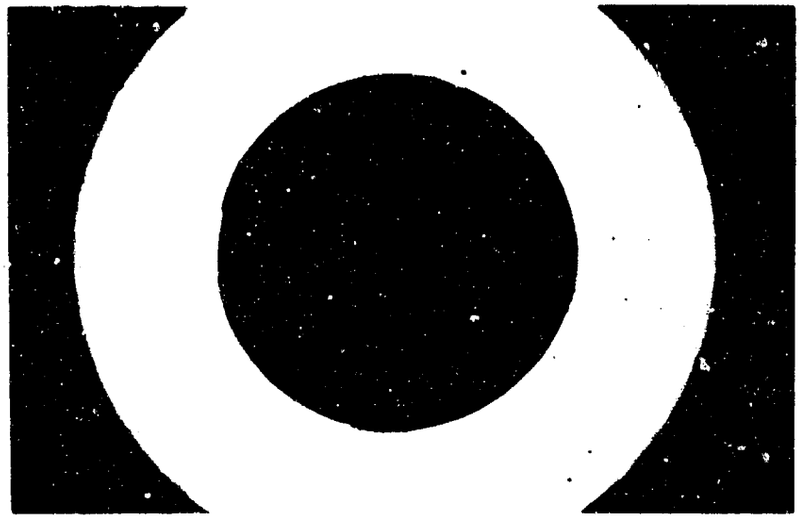


a. Barrel No. 1
20,000 Rounds
Muzzle End 6.5X

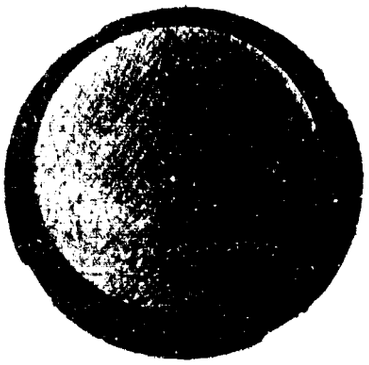
b. Barrel No. 1
20,000 Rounds
Mid Section 6.5X

c. Barrel No. 1
20,000 Rounds
Breech End 6.5X

Figure 2 (1 of 3). Cross Section of Three of Barrels Tested



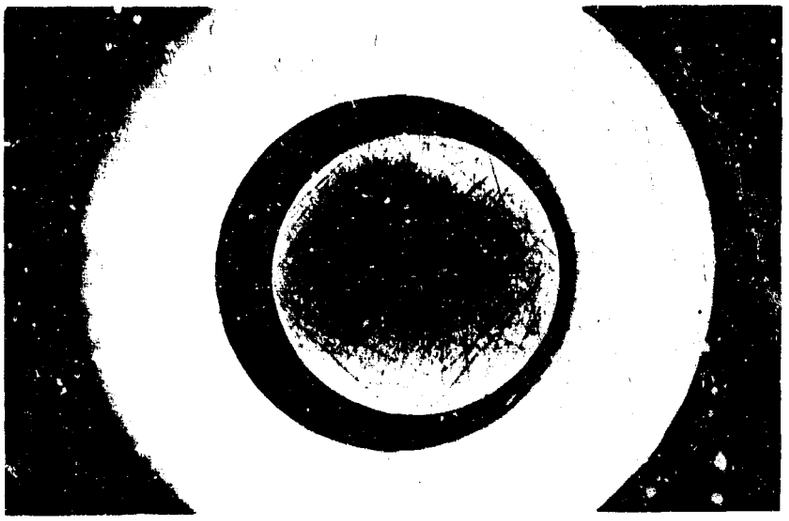
d. Barrel No. 3
20,000 Rounds
Muzzle End 6.5X



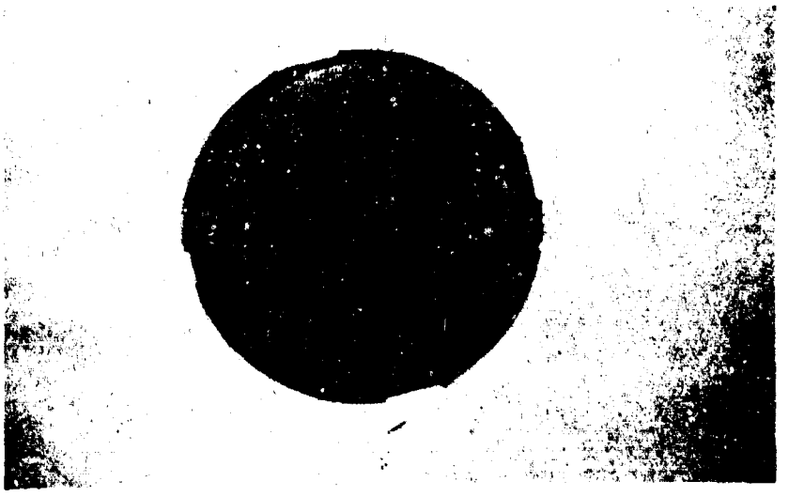
e. Barrel No. 3
20,000 Rounds
Mid Section 6.5X

f. Barrel No. 3
20,000 Rounds
Breech End 6.5X

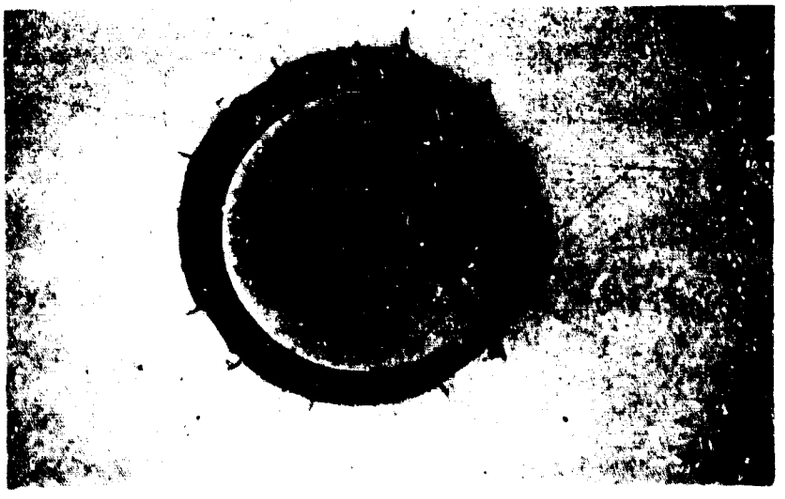
Figure 2 (Cont'd). Cross Section of Three of Barrels Tested



g. TI-KOTE®C Barrel
20,000 Rounds
Muzzle End 6.5X



h. TI-KOTE®C Barrel
20,000 Rounds
Mid Section 6.5X



j. TI-KOTE®C Barrel
20,000 Rounds
Breech End 6.5X

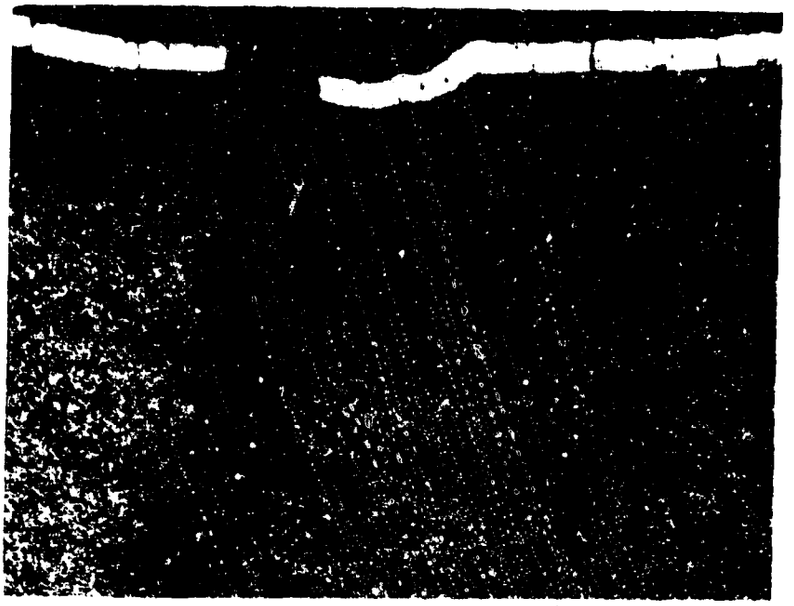
Figure 2 (3 of 3). Cross Section of Three of Barrels Tested

An attempt was made to observe the effect of one postulated failure m mechanism that the reaction gases would penetrate the coating, react with steel and cause it to be more brittle. Shown in Figure 3 is the higher magnification cross section of barrel number 1, in which microhardness traverse has been made from the crack area to the center area of the barrel. Figure 4 shows microhardness identations placed across the crack. All of the other hardnesses were roughly equivalent, and did not appear to support that the gases cause hardening and embrittling of substrate material on a gross scale.

To decrease the tendency of cracks, the base of the lands and the top corners of the rifling are smoothly radiused before plating. Apparently this smoothing is done by the electrochemical polish step just previous to application of the chromium. Comparison photomicrographs are shown in Figure 5 of the shape of the lands for a chromium plated barrel and of the barrels to which the refractory coatings was applied. A difference is noted and the smooth curvature of the chromium barrel should translate into improved performance. The plating of smoother lands should result in improved performance of the refractory coated barrel also.

Conclusions

Based on these initial test firing results the following preliminary conclusions have been drawn: the potential of refractory hard material to develop improved performance through increasing the erosion and thermal mechanical resistant of the barrel appears to be possible. Improvements

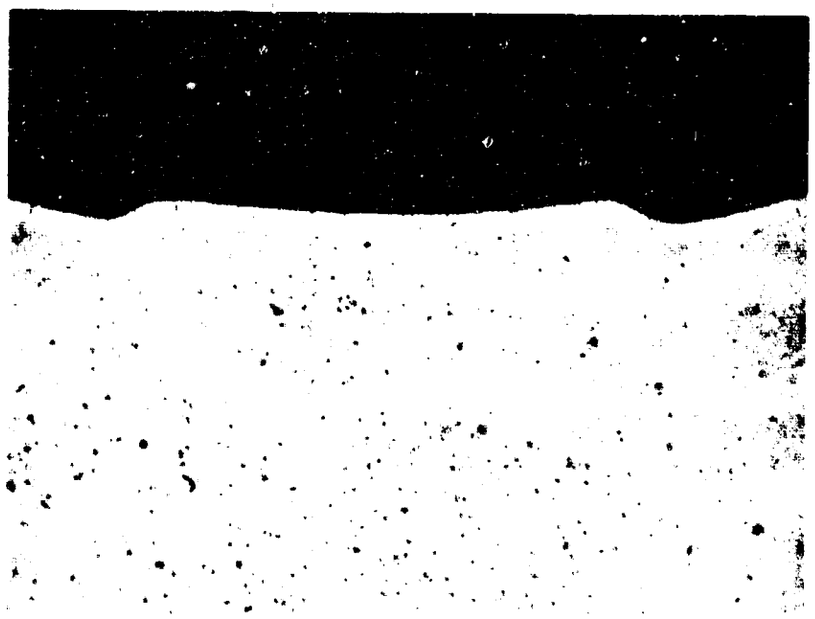


Barrel Number 1 (100X)

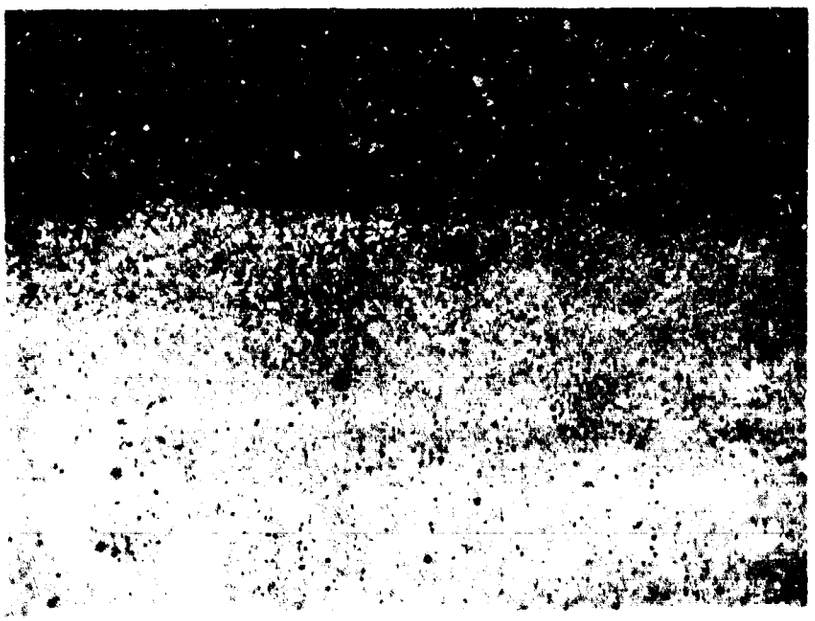
Figure 3. Cross Section of Tested Barrel Showing Hardness Traverse

Barrel Number 1 (500X)

Figure 4. Cross Section of Chromium Barrel Indicating Slight Hardening Around Crack



(a) Chromium-Plated Rifling (50X)



(b) TI-KOTE® C Plated Rifling (50X)

Figure 5. Chromium-Plated and TI-KOTE® C Barrel Sections Showing Different Shape of Rifling

in terms of developing a more satisfactory adhesion, more optimum coating thickness, optimum coating diameter and internal barrel geometry will be required.

General Discussion

Chairman: P. Rummel
Watervliet Arsenal
Watervliet, N. Y.

GENERAL DISCUSSION

Mr. F. Rummel, Watervliet Arsenal

In the past day and a half we have considered the design of the gun tube, the effects of additives, the behavior of coatings, and tube materials erosion, so I think we pretty well covered the waterfront. We have rather a short time available here and I would, from the hardware design for mass production end of things, remind all of you investigators and information developers that some very real constraints face the systems design people in weapons: the question of cost; some of the solutions may be technically feasible, but we can't afford them; the question of producibility, and particularly under mobilization conditions. Will the equipment and the plant and technical know-how be available? Will the materials be available? Some of you involved in chrome plating in production know that a laboratory process is a long way from the finished product when it comes to shipping hundreds of gun tubes a week out the door. So Quality Control and Process Control, etc., are also a part of it and we can't quit with a laboratory demonstration. It has to go a lot further before we dare commit it to a weapons system and guarantee it will be available in so many guns a month when someone wants them. The logical question is, "here we are, where do we go from here?" We could make that a little simpler and say, "Five years from today where do we want to be? What do we want to know that we don't know now?"

Maybe five years is a little long-ranged, but we only get there a year at a time, so perhaps two to five years. Considering the limited funds that are going to be available, we have a lot more problems than we have money to explore them, and that's going to get worse, I think, not better. So, with limited funds, where are we going to try to be five years from now in the understanding and control of gun tube erosion, from the smallest to the largest? Well, as a start, we have asked the chairmen of the previous sessions, and a couple of other unsuspecting citizens to give us their ideas, and then after that, I would leave it open and try to derive some mutual guidance from this, in rather general terms. So I have asked Mr. Warlick from the Navy, Mr. Davis, Air Force, Dr. Picard from Picatinny, and Mr. Gay from BRL to give us from two to five minutes of ideas from their personal views and unofficially representing their agency; where you want to be or what do you think we should be doing the next two to five years on this subject.

Mr. G. L. Warlick, Naval Ordnance Station

I would like to make it clear that any thoughts I may have are personal and not necessarily that of the Navy.

The various papers have presented different methods of controlling, or reducing, barrel erosion, each showing significant gains for a particular gun system. There are many gun system parameters that are not common in the several papers, such as propellant flame temperature, rate of fire, rotating bands, chamber pressure, etc. It is not clear that the same degree of success would have been obtained under a

different set of conditions. I feel that it is necessary to get a better understanding of the mechanics of erosion before the optimum solution of barrel erosion can be applied to all gun systems.

It appears that the total erosion is dependent on a number of contributing parameters such as propellant flame temperature, projectile weight, rotating bands, muzzle velocity, etc. Until the significance of each contributing factor can be determined, erosion control will be subject to a cut-and-try approach.

Significant progress has been made by the several agencies represented here in reducing erosion in various gun systems. It appears that the simplest solution of barrel erosion is cool burning propellants where gun restraints will accept an increase in charge weight. However, the ever-increasing demands for higher velocity and reduced gross gun weight essentially eliminates low force propellants as a universal solution to barrel erosion. Although the papers indicate significant gains in barrel life may be obtained by the use of various additives, it is not clear that the additive would have been equally effective in another gun system.

In view of the universal problem of gun erosion, it appears desirable to establish a committee, representing the several Services, on the working level for the exchange of ideas and coordination of effort.

Mr. D. Davis, Eglin AFB

First of all I would like to say that the Air Force has, essentially, two standard gun systems. We have the 20mm M61 and the similar 7.62mm minigun. Although we are not completely happy with the barrel life and would like to have better barrels, we are not really too much concerned about either of them at present; they are both adequate. What we are concerned with, and this is reflected in our current programs, is how to build better gun barrels for the future generation of weapons which we expect to see in our aircraft in five years or so.

These new guns will have much higher performance. This is an unclassified session so I can't tell you the muzzle velocity, rate-of-fire and other performance characteristics, but suffice it to say they will have high energy density cartridges and high rates of fire, and the erosion problem will be much more severe than anything in being today. This is the problem we are working on. This is the reason that in the work described by Karl Meyer this morning he used .220 Swift ammunition. It was used because it has the highest velocity, highest energy, and most severe erosion characteristics of any round commercially available and provides a reasonable simulant of what our future problems will be.

In some of the papers presented during this session "standard" erosion models were mentioned and hope of solving the general erosion problem expressed. I don't think this will happen. There are several mechanisms of erosion and the one you must be concerned with is the one which is dominant in your particular gun. The

dominant mechanism will differ and will not depend only on chamber pressure, muzzle velocity, and propellant flame temperature, but also on the rate of fire and firing schedule. The ideal solution to the erosion problem in one gun will not necessarily solve the problem for another system. Each gun system will require its own solution. I thank you.

Dr. J. F. Picard, Picatinny Arsenal

For the last two days I have listened with great interest, to the various papers presented here. I see that the work reported can be divided among two major categories; one dealing with attempts to improve the gun barrel life through plating with various metals, whilst the other is attempting to increase the life of the gun tube by the use of chemical additives either added to the round or the propellant itself. But I was somewhat dismayed at the fact that very little scientific approach had been used, most of this work was carried out on a hit or miss basis. In my opinion it is time to get together and try to establish a fundamental research program that will lead to a better understanding of the phenomenae responsible for erosion in gun barrel. Such a fundamental approach can lead to the development of either superior coating or plating materials and/or perhaps more effective chemical additives.

Maybe one might discover that a combination of chemical additive and plating will permit the use of much higher flame temperature propellant that conversely will contribute to higher velocity, higher rate of firing and muzzle velocity.

On the other hand the potential of developing propellant with a high force-low flame temperature cannot be neglected. There also exists several approaches to be explored. In my opinion this can be achieved through a better understanding of combustion, gas kinetic and thermodynamics as related to guns. Along this line let me cite the fact that in the field of rocketry this has been explored quite thoroughly and the results obtained have paid high dividends.

Obviously such a problem cannot be tackled by one or two groups alone. It can only be achieved by working together and having, from time to time, exchange of ideas and information. In other words, it was noticeable that a lack of communication exists between the Services. A meeting of this sort, if held at least once a year, should do a great deal toward improving this situation.

In conclusion, I would like to suggest that the propellant chemists be made aware of any new weapon concepts, as early as possible, and be called upon to suggest what propellant should be used or developed for this application. Too often the propellant chemist is asked to supply a propellant for a given weapon once the latter has been designed. This approach should improve the chances of getting a better weapon for less money.

Mr. S. W. Hollingum, U. K.

It is not possible to draw a clear conclusion without greater study of the papers individually. We have just heard some excellent remarks about scientists and engineers getting together right in the beginning of the project. This is one of the things I was going to

way, because we at Fort Halstead have had an opportunity to do this. We have designers, system engineers, chemists, physicists and metallurgists all working together. Our metallurgical people are impressed by what is going on with exotic superalloys and structured metals here. We have a little envy, because we do not have funds to do that. This question of funds perhaps is more important a factor than one really appreciates. We must look at the whole thing and decide what is going to be the economic solution. Obviously if we can get together and consider where a solution can be obtained by using the correct additive, and the best steel liners, we then can have perhaps a more economical solution. In meetings and discussions like this we can get together, find what each other is doing and try to set common goals. But the biggest problem, as mentioned by one of the session chairmen, is that every weapon has specific problems.

You have achieved a great deal of success in this conference. Obviously much progress has been made with coatings and various additives.

Dr. A. K. Roberts, Canada

I have talked with Dr. Picard about the working arrangements we had in the past with Picatinny Arsenal. I personally hope that we will be able to re-establish a working relationship with the United States in this field. My own feeling is that our contributions will be along the lines of understanding the fundamental mechanisms.

Mr. H. F. Gay, Aberdeen Proving Ground

When I heard flame temperatures of 5400 degrees (Fahrenheit) mentioned, I was surprised because I am accustomed to degrees Kelvin. It reminded me that there is a DOD directive that says we should go to the metric system. Since most of us are newcomers in this field, perhaps we should follow that directive as a first step toward uniformity.

Mr. F. R. Gruner, Army Weapons Command

In review of the many excellent papers presented at this meeting on the general problem of gun barrel erosion, it seems that many laboratories are working on the same problems. There is evidently much duplication of effort. Elimination or a great reduction of this duplication of effort would make available more man hours with the same funds toward more rapid solution of the erosion problem.

A coordinating group that could work up a general plan of research and development would seem advisable. Following the plan, specific tasks could be assigned to a laboratory in its area of greatest capacity.

From these combined efforts in a definite plan, much more rapid progress could be made toward solution of the erosion problem.

Mr. Rummel

The last point is well taken. There has been a variety of discussions on the various possibilities of coordination and discussions

among the Army groups and possibly interservice groups. I think one contribution from the Watervliet Arsenal out of this meeting is a guarantee to update and distribute the bibliography on "Gun Tube Erosion and Control." This is a start in a small way in improving communications. I will remind you again, those who have published papers which have not been included, to let us know. We will be putting out a revised bibliography with the proceedings. This is a specific action. It is rather difficult to end a meeting like this with items such as, "we will do this and you do that." This was not the point of this meeting. Some useful actions may however result, and at least we have a better view of the current status of work and of the people working in these fields.

Dr. I. Ahmad, Watervliet Arsenal

I certainly agree with Mr. Gruner. We should not leave this meeting with loose ends. We have reviewed the state-of-the-art and we appreciate that we have not been following the systems approach and we, at this time, do not have adequate communications with each other. Rather than just stating our realization of these deficiencies, I think it is time to take action. We should take concrete steps. We can form a small committee by which we can try to establish communications between services. Perhaps have Mr. Davis from the Air Force, Mr. Warlick from the Navy, some people from Watervliet, Picatinny, and Aberdeen, on this committee. Later on, the directors of each sections of these organizations can meet each other and

encourage the workers on the bench level to establish contacts between themselves. Meetings like this, perhaps on a smaller scale, should be arranged after six months or a year to discuss the progress made in this field.

Dr. R. E. Weigle, Watervliet Arsenal

In closing, I make the observation that we have made a start towards establishing a basis of knowledge concerning erosion and its control. By continuing our communications, as mentioned by several speakers that just preceded me, we will hope to improve upon that base and, of course, capitalize upon it. That is why we are in this business. Speaking for Watervliet Arsenal, we enjoyed having you all with us for the last few days and we look forward to maintaining the contacts we established with you. To those of you at the bench level, we trust this interaction will result in formulating some meaningful research programs leading to the solution of the problem of erosion.

General Bibliography on Gun Tube Erosion and Control

BIBLIOGRAPHY

INTRODUCTION

This selective list supplements and updates the bibliography in the 1946 report of the National Defense Research Committee, "Hypervelocity Guns and the Control of Gun Erosion".

This data is selective in that no exhaustive search was made, nor was the foreign literature reviewed extensively. However, on request of the Watervliet Arsenal, the Defense Documentation Center has compiled two bibliographies of technical reports published since 1946. One is classified; the other is unclassified. There are no citations to classified material in this bibliography.

A copy of the DDC unclassified bibliography starts on page 3.10-7 and it does not include the technical reports found on pages 3.10-4 through 3.10-6.

It is hoped that this compilation of the literature will make the investigations into the problems of gun erosion and control, and perhaps their solutions, somewhat easier. There are, undoubtedly, some articles and reports that have been overlooked in this bibliography. We plan to publish a more comprehensive bibliography at a later date and readers are encouraged to send any references they have, or any suggestions for improving the format, to Watervliet Arsenal, ATTN: SWEWV-RDT.

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TEST FOR SPIRAL WEAR IN A NON-PLATED BARREL (U)
NOV 54 1V WHITE,E.E.;
REPT. NO. 1312

AD- 47 988L
ABERDEEN PROVING GROUND MD
EROSION TESTS OF BORE PRE-PLATING PREPARATIONS FOR 20MM M24A1 TUBES (U)
DEC 54 1V MEADE,JOHN C.;
PROJ: TS3 3014

AD- 48 088L
ABERDEEN PROVING GROUND MD
THIRD REPORT ON THE DEVELOPMENT TESTS OF THE 90MM GUN, T119, MATERIAL (U)
DEC 53 1V NELSON,R.H.;
PROJ: TR3 3045

AD- 49 310
NAVAL WEAPONS LAB DAHLGREN VA
RAPID FIRE TEST OF IRON-BANDED PROJECTILES IN THE 3''/70 CALIBER GUN TYPE C MOD 6 SERIAL 24490 (U)
DEC 54 1V HUNT,M.L.;BUTLER,R.B.;
REPT. NO. 1316

AD- 50 511L
ABERDEEN PROVING GROUND MD
EROSION TEST OF 20MM M39 BARRELS EQUIPPED WITH FLUSH TYPE ORIFICE PLUGS (U)
OCT 54 1V DAVIS,DALE M.;
PROJ: TS3 3047

AD- 51 035
OLIN MATHIESON CHEMICAL CORP NEW HAVEN CONN
CONTINUATION OF RESEARCH, DESIGN AND FABRICATION OF FLUID-COOLED PERMEABLE GUN BARRELS AND LINERS (U)
OCT 54 1V KENNEDY,H.A.;HALL,R.L.;
CONTRACT: DA19 0590RD1892

AD- 51 476
MATERIALS ADVISORY BOARD (NAS-NRC) WASHINGTON D C
RESEARCH AND DEVELOPMENT OF MATERIALS FOR GUN BARREL INTERIOR PROTECTION (U)
DEC 54 1V
REPT. NO. 86 M
CONTRACT: DA49 025SC83

AD- 53 543L
ABERDEEN PROVING GROUND MD
A CALIBRATION TEST OF AN EROSION GAGE FOR EVALUATING PERFORMANCE LIFE OF LINED AND PLATED BARRELS FOR THE CALIBER.50. M2, HEAVY BARREL MACHINE GUN (U)
MAY 53 1V MICHELSON,I.;
PROJ: TS3 3017

AD- 53 575L
ABERDEEN PROVING GROUND MD
A TEST OF REDUCED BORE DIAMETER TUBES 20MM, M24A1 (U)
JAN 54 1V DAVIS,D.M.;
PROJ: TS3 3014

AD- 53 885L
ABERDEEN PROVING GROUND MD
A TEST OF 20MM, M3 AND M24A1 PRODUCTION TUBES WITH VARIOUS THICKNESS OF CHROME PLATE (U)
MAY 54 1V DAVIS,D.M.;
PROJ: TS3 3014

AD- 55 222
NAVAL WEAPONS LAB DAHLGREN VA
BALLISTIC QUICKNESS MUZZLE VELOCITY AS A FUNCTION OF PROPELLANT CHARGE WEIGHT AND GUN EROSION (U)
DEC 54 1V ROSSBACHER,R.I.;

AD- 56 039
OLIN MATHIESON CHEMICAL CORP NEW HAVEN CONN
CONTINUATION OF RESEARCH, DESIGN AND FABRICATION OF FLUID-COOLED PERMEABLE GUN BARRELS AND LINERS (U)
NOV 54 1V KENNEDY,H.A.;HALL,R.L.;
CONTRACT: DA19 0590RD1892

AD- 57 765
ARMY ARMOR BOARD FORT KNOX KY
TEST OF CALIBER .50 BARREL EROSION GAGE (U)
MAR 55 1V BROWN,PERCY H. JR.;
REPT. NO. 1664 2

AD- 58 519
NAVAL WEAPONS LAB DAHLGREN VA
BARREL LIFE TEST OF 5''/54 CALIBER BARREL MARK 18 MOD 0 SERIAL NO. 16058 (U)
MAR 55 1V SLOAN,D.C.;
REPT. NO. 1337

AD- 60 873
OLIN MATHIESON CHEMICAL CORP NEW HAVEN CONN
FLUID COOLED PERMEABLE GUN BARRELS (U)
DESCRIPTIVE NOTE: FINAL NARRATIVE SUMMARY REPT.
MAY 55 1V
CONTRACT: DA-19-059-ORD-1891

AD- 61 207
NATIONAL BUREAU OF STANDARDS WASHINGTON D C
STUDIES ON ELECTROPLATING TO RETARD GUN EROSION (U)
OCT 54 1V LAMB,V.A.;YOUNG,J.P.;
CONTRACT: NORD02753

AD- 62 805
JOHNS HOPKINS UNIV BALTIMORE MD
THE ALTERED LAYER IN ERODED VENTS (U)
FEB 46 1V WAGNER,R.L.;SHAPIRO,Z.M.;
REPT. NO. M A 311JHU 7C
CONTRACT: W36 034ORD4126

AD- 64 218
NAVAL WEAPONS PLANT WASHINGTON D C
METALLURGICAL INVESTIGATION OF ''GAS WASH CRATERS'' IN 5''/38 CALIBER GUN BARREL SER. NO. 4475 (U)
APR 55 1V
REPT. NO. T 18 55
MONITOR: NAVWEPS 4852

AD- 64 947
IIT RESEARCH INST CHICAGO ILL
NOZZLE EROSION, BURNING CHARACTERISTICS, COVOLUME AND IMPETUS OF LIQUID PROPELLANTS (U)
DESCRIPTIVE NOTE: PHASE REPT. NO. 2.
MAY 55 23P
REPT. NO. PR2
CONTRACT: DA11 022ORD1157
PROJ: TS4-4020

AD- 67 236
ABERDEEN PROVING GROUND MD
EROSION TEST OF BALL-PROPELLANT-LOADED T130 CARTRIDGES IN 20MM AIRCRAFT GUN - MK 12 MOD 0 (U)
JUL 55 45P SHUSIS,EDWARD C.;
REPT. NO. 46
PROJ: TS1 47

AD- 67 240L
ABERDEEN PROVING GROUND MD
A TEST OF CARTRIDGE, 20 MM, TP, M99, LOT NO. LC3-1, WITH M36A1- TYPE PRIMERS CHARGED WITH STYPHNATE MIXTURE 5061. (U)
APR 55 101P BENSON,R.W.;
REPT. NO. 55
PROJ: TS1 46

AD- 67 261L
ABERDEEN PROVING GROUND MD
A TEST OF CARTRIDGE, ARMOR-PIERCING-INCENDIARY, 20MM, T21E1, LOT NO. FA-X20-1963, ASSEMBLED WITH PROJECTILES CONTAINING ZIRCONIUM INCENDIARY MIXTURE (U)
JUL 55 1V BENSON,R.W.;
PROJ: TS1 46

AD- 67 795L
ABERDEEN PROVING GROUND MD
A TEST OF CARTRIDGE, APIT, CALIBER, 50, M20 ASSEMBLED WITH BULLETS CHARGED WITH A ZIRCONIUM INCENDIARY COMPOSITION (U)
MAY 55 1V BENSON,R.W.;HARTUNG,J.H.;HANKINS, A.R.;
PROJ: TS1 46

AD- 67 800L
ABERDEEN PROVING GROUND MD
EROSION TEST OF SPECIAL HEAT-TREATED TUBES 20MM, M24A1 (U)
MAY 55 1V MEADE, JOHN C.;
PROJ: TS3 3014

AD- 68 151
ABERDEEN PROVING GROUND MD
EROSION AND COOK-OFF TEST OF CARTRIDGE, 20 MM, T199E1 COATED WITH ''TEFLON'' (U)
JUL 55 1V HERMAN, W.H.;
REPT. NO. 47
PROJ: TS1 47

AD- 70 571
ABERDEEN PROVING GROUND MD
A TEST OF THREE CALIBER .60 MACHINE GUN BARRELS ASSEMBLED WITH 12-INCH, SHOULDERLESS LINERS FABRICATED FROM CHROMIUM BASE ALLOY (U)
SEP 50 1V HANKINS, A.R.;
PROJ: TS3 3039

AD- 70 572
ABERDEEN PROVING GROUND MD
A TEST OF EROSION AND PERFORMANCE CHARACTERISTICS OF STELLITE-LINED BARRELS FOR M1919A4 AND M1919A6 CALIBER .30 MACHINE GUNS (U)
MAY 50 1V DUGGAN, W.;
PROJ: TS3 3039

AD- 70 573
ABERDEEN PROVING GROUND MD
A TEST OF EROSION AND OTHER PERFORMANCE CHARACTERISTICS OF CHROMIUM PLATED BARRELS FOR THE M1919A6, CALIBER .30 MACHINE GUN (U)
SEP 50 1V HILL, JAMES S.;
PROJ: TS3 3039

AD- 70 575
ABERDEEN PROVING GROUND MD
EROSION GAGES FOR EVALUATING PERFORMANCE LIFE OF CALIBER .30 AND .60 LINED BARRELS (U)
AUG 50 1V GUSTAFSON, G.A.;
PROJ: TS3 3039

AD- 70 576
ABERDEEN PROVING GROUND MD
AN EROSION TEST OF SPECIAL LINED CALIBER .60 BARRELS (U)
JUN 50 1V HANKINS,A.R.;
PROJ: TS3 3039

AD- 70 577
ABERDEEN PROVING GROUND MD
TEST OF CARTRIDGE, BALL, CALIBER .50, M2, ASSEMBLED WITH NONCORROSIVE PRIMERS (U)
AUG 50 1V
PROJ: TS1 10

AD- 70 578
ABERDEEN PROVING GROUND MD
A TEST TO DETERMINE THE RELATIVE MERITS OF CALIBER THIRTY AMMUNITION LOADED WITH BALL-TYPE POWDER AND THAT LOADED WITH IMR POWDER (U)
DEC 50 1V DUGGAN,WALTER;
PROJ: TS1 35

AD- 70 617
ABERDEEN PROVING GROUND MD
TEST TO DETERMINE EROSION AND COOK-OFF CHARACTERISTICS OF VARIOUS CALIBER .50 BARREL TYPES WHEN USED IN THE M3 MACHINE GUN TO FIRE USAF COMBAT AND TRAINING SCHEDULES. VOLUME I (U)
APR 50 1V MICHELSON,IRVIN;
PROJ: TS3 3039

AD- 70 618
ABERDEEN PROVING GROUND MD
TEST TO DETERMINE EROSION AND COOK-OFF CHARACTERISTICS OF VARIOUS CALIBER .50 BARREL TYPES WHEN USED IN THE M3 MACHINE GUN TO FIRE USAF COMBAT AND TRAINING SCHEDULES. VOL II. (U)
APR 50 1V
REPT. NO. 5
PROJ: TS3 3039

AD- 70 619
ABERDEEN PROVING GROUND MD
TEST TO DETERMINE EROSION AND COOK-OFF CHARACTERISTICS OF VARIOUS CALIBER .50 BARREL TYPES WHEN USED IN THE M3 MACHINE GUN TO FIRE USAF COMBAT AND TRAINING SCHEDULES. VOLUME III (U)
APR 50 1V MICHELSON, IRVIN;
REPT. NO. 5
PROJ: TS3 3039

AD- 71 378L
ABERDEEN PROVING GROUND MD
EROSION TEST OF REDUCED-BORE CHROME-PLATED TUBES M24A1, 20MM (U)
MAY 55 1V MEADE, JOHN C.;
PROJ: TS3 3014

AD- 71 379L
ABERDEEN PROVING GROUND MD
EROSION TEST OF REDUCED-BORE CHROME-PLATED TUBES M24A1, 20MM (U)
MAY 55 1V MEADE, JOHN C.;
PROJ: TS3 3014

AD- 75 451
MATERIALS ADVISORY BOARD (NAS-NRC) WASHINGTON D C
TEMPERATURES, PRESSURES AND THERMAL STRESS RELATIONS (U)
OCT 55 128P BENDERSKY, D.; BERGDOLT, V.E.; HAWKINS, G.A.;
REPT. NO. MAB-98-M
CONTRACT: DA49 025SC83

AD- 75 860
BALLISTIC RESEARCH LABS ABERDEEN PROVING GROUND MD
A METALLURGICAL ANALYSIS OF EROSION IN STEEL VENTS (U)
JUL 55 47P DIETER, GEORGE E.; RINK, JOHN R.;
REPT. NO. BRL-941
PROJ: ORD-TB3-0110

AD- 76 052
OLIN MATHIESON CHEMICAL CORP NEW HAVEN CONN
CONTINUATION OF RESEARCH, DESIGN AND FABRICATION OF FLUID-COOLED PERMEABLE GUN BARRELS AND LINERS (U)
DESCRIPTIVE NOTE: MONTHLY PROGRESS REPT. NO. 12, 1-31 MAY 55.
JUN 55 11P KENNEDY,H.A.;HALL,R.L.;
CONTRACT: DA19 059ORD1892
PROJ: TS3-3039

AD- 76 055
OLIN MATHIESON CHEMICAL CORP NEW HAVEN CONN
CONTINUATION OF RESEARCH, DESIGN AND FABRICATION OF FLUID-COOLED PERMEABLE GUN BARRELS AND LINERS (U)
OCT 54 20P KENNEDY,HALL,R.L.;
CONTRACT: DA19 059ORD1892
PROJ: TS3-3039

AD- 81 654
CRANE CO CHICAGO ILL
BARREL LIFE IMPROVEMENT. CALIBER .50 EXPERIMENTAL WAX PELLET LOADED AMMUNITION (U)
DEC 55 38P STERBA,D.R.;
REPT. NO. 1687-19
CONTRACT: DA11 022ORD1687
PROJ: TS3-3039

AD- 81 655
CRANE CO CHICAGO ILL
BARREL LIFE IMPROVEMENT. MOLYBDENUM LINED CALIBER .50 HEAVY BARRELS (U)
JAN 55 1V STERBA,D.R.;
CONTRACT: DA11 022ORD1687

AD- 87 167
RENSSELAER POLYTECHNIC INST TROY N Y
STUDY OF EROSION PRODUCTS OF GUN BARRELS (U)
1V

AD- 89 388L
ABERDEEN PROVING GROUND MD
EROSION AND PERFORMANCE TESTS OF CALIBER .50, M3 AC, MACHINE GUN BARRELS, D7265156 (U)
AUG 55 1V MICHELSON,IRVIN;
PROJ: TS3 3039

AD- 91 389
NAVAL WEAPONS LAB DAHLGREN VA
BARREL LIFE TEST OF 3''/50 CALIBER BARREL MK 22 MOD 9 SERIAL NO. 29577 (U)
DESCRIPTIVE NOTE: PARTIAL REPT. NO. 23 (FINAL),
APR 56 48P DUCH,J.W.;
REPT. NO. 1450

AD- 92 373
NAVAL WEAPONS LAB DAHLGREN VA
AN INVESTIGATION OF COPPERING IN 5''/38 CALIBER GUN BARRELS (U)
APR 56 1V ROSSBACHER,R.I.;TUBMAN,B.D.;
REPT. NO. 1456

AD- 93 314
ROYAL ARMAMENT RESEARCH AND DEVELOPMENT ESTABLISHMENT FORT HALSTEAD (ENGLAND)
GROOVE MARKING TRIALS IN O.Q.F. 17 PR (U)
FEB 56 12P HILLSON,S.P.;
REPT. NO. P-1/56

AD- 95 358
CATHOLIC UNIV OF AMERICA WASHINGTON D C
EROSION STUDY OF 20MM. MK. 12 AIRCRAFT MACHINE GUN (U)
AUG 55 120P BRENNAN,JAMES G.;AUSTIN,THEODORE D.;
PYEATT,SUSAN;
REPT. NO. CU F 55 7
CONTRACT: NORD10260

AD- 95 359 11/6 19/6
CATHOLIC UNIV OF AMERICA WASHINGTON D C
EROSION AND CORROSION OF METALS (U)
DESCRIPTIVE NOTE: FINAL REPT. 21 DEC 55
DEC 55 11P CASTELLAN,G.W.;SULLIVAN,JAMES T. JR.;BARCLAY,JAMES A.;
REPT. NO. CU/F/55.8
CONTRACT: NORD-10260

AD- 99 595
NAVAL PROVING GROUND DAHLGREN VA
RECOVERY FIRING TESTS OF 3''/70 AA PROJECTILES FOR THE STUDY OF PROJECTILE BODY ENGRAVING, CASE, ATTACHMENT, BODY RELIEF, AND BULLET PULL EFFECTS (U)
DESCRIPTIVE NOTE: PARTIAL REPT.,
MAY 56 1V BUTLER,R.B.;DE GAETANO,FELIX P.;
REPT. NO. 1464

AD- 99 769L
ABERDEEN PROVING GROUND MD
PERFORMANCE TESTS OF CALIBER .50, M3, AC, LINED AND PLATED MACHINE GUN BARRELS D7265156 AND CARTRIDGE, BALL, CALIBER .50, M2, RELATED TO DAMAGE TO JET ENGINES (U)
MAR 56 1V HARTUNG,CALVIN C.;
PROJ: TS1 46

AD-102 044L
ABERDEEN PROVING GROUND MD
EROSION TEST OF ROCK ISLAND HCD PLATE TUBES, 20MM, M24A1 (U)
MAR 55 1V MEADE,JOHN C.;
PROJ: TS3 3014

AD-102 069
NAVAL WEAPONS LAB DAHLGREN VA
BARREL LIFE TESTS WITH NACO (NAVY COOL) PROPELLANTS OF 3''/50 CALIBER BARRELS MK 22 MOD 9 SERIAL NOS. 29533 AND 29561 (U)
JUL 56 1V DUCH,J.W.;
REPT. NO. 1479

AD-103 558
NAVAL WEAPONS LAB DAHLGREN VA
OPTIMAL DESIGN OF GUN BORE PLUG EROSION GAUGES II (U)
JUL 56 1V ROSSBACHER,R.I.;
REPT. NO. 1478

AD-103 710L
ABERDEEN PROVING GROUND MD
A TEST TO DETERMINE COMPARATIVE EROSION CHARACTERISTICS OF FOUR LOTS OF CARTRIDGE, AP, CALIBER .30 M2 (U)
NOV 55 1V BENSON,R.W.;
PROJ: TS1 46

AD-104 620L
ABERDEEN PROVING GROUND MD
COMPARATIVE EROSION CHARACTERISTICS OF EXPERIMENTAL PROPELLANTS FOR CALIBER .50 AMMUNITION (U)
MAR 56 1V SIEWERT,J.R.;
PROJ: TS1 46

AD-104 697L
ABERDEEN PROVING GROUND MD
CALIBRATION OF GAGE, BARREL EROSION, 20MM, T23 FOR GUNS M39 AND T171 (U)
JAN 56 132P EHRHARDT,RUSSELL;DAVIS,D.M.;
REPT. NO. 21
PROJ: TS3 3047

AD-104 874
ABERDEEN PROVING GROUND MD
S APECIAL TEST OF 20MM, M24A1 CHROMEPLATED TUBES RECEIVED FROM WATERVLIET ARSENAL (U)
AUG 55 1V MEADE,JOHN C.;
PROJ: TS3 3014

AD-106 721L
ABERDEEN PROVING GROUND MD
EROSION STUDY OF TUBE, 120MM, M1A3E1 (U)
MAY 55 1V KELLER,JAMES W.;
PROJ: TR1 1031H

AD-107 252L
ABERDEEN PROVING GROUND MD
A TEST OF EROSION AND PERFORMANCE CHARACTERISTICS OF NITRIDED AND CHROMIUM-PLATED BARRELS FOR THE CALIBER .30, M1919A4, MACHINE GUN, EMPLOYING CARTRIDGES, AP, CALIBER .30, M2 ASSEMBLED WITH BALL AND IMR PROPELLANTS (U)
JAN 56 1V MICHELSON, IRVIN;
PROJ: TS2 2023

AD-108 521L
ABERDEEN PROVING GROUND MD
TEST OF BARREL EROSION GAGE FOR GUN, 75MM, T83E7 (U)
MAY 56 29P HEINSHOHN, WILLIAM B.;
PROJ: ORD-TR1-1301

AD-108 847
CATHOLIC UNIV OF AMERICA WASHINGTON D C
HEATING AND EROSION STUDIES IN GUNS (U)
DESCRIPTIVE NOTE: FINAL REPT. ON TASK 3.
FEB 56 120P BOYD, MARJORIE; DOOLING, J.S.;
REPT. NO. CU/F/56.1
CONTRACT: NORD10260

AD-109 013L
ABERDEEN PROVING GROUND MD
DETERMINATION OF EROSION CHARACTERISTICS OF IMR AND BALL-TYPE PROPELLANTS AFTER STORAGE AT ELEVATED TEMPERATURE (U)
AUG 56 1V HARTUNG, J.;
PROJ: TS1 46

AD-111 881
DETROIT CONTROLS CORP REDWOOD CITY CALIF
LIQUID PROPELLANT GUN SYSTEMS. TASK I. BIPROPELLANT AND MONOPROPELLANT GUN SYSTEMS. TASK II. HEAT TRANSFER IN LIQUID PROPELLANT GUNS (U)
DESCRIPTIVE NOTE: COMBINED MONTHLY PROGRESS REPT. NO. 32.
APR 56 11P BROXHOLM, T.M.; ELMORE, L.C.; GIEDT, W.H.;
REPT. NO. RC-194
CONTRACT: NORD16217

AD-112 005
NAVAL WEAPONS LAB DAHLGREN VA
BARREL LIFE TEST OF 5''/54 CALIBER BARREL TYPE J MOD 0 NO. 16232 (U)
DESCRIPTIVE NOTE: FINAL REPT.,
OCT 56 1V THOMPSON,J.A.;
REPT. NO. 1501

AD-112 601
IIT RESEARCH INST CHICAGO ILL
RESEARCH STUDY ON INTERIOR BALLISTIC DESIGN OF RECOILLESS RIFLES (U)
DESCRIPTIVE NOTE: MONTHLY PROGRESS REPT. NO. 10,
NOV 56 6P GEISLER,W.;
CONTRACT: DA11 0220RD2045
PROJ: TS4-4020

AD-112 683
FRANKFORD ARSENAL PHILADELPHIA PA PITMAN-DUNN RESEARCH LABS
EFFECT OF PROPELLANT FLAME TEMPERATURE UPON BARREL EROSION (U)
1V LEVY,M.E.;SILVERSTEIN,M.S.;

AD-114 818
ABERDEEN PROVING GROUND MD
A TEST OF 20MM, M-39 BARRELS WITH SIX EXPERIMENTAL RIFLING CONFIGURATIONS (U)
DESCRIPTIVE NOTE: REPT. NO. 39,
OCT 56 1V FISHER,ROBERT;
REPT. NO. 39
PROJ: TS3 3047

AD-116 315
WATERTOWN ARSENAL LABS MASS
PERFORMANCE OF CALIBRE .604 CHROMIUM-IRON INSERTS IN EROSION GAGE WEAPON (U)
AUG 56 42P DUFFY,WILLIAM H.;

AD-120 870L
ABERDEEN PROVING GROUND MD
EROSION TEST OF EXPERIMENTAL 75MM T83 TUBES, WITH VARIABLE TWIST RIFLING (U)
NOV 56 1V HENISOHN,W.B.;FIELDS,M.C.;
PROJ: TR1 1020

AD-121 119
ABERDEEN PROVING GROUND MD
A TEST OF THE COOK-OFF AND EROSION CHARACTERISTICS OF CARTRIDGE, TP, 20MM T199E1, LOADED WITH BALL PROPELLANT (WCX-47). WHEN FIRED IN THE M-39 GUN, AND A TEST OF THE COOK-OFF CHARACTERISTICS OF FUZE, M-505, AND PROJECTILE, T-282E1, RESPECTIVELY WHEN ASSEMBLED TO OTHERWISE INERT CARTRIDGE (U)
OCT 56 244P FISHER,ROBERT;
REPT. NO. 55
PROJ: TS1 47

AD-122 070
ABERDEEN PROVING GROUND MD
EROSION STUDY OF TUBE; 105MM, T140 SERIES USING VARIOUS MODIFIED SHOT, TP-T, T79E1 (U)
JAN 57 1V CAROTHERS,H.E.M.;
REPT. NO. 2
PROJ: TA1 1503

AD-123 655L
ABERDEEN PROVING GROUND MD
EROSION TEST OF 20MM T160E3 AND T160E4 (M39) REDUCED BORE, NITRIDED, AND SPECIAL CHROMEPLATED BARRELS (U)
FEB 57 1V DOILNEY,S.;
PROJ: TS3 3047

AD-123 656L
ABERDEEN PROVING GROUND MD
A TEST OF NITRID BARRELS FOR GUN, MACHINE, CALIBER..30, M1919A4 (U)
NOV 56 29P LINDLEY,R. O. , JR;
PROJ: ORD-TS3-3039

AD-125 369
WATERTOWN ARSENAL LABS MASS
TESTING OF CHROMIUM-IRON ALLOY BORE PLATE IN .588
CALIBER EROSION GAGE WEAPON INSERTS (U)
DESCRIPTIVE NOTE: PROGRESS REPT.,
NOV 56 1V DUFFY,WILLIAM H.;LEVY,CHARLES;
REPT. NO. TR731 405 C
PROJ: TR3 3003

AD-128 688
NAVAL WEAPONS LAB DAHLGREN VA
LIFE TEST WITH NACO (NAVY COOL) PROPELLANT OF 5''/54
CALIBER BARREL MK 18 MOD 0 SERIAL NO. (U)
APR 57 1V DUCH,J.W.;
REPT. NO. 1532

AD-132 514
FRANKFORD ARSENAL PHILADELPHIA PA
BARREL EROSION TESTS OF EXPERIMENTAL PROPELLANTS FOR
CALIBER .50 AMMUNITION (U)
FEB 57 13P CRANE,BENTLY A.;
REPT. NO. FA-MEMO-1734
PROJ: ORD-TB1-46

AD-134 840
SPRINGFIELD ARMORY MASS
INVESTIGATION CONCERNING THE EROSION AND ACCURACY
LIFE OF TWO BARREL BLANKS, ALUMINUM, CALIBER .30, M1(U)
1V PASTORE,M.W.;

AD-135 307
BALLISTIC RESEARCH LABS ABERDEEN PROVING GROUND MD
EXPERIMENTS ON THE EROSION OF STEEL BY PROPELLANT
GASES USING THE VENT TECHNIQUE (U)
MAR 57 46P JONES,R.N.;WEINER,E.R.;
REPT. NO. BRL-1012
PROJ: ORD-TB3-0110

AD-137 444
NAVAL WEAPONS LAB DAHLGREN VA
EVALUATION OF THE BARREL EROSION GAUGE T-23 FOR 20MM MK 11 BARRELS (U)
DESCRIPTIVE NOTE: FINAL REPT.,
JUL 57 1V QUILLIN,R.H.;
REPT. NO. NPG-1547

AD-142 380
ABERDEEN PROVING GROUND MD
PERFORMANCE TEST OF CAL .50 GUN BARRELS (U)
NOV 57 1V SMITH,R.W.;
MONITOR: AFAC TR57 116 00000000057 116 000000000

AD-142 703
YALE UNIV NEW HAVEN CONN LABS OF PHARMACOLOGY AND TOXICOLOGY
RESEARCH AND DEVELOPMENT TO IMPROVE ARTILLERY AMMUNITION AND MATERIEL (U)
APR 52 1V CLARKE,H.G. JR.;MORSELL,WILLIAM M.;
CONTRACT: DA36 0340RD690

AD-143 959
SPRINGFIELD ARMORY MASS
POST-FIRING EXAMINATION OF FOUR NITRIDED BARRELS, LIGHT MACHINE GUN, CALIBER .30, M1919A4 (U)
1V PASTORE,M.W.;

AD-144 104
NAVAL WEAPONS PLANT WASHINGTON D C
RESULTS OF FIRING TEST OF 40MM GUN TYPE A MOD NO. 7 CONTAINING EROSION RESISTANT LINER CM 370 (U)
AUG 49 1V JUERGENS,JOHN G.;LURIE,WILLIAM;
REPT. NO. T 15 49 A

AD-144 334
ABERDEEN PROVING GROUND MD
DEVELOPMENT OF MODIFIED TP SHOT, T147E3 FOR 120MM GUN, T123 (U)
SEP 57 1V PETERS,J.D.;
PROJ: TA1 1503

AD-144 970
BALLISTIC RESEARCH LABS ABERDEEN PROVING GROUND MD
EROSION IN VENT PLUGS (U)
JAN 45 71P WIEGAND,JAMES H.;
REPT. NO. BRL-520

AD-146 928
AIR PROVING GROUND CENTER EGLIN AFB FLA
CALIBRATION OF M10 BARREL WEAR GAUGE WITH M61 GUN (U)
1V PARK,E.G.;
MONITOR: AFPGC TR58 44 000000000

AD-149 316
ABERDEEN PROVING GROUND MD
THE EFFECT OF WEAR AND TEMPERATURE ON VELOCITY CHARACTERISTICS OF PROJECTILES FIRED FROM UNCONDITIONED 105MM AND 155MM HOWITZERS AND 155MM GUNS AND THE EFFECTIVENESS OF THE DECOPPERING AGENT USED IN THE 105MM HOWITZER (U)
NOV 57 1V MAISEL,H.;
PROJ: TR3 3017 50

AD-153 641
ROCK ISLAND ARSENAL ILL
1V

AD-155 152
LAKE CITY ARSENAL INDEPENDENCE MO
EVALUATION OF SWISS 20MM OERLIKON PROJECTILES (U)
OCT 57 1V HAGENBUCH,L.M.;
REPT. NO. 57 4
PROJ: OAC 56 185

AD-155 201
ABERDEEN PROVING GROUND MD
EROSION TEST OF EXPERIMENTAL 75MM T83 SERIES TUBES, WITH VARIABLE TWIST RIFLING (U)
AUG 57 1V BLACKKETTER,DENNIS O.;
PROJ: TR1 1020C

AD-159 713
NATIONAL BUREAU OF STANDARDS WASHINGTON D C
EXPERIMENTAL PLATING OF GUN BORES TO PREVENT EROSION (U)
MAR 58 1V LAMB,VERNON A.;YOUNG,JOHN P.;
REPT. NO. 5797

AD-159 806
ABERDEEN PROVING GROUND MD
EROSION TEST OF M39 GUN BARRELS CHROMEPLATED BY CODE A , CODE B ,AND NATIONAL BUREAU OF STANDARDS PRODUCTION ENGINEERING (U)
MAR 58 1V FISHER,R.;
REPT. NO. MR269

AD-159 807
ABERDEEN PROVING GROUND MD
AN EROSION TEST OF PRODUCTION AND SPECIAL BARRELS FOR THE GUN, AUTOMATIC, 20MM, M39 (U)
APR 58 1V FISHER,R.;
PROJ: TS3 3047

AD-159 808
ABERDEEN PROVING GROUND MD
AN EROSION TEST OF TWO SETS OF M39 GUN BARRELS WITH SPECIAL RIFLINGCONFIGURATIONS AS SUGGESTED BY THE NATIONAL BUREAU OF STANDARDS (U)
MAY 58 1V HARTUNG,C.C.;
PROJ: TS3 3047

AD-159 817
ABERDEEN PROVING GROUND MD
A TEST OF THREE GROUPS OF M39 BARRELS PLATED BY THE NATIONAL BUREAUOF STANDARDS, CONTAINING: MUZZLE CHOKE TO .010-INCH; PLATING BY A SPECIALHIGH-SPEED CHROME PROCESS; AND INCREASED THICKNESS OF CHROME PLATING TO AMAXIMUM OF .017-INCH, RESPECTIVELY, AND INCORPORATING AN INTEGRAL PLATED GAS PORT (U)
MAR 58 1V FARIS,R.;
PROJ: TS3 3047

AD-206 931
ABERDEEN PROVING GROUND MD
DEVELOPMENT OF AN OBTURATOR DEVICE FOR 120-MM AP-T AND TP-T SHOT (U)
OCT 58 1V DEMPSEY,R.;
REPT. NO. MR280

AD-211 483
ABERDEEN PROVING GROUND MD
EROSION TEST OF MODIFIED 90-MM, GUN TUBE, M1A3, NO. 20135 (U)
FEB 59 1V GRAVES,H.C.;
PROJ: OAC 1 58

AD-211 541
WATER POLLUTION RESEARCH BOARD WATFORD (ENGLAND)
GUN EROSION. DEVELOPMENT OF STANDARDIZED EROSION TESTS (U)
NOV 43 1V KOSTING,PETER R.;
REPT. NO. 731 72

AD-211 633
ABERDEEN PROVING GROUND MD
TEST OF GUN TUBE, 76-MM, M32 NO. 31757, WITH NARROW LANDS, (U)
MAR 59 1V GRAVES,HARRY C.;
REPT. NO. DPS TR 201 1
PROJ: TR 201

AD-219 673
ABERDEEN PROVING GROUND MD
EROSION AND PERFORMANCE OF 20-MM, M61 GUN BARRELS, STANDARD AND CHROME-PLATED TYPES (U)
JUL 59 1V PATTON,MERLE G.;
PROJ: TS3 3034

AD-221 585
OFFICE OF SCIENTIFIC RESEARCH AND DEVELOPMENT WASHINGTON D C
SEP 46 1V
REPT. NO. D1 NDRC V1

AD-222 047
NAVAL WEAPONS LAB DAHLGREN VA
BALLISTIC TEST OF EROSION-RESISTANT LINER, 40MM GUN BARREL, TYPE A MOD. 2 NO. 4 MOLYBDENUM LINED)WESTINGHOUSE BL186((U)
1V HERNDON,G.W.)

AD-223 993
NAVAL WEAPONS LAB DAHLGREN VA
1V

AD-224 605
BATTELLE MEMORIAL INST COLUMBUS OHIO
1V

AD-224 606
BATTELLE MEMORIAL INST COLUMBUS OHIO
1V

AD-224 607
BATTELLE MEMORIAL INST COLUMBUS OHIO
1V

AD-224 772
PITTSBURGH UNIV PA
1V

AD-227 125
ABERDEEN PROVING GROUND MD
SERVICE LIFE OF 76-MM GUN TUBE, M32 (T91E3) (U)
OCT 59 1V RIEL,R.H.)
PROJ: TW 417

AD-229 289
ABERDEEN PROVING GROUND MD
A TEST OF CARTRIDGE, BALL, 7.62-MM, M80EXPERIMENTAL WITH BULLET 61T-94 (U)
DEC 59 1V HANEL,O.S.)
PROJ: OAC-I/59

AD-229 940
SPRINGFIELD ARMORY MASS
COMPARATIVE EVALUATION OF CHROMIUM PLATED M14 RIFLE BARRELS FABRICATED FROM CHROME-MOLY-VANADIUM STEEL AND ORD 4150 RESULPHURIZED STEEL, MIL-S-11595 (ORD) (U)
1V JONES,T.P.;KOETSCH,E.F.;

AD-230 013
WATER POLLUTION RESEARCH BOARD WATFORD (ENGLAND)
IN-BORE HEATING OF PROJECTILE FINS (U)
DEC 59 1V TRAVERSE,HUGO A.;MCDONOUGH,JOHN P.;
REPT. NO. TR171 1 2
PROJ: TW 418

AD-231 266
FRANKFORD ARSENAL PHILADELPHIA PA PITMAN-DUNN RESEARCH LABS
BARREL EROSION TESTS OF PROPELLANTS FOR CALIBER .30 AMMUNITION (U)
1V NARDI,A.V.;

AD-238 852
NATIONAL BUREAU OF STANDARDS WASHINGTON D C
1V YOUNG,JOHN P.;

AD-243 922
ABERDEEN PROVING GROUND MD
ENGINEERING EVALUATION OF COLD-WORKED TUBES, 90-MM, M41 (MODIFIED) (U)
OCT 60 1V PERRINE,R.H.;
REPT. NO. DPS OTA 61

AD-252 950
ABERDEEN PROVING GROUND MD
TEST OF GUN TUBE, 76-MM, M32, NO. 31757, WITH NARROW LANDS (U)
MAR 61 1V RAUSCHER,HARRY H.;
REPT. NO. DPS 170

AD-253 734
ABERDEEN PROVING GROUND MD
SERVICE LIFE OF 120-MM GUN TUBE, M58 (T123E1) (U)
APR 61 1V DOLTON,T.A.;
REPT. NO. DPS 175

AD-255 213
ABERDEEN PROVING GROUND MD
BORE-EROSION STUDY OF TWO EXPERIMENTAL AND ONE STANDARD 120-MM, M58 GUN TUBES (U)
APR 61 1V DOLTON,T.A.;
REPT. NO. DPS 198

AD-258 330
ABERDEEN PROVING GROUND MD
EFFECT OF TUBE WEAR ON ROUND TO ROUND DISPERSIO IN 90-MM TUBES, M41, WITH SHELL, HEAT, T300E55, (U)
JUN 61 1V DOLTON,T. A. ;
REPT. NO. DPS-226

AD-266 435
WATER POLLUTION RESEARCH BOARD WATFORD (ENGLAND)
METALLURGICAL EXAMINATION OF 20MM M61 MACHINE GUN BARRELS AFTER TEST FIRING AT LOW TEMPERATURES (U)
NOV 61 1V INGRAHAM,JOHN M.;
REPT. NO. TR739 3 1

AD-268 996
ABERDEEN PROVING GROUND MD
THERMAL STUDIES OF 81-MM TITANIUM MORTAR BARREL (U)
DEC 61 1V POUGHKEEPSIE,F.B.;
REPT. NO. DPS 405

AD-269 058
LAKE CITY ARSENAL INDEPENDENCE MO
STUDY OF THE WELDED ROTATING BAND FOR 20MM AIRCRAFT AMMUNITION (U)
AUG 61 1V LITTLEFORD,FRANK W.;
REPT. NO. IED R 61 13

AD-271 882
ABERDEEN PROVING GROUND MD
STANDARDIZATION OF PROPELLANT, MP, M1 WITH SHELL, HEP-T, M393 FOR 105-MM GUNS, M68 (US) AND L7A1 (UK) (U)
FEB 62 1V RIEDEN,W.J.;
REPT. NO. DPS 452

AD-300 163
ROYAL ARMAMENT RESEARCH AND DEVELOPMENT ESTABLISHMENT FORT HALSTEAD (ENGLAND)
THE ASSESSMENT OF FLAKING OF CHROMIUM IN PLATED 3 INCH MK N. 1 BARRELS AFTER PROOF INCLUDING RECOMMENDATIONS ON AN ACCEPTANCE SPECIFICATION (U)
MAY 58 14P SPENCER-TIMMS,E.S.;BENNETT,B.O.;
REPT. NO. MX-35/58

AD-300 166
ROYAL ARMAMENT RESEARCH AND DEVELOPMENT ESTABLISHMENT FORT HALSTEAD (ENGLAND)
THE PROBABLE EFFECT OF DECOPPERING ALLOYS ON THE CRACKING OF GUN BARRELS, PART I. THE DETECTION AND ANALYSIS OF TIN AND LEAD DEPOSITS IN CRACKS IN GUN BARRELS. PART II. METALLURIGICAL EVIDENCE FROM GUN BARRELS AND FROM SIMULATED TESTS (U)
MAY 58 1V COCKETT,G.H.;BARON,H.G.;
REPT. NO. MX-9/58

AD-302 295
ROYAL ARMAMENT RESEARCH AND DEVELOPMENT ESTABLISHMENT FORT HALSTEAD (ENGLAND)
ORDNANCE, Q.F. 3-INCH MK. N1 (3-INCH 70 CAL.) DEVELOPMENT FIRINGS OF BARREL BE386 USING STEEL CARTRIDGE CASES (U)
AUG 58 4P KNAPMAN,L.J.;
REPT. NO. P-51/58

AD-319 339
ROYAL ARMAMENT RESEARCH AND DEVELOPMENT ESTABLISHMENT FORT HALSTEAD (ENGLAND)
EXAMINATION OF LINEAR FROM AN AMERICAN 3''/70.MK.26 MOD.0 WATER COOLED GUN. BARREL NO. 26748 (U)
SEP 60 1V MORRIS,J.;
REPT. NO. MX-48/60

AD-346 027
ROYAL ARMAMENT RESEARCH AND DEVELOPMENT ESTABLISHMENT FORT HALSTEAD (ENGLAND)
EXAMINATION OF LINER STEELS FROM THREE 3-INCH MK, N. 1 GUN BARRELS AND THE EFFECTS OF FIRING TRIALS UPON THE LINERS. (U)
NOV 63 20P MORRIS,J.;
REPT. NO. M-M-32-63

AD-348 022 19/6
ROYAL ARMAMENT RESEARCH AND DEVELOPMENT ESTABLISHMENT FORT HALSTEAD (ENGLAND)
FINAL TRIALS OF 'SMEAR' AMMUNITION IN THE Q.F. 3-INCH MK. N1 GUN (U)
JAN 64 14P REES-JONES,P. E. ;
MONITOR: RARDE M3 64

AD-349 893L
ABERDEEN PROVING GROUND MD
INITIAL PRODUCTION TEST OF PROJECTILE, HE, TNT, WITH MICRO-CEL-E, 175-MM, M437E1, WITH FUZE, PD, XM572, AND CHARGE, PROPELLING, 175-MM, M86 (U)
APR 64 1V REICH,DONALD G. ;
PROJ: 2 3 0041 01C
MONITOR: APG DPS 1283

AD-365 872
DETROIT CONTROLS CORP REDWOOD CITY CALIF
SUMMARY OF CURRENT WORK IN THE FIELD OF LIQUID PROPELLANT GUNS AND HIGH ELOCITY PROJECTILES. (U)
DEC 54 21P
REPT. NO. M-10

AD-406 997L
ABERDEEN PROVING GROUND MD
COMPONENT TESTS OF CARTRIDGE, 105-MM, HEAT-M456, WITH TITANIUM DIOXIDE ADDITIVE, TO DETERMINE GUN TUBE WEAR CHARACTERISTICS, (U)
JUN 63 68P GREPPS,P.R.;
MONITOR: APG DPS978

AD-407 795
SPRINGFIELD ARMORY MASS
PRODUCTION HARD-CHROMIUM-PLATING OF THE M14 RIFLE
BARREL, (U)
JAN 63 11P GIRARD,R.J.;KOETSCH,E.F.;
PROJ: DA502 08 006
MONITOR: SA TR18 1082

AD-413 160L
ABERDEEN PROVING GROUND MD
COMPONENT DEVELOPMENT TESTS OF CATRIDGE, 105-MM,
APDS-T, M392 SERIES WITH TITANIUM DIOXIDE ADDI
TIVE, TO DETERMINE GUN TUBE WEAR
CHARACTERISTICS. (U)
AUG 63 74P
PROJ: DA PROJ. 504 03 089
MONITOR: APG DPS1005

AD-413 951
AIR PROVING GROUND CENTER EGLIN AFB FLA
MEMORANDUM ON MUZZLE VELOCITY OF THE 20MM M56A2
AND M55A2 ROUNDS AS A FUNCTION OF TEMPERATURE OF
PROPELLANT AND OF BARREL WEAR, (U)
AUG 63 26P GARRETT,GREER S.;
PROJ: 5845
MONITOR: APGC TDR63 48

AD-416 237
PICATINNY ARSENAL DOVER N J AMMUNITION ENGINEERING
DIRECTORATE
REDUCTION OF GUN EROSION. PART II. BARREL WEAR-
REDUCIN ADDITIVE, (U)
AUG 63 88P WOLFF,ROBERT O.;
MONITOR: AED TR3096

AD-443 079L
ABERDEEN PROVING GROUND MD
ENGINEER DESIGN TEST OF TWO 90-MM RECOILLESS RIFLES,
M67, EQUIPPED WITH FIBER GLASS TUBES. (U)
DESCRIPTIVE NOTE: FINAL REPT.,
1V CHEATER,HARVEY W. ;
PROJ: 8 3 4000 14F
MONITOR: APG DPS1383

AD-451 179
FRANKFORD ARSENAL PHILADELPHIA PA
SOLID PROPELLANTS FOR SAMLL ARMS AMMUNITION. A REVIEW AND RECOMMENDED RESEARCH, (U)
SEP 64 46P LEVY, M. E. ;
REPT. NO. R1733
PROJ: DA-1W523801A293
TASK: 1W523801A29312

AD-456 161
SPRINGFIELD ARMORY MASS
UTILIZATION OF OCCLUDED DIAMONDS IN CHROMIUM PLATE ON THE SPIW STRIPPER, (U)
DEC 64 13P HASSION, FRANCIS X. ; SZANTO, JOSEPH ;
REPT. NO. TR18 1087
PROJ: M1 3 23043 01M1M6

AD-460 512
NAVAL PROPELLANT PLANT INDIAN HEAD MD
FEASIBILITY STUDY OF THE USE OF A BARREL WEARREDUCING ADDITIVE IN NAVY GUNS. (U)
DESCRIPTIVE NOTE: TECHNICAL MEMO.,
JAN 65 17P TEMCHIN, J. R. ;
REPT. NO. TM-223
TASK: RMMP22004 286 1F009 06 01

AD-462 866
GENERAL ELECTRIC CO BURLINGTON VT MISSILE AND ARMAMENT DEPT
XM-134 MINIGUN. PERFORMANCE EVALUATION PROGRAM. VOLUME II. DETAILED ANALYSIS. (U)
DESCRIPTIVE NOTE: ENDURANCE TEST REPT.
MAR 65 1V
REPT. NO. 65APB7-2
CONTRACT: DA19 020AMC00410Y

AD-463 363L
DEVELOPMENT AND PROOF SERVICES ABERDEEN PROVING GROUND MD
PRODUCT IMPROVEMENT TEST OF HOWITZER, 155-MM, T255E3 (M126) (RANGE DISPERSION TEST OF TUBES, NO. 16770 AND 16771). (U)
DESCRIPTIVE NOTE: FINAL REPT.,
MAY 65 45P FLETCHER,D. H. ;
REPT. NO. DPS-1676
PROJ: 2 3 0068 15F

AD-471 432
ABERDEEN PROVING GROUND MD
TEST OF THE ACCURACY LIFE OF THE 155 MM GUN, M1A1E1, NO. 3052. (U)
DESCRIPTIVE NOTE: REPT. NO. 1. REPT. NO. 31 ON ORDNANCE PROGRAM NO. 5084.
JUL 44 1V
REPT. NO. OP-5084-31-VOL-2
PROJ: 3993

AD-477 317 19/6
NAVAL WEAPONS PLANT WASHINGTON D C
RESULTS OF EXAMINATION OF 3 IN./50 CALIBER GUN TYPE J. MOD 0, SERIAL NO. 24496, CONTAINING EROSION RESISTANT LINER BL-337. (U)
DESCRIPTIVE NOTE: TECHNICAL REPT.,
NOV 51 42P JURGENS ,JOHN G. ;LURIE, WILLIAM ;
REPT. NO. NGF-T-30-51
MONITOR: NAVORD 1633

AD-480 086L 19/6 19/3
DEVELOPMENT AND PROOF SERVICES ABERDEEN PROVING GROUND MD
ENGINEERING TEST OF 152-MM GUN-LAUNCHER, XM81E12, AND RECOIL MECHANISM, XM551 (LIFE TEST). (U)
DESCRIPTIVE NOTE: PARTIAL REPT. NO. 2, 23 SEP-1 DEC 65,
FEB 66 69P GROAK,G. S. ,JR.,
REPT. NO. DPS-1913
PROJ: RDT/E-1X57919D334 ,USATECOM-1-4-2521-03

AD-480 424L 19/6
DEVELOPMENT AND PROOF SERVICES ABERDEEN PROVING GROUND MD
ENGINEERING TEST OF GUN, 175-MM, M113, USING WEAR ADDITIVE (FIRED WITH CHARGE, PROPELLING, 175-MM, M86A1) (SAFETY RELEASE AND VELOCITY COMPARISON). (U)
DESCRIPTIVE NOTE: PARTIAL REPT. 16-29 DEC 65,
MAR 66 54P SINE,S. S. ;
REPT. NO. DPS-1954
PROJ: USATECOM-2-3-0099-07

AD-481 702L 19/6
DEVELOPMENT AND PROOF SERVICES ABERDEEN PROVING GROUND MD
PRODUCT IMPROVEMENT TEST OF CHARGE, PROPELLING, M86E1, FOR 175-MM (EVALUATION OF SWEDISH ADDITIVE IN REDUCING 175-MM GUN TUBE EROSION). (U)
DESCRIPTIVE NOTE: FINAL REPT. APR 64-FEB 66,
APR 66 43P HARRIS,JOHN W. ;
REPT. NO. DPS-1993
PROJ: USATECOM-2-3-0041-19

AD-483 309 19/6
SPRINGFIELD ARMORY MASS
BARREL EROSION STUDY OF RIFLES, 5.56MM, M16 AND XM16E1 - A JOINT ARMY-AIR FORCE TEST. (U)
DESCRIPTIVE NOTE: TECHNICAL REPT.,
JAN 66 236P LANDRY ,P. R. ;NILSSON,C. E. ;
REPT. NO. SA-TR11-5000

AD-489 434L 19/6
ARMY GENERAL EQUIPMENT TEST ACTIVITY FORT LEE VA
ENGINEERING TEST OF CARRIER, COMBINATION TOOL AND CLEANING MATERIAL FOR RIFLE, 7.62MM, M14E2. (U)
DESCRIPTIVE NOTE: FINAL TEST REPT. 4 APR-1 AUG 66,
AUG 66 32P LAUGHLIN,ROBERT C. ;
PROJ: USATECOM-8-6-6400-03

AD-493 520 19/6
BALLISTIC RESEARCH LABS ABERDEEN PROVING GROUND MD
THE COOLING OF GUNS, (U)
APR 39 20P LANE, J. R. ;
REPT. NO. BRL-146

AD-493 692 19/6
BALLISTIC RESEARCH LABS ABERDEEN PROVING GROUND MD
EFFECT OF EROSION OF 40MM BOFORS GUNS ON YAW ORDNANCE
PROGRAM NO. 5444. (U)
DESCRIPTIVE NOTE: MEMORANDUM REPT.,
MAY 42 11P HITCHCOCK, H. P. ;
REPT. NO. BRL-MR-47

AD-494 204 19/4 19/1 14/5
BALLISTIC RESEARCH LABS ABERDEEN PROVING GROUND MD
FLASH RADIOGRAPHS OF 105MM CANISTER T-18. (U)
DESCRIPTIVE NOTE: MEMORANDUM REPT.,
SEP 44 27P CLARK, J. C. ;
REPT. NO. BRL-MR-320
PROJ: ORD-4559

AD-494 656 19/6
BALLISTIC RESEARCH LABS ABERDEEN PROVING GROUND MD
THE APPLICATION OF EROSION IN VENT PLUGS TO
RECOILLESS GUNS. (U)
DESCRIPTIVE NOTE: MEMORANDUM REPT.,
JAN 45 13P WEIGAND, JAMES H. ;
REPT. NO. BRL-MR-340
PROJ: ORD-4587

AD-494 762 19/6
BALLISTIC RESEARCH LABS ABERDEEN PROVING GROUND MD
TEST OF 37MM CHROME-PLATED TUBES. (U)
DESCRIPTIVE NOTE: MEMORANDUM REPT.,
JUN 45 27P LANE, J. R. ;
REPT. NO. BRL-MR-380
PROJ: ORD-4559

AD-494 996L 19/6
WATERTOWN ARSENAL LABS MASS
THE EROSION OF 37-MM. M1A2 GUN TUBES, INCLUDING THE EFFECT OF PROPELLENT POWDERS FNH-M1 AND FNH-M2 AND OF BAND DIAMETER. (U)
DESCRIPTIVE NOTE: EXPERIMENTAL REPT.,
AUG 44 48P KOSTING,PETER R. ;
REPT. NO. WAL-731/115

AD-609 672
WATERTOWN ARSENAL LABS MASS
RESEARCH AND DEVELOPMENT OF MATERIALS FOR GUNS AT WATERTOWN ARSENAL LABORATORIES. IMPACT PROPERTIES OF STEEL MICROSTRUCTURES. (U)
DESCRIPTIVE NOTE: MONOGRAPH SERIES,
MAY 59 21P LUTZ,ROBERT R. ;
MONITOR: WAL , MS2

AD-618 135
WATERTOWN ARSENAL LABS MASS
PROGRESSIVE STRESS DAMAGE AND STRENGTH OF CENTRIFUGALLY CAST, COLDWORKED GUN TUBES. (U)
JUN 49 64P NEWHALL,DONALD H. ;KOSTING, PETER R. ;
REPT. NO. WAL-731/281
PROJ: TR3 3003C

AD-654 341 19/6
PICATINNY ARSENAL DOVER N J AMMUNITION ENGINEERING DIRECTORATE
A TEST TO DETERMINE THE CAUSE OF BARREL EROSION IN THE 40MM M75 LAUNCHER. (U)
DESCRIPTIVE NOTE: TECHNICAL REPT.,
JUN 67 43P DECKER,DELBERT B. ;
MONITOR: PA TR-3576

AD-802 073 19/6
BALLISTIC RESEARCH LABS ABERDEEN PROVING GROUND MD
A SIMPLIFIED METHOD FOR CALCULATING EROSION IN GUNS. (U)
DESCRIPTIVE NOTE: MEMORANDUM REPT.,
JUN 51 18P BREITBART,SIDNEY ;
REPT. NO. BRL-MR-549
PROJ: ORD-TB3-0110R

AD-802 140 11/2
BALLISTIC RESEARCH LABS ABERDEEN PROVING GROUND MD
ON EROSION OF HOT PRESSED CERAMIC MATERIALS BY POWDER GASES. (U)
DESCRIPTIVE NOTE: MEMORANDUM REPT.,
OCT 49 38P BREITBART,SIDNEY ;
REPT. NO. BRL-MR-498
PROJ: ORD-TB3-0110R

AD-803 036 19/6 11/9
PICATINNY ARSENAL DOVER N J PLASTICS AND PACKAGING LAB
FEASIBILITY OF USING GLASS-REINFORCED PLASTICS IN THE 81 MM MORTAR. I. PRELIMINARY MATERIALS INVESTIGATION AND DETAILED FABRICATION PROCEDURES. (U)
DESCRIPTIVE NOTE: TECHNICAL REPT.,
NOV 66 35P EIG,MERRILL ;
PROJ: DA-1C024401A329
MONITOR: PA TR-3400

AD-804 352L 19/1
DEVELOPMENT AND PROOF SERVICES ABERDEEN PROVING GROUND MD
PRODUCT IMPROVEMENT TEST OF CARTRIDGE, 4.2-INCH, HE, M329A1 (MODIFIED WITH STEEL ROTATING DISK). (U)
DESCRIPTIVE NOTE: FINAL REPT. 13 OCT-7 NOV 66,
DEC 66 50P PARSNIP,JOHN T. ;
REPT. NO. DPS-2233
PROJ: USATECOM-8-7-3110-08

AD-670 939 19/6 20/11
ARMY MATERIALS AND MECHANICS RESEARCH CENTER WATERTOWN MASS
PROPOSED METHOD OF CORRECTING MAGNETIC RECORDING BORESCOPE RESULTS FOR DETECTOR LIFT-OFF VARIATIONS. (U)
DESCRIPTIVE NOTE: TECHNICAL REPT.,
MAY 68 29P FOWLER,KENNETH A. ;
REPT. NO. AMMRC-TR-68-09
PROJ: DA-1C024401A110

AD-695 364 19/6
NAVAL ORDNANCE LAB WHITE OAK MD
THE USE OF AUTOFRETTAGED LOOSE BARREL LINER CONSTRUCTION FOR HYPERVELOCITY LAUNCHERS, (U)
MAY 63 18P DAWSON,V. C. D. ;SEIGEL, A. E. ;
REPT. NO. NOLTR-63-78

AD-801 673L 19/6
DEVELOPMENT AND PROOF SERVICES ABERDEEN PROVING GROUND MD
ENGINEERING TEST OF GUN, 175-MM, M113, USING WEAR ADDITIVE (FIRED WITH CHARGE, PROPELLING, 175-MM, M86A1) (TUBE EROSION AND WEAPON SYSTEM PHASES). (U)
DESCRIPTIVE NOTE: FINAL REPT. 1 FEB-8 JUL 66,
SEP 66 161P COLLINS,DEWARD W. ;
REPT. NO. DPS-2147
PROJ: USATECOM-2-3-0099-07

AD-801 741 19/4
BALLISTIC RESEARCH LABS ABERDEEN PROVING GROUND MD
A THERMAL THEORY FOR EROSION OF GUNS BY POWDER GASES, (U)
JAN 51 23P JONES,R. N. ;BREITBART,S. ;
REPT. NO. BRL-747
PROJ: ORD-TB3-0110R

AD-801 783 19/6
BALLISTIC RESEARCH LABS ABERDEEN PROVING GROUND MD
AN EXPERIMENTAL TRAVELING CHARGE GUN, (U)
OCT 51 74P VEST,DOUGLAS C. ;
REPT. NO. BRL-773
PROJ: ORD-TB3-0110V

AD-804 406L 19/6 19/4
DEVELOPMENT AND PROOF SERVICES ABERDEEN PROVING GROUND MD
ENGINEER DESIGN TEST OF MODIFIED FLASH SUPPRESSOR FOR 5.56-MM, CAR-15 SUBMACHINE GUN. (U)
DESCRIPTIVE NOTE: FINAL REPT. 7 JUL-15 OCT 66,
DEC 66 38P STALEY,L. E. ;
REPT. NO. DPS-2215
PROJ: USATECOM-8-6-0200-06

AD-807 620L 19/6 19/4
DEVELOPMENT AND PROOF SERVICES ABERDEEN PROVING GROUND MD
ENGINEER DESIGN TEST OF HOWITZER, 155-MM, M1A1 WEAR AND FATIGUE TEST). (U)
DESCRIPTIVE NOTE: FINAL REPT. OCT 65-NOV 66,
FEB 67 50P HARRIS,JOHN W. ;
REPT. NO. DPS-2235
PROJ: USATECOM-2-3-0075-07

AD-808 542 19/6
CHEMICAL INSPECTORATE LONDON (ENGLAND)
ANALYSIS OF GUN-BARREL WEAR-REDUCING ADDITIVES AND DEVELOPMENT OF IMPROVED MATERIALS, (U)
AUG 66 8P NORTON,E. S. ;
REPT. NO. CI MEMO-199

AD-809 233 19/6
WATERVLIET ARSENAL N Y BENET LABS
FIRING LIFE OF 175MM M113 GUN TUBES WITH SEVERE NODULAR CHROMIUM BORE DEPOSITS. (U)
DESCRIPTIVE NOTE: TECHNICAL REPT.,
JAN 67 43P GRECO,V. PETER ;SLAWSKY, MARTIN L. ;SHARKE,KARL G. E. ;
PROJ: DA-M7-5-P0858-01-M7-M7
MONITOR: WVT 6707

AD-809 300L 19/6
PICATINNY ARSENAL DOVER N J PLASTICS AND PACKAGING LAB
FEASIBILITY OF USING GLASS-REINFORCED PLASTICS IN THE 81 MM MORTAR. II. DESIGN CONSIDERATIONS. (U)
DESCRIPTIVE NOTE: TECHNICAL REPT.,
FEB 67 46P EIG,MERRILL ;
PROJ: DA-1C024401A329
MONITOR: PA TR-3401

AD-811 021L 15/2
DEVELOPMENT AND PROOF SERVICES ABERDEEN PROVING GROUND MD
ENGINEER DESIGN TEST OF BURSTER, M71, OXAMIDE-LOADED (SAFETY TEST). (U)
DESCRIPTIVE NOTE: FINAL REPT. 20 OCT-1 NOV 66,
APR 67 29P COLLINS,DEWARD W. ;
REPT. NO. DPS-2326
PROJ: USATECOM-5-6-0525-01

AD-811 031L 19/4 19/1
DEVELOPMENT AND PROOF SERVICES ABERDEEN PROVING GROUND MD
PRODUCT IMPROVEMENT TEST OF CARTRIDGE, HE, 81-MM, M374 (MODIFIED TWO-PART ALUMINUM ALLOY OBTURATING BAND). (U)
DESCRIPTIVE NOTE: FINAL REPT. 18 JUL 66-3 MAR 67,
APR 67 130P HARRINGTON,RONALD C. ;
REPT. NO. DPS-2337
PROJ: USATECOM-8-6-3010-21

AD-811 220L 19/6
DEVELOPMENT AND PROOF SERVICES ABERDEEN PROVING GROUND MD
INITIAL PRODUCTION TEST OF 81-MM MORTAR, M29E1, WITH MOUNT, M23A3, (U)
DESCRIPTIVE NOTE: FINAL REPT.,
APR 67 32P HOLWAGER,R. D. ;
REPT. NO. DPS-2339
PROJ: USATECOM-8-6-3005-05

AD-813 956L 19/6
DEVELOPMENT AND PROOF SERVICES ABERDEEN PROVING GROUND MD
ENGINEER DESIGN TEST OF AMMUNITION ADDITIVE FOR 105-MM GUN, M68 (IMPROVEMENT OF ADDITIVE EFFECT). (U)
DESCRIPTIVE NOTE: FINAL REPT. SEP 64-NOV 66,
MAY 67 37P FLETCHER,D. H. ;
REPT. NO. DPS-2368
PROJ: USATECOM-1-4-6725-04

AD-814 514L 19/1
DEVELOPMENT AND PROOF SERVICES ABERDEEN PROVING GROUND MD
ENGINEER DESIGN TEST OF HOWITZER, TOWED, 105-MM, M101 SERIES (FATIGUE TEST OF CANNON, HOWITZER, 105-MM, M2A2). (U)
DESCRIPTIVE NOTE: FINAL REPT. APR 66-MAR 67,
MAY 67 59P RAUSCHER,H. H. ;STEINBERG, B. ;
REPT. NO. DPS-2379
PROJ: USATECOM-2-4-0021-05

AD-815 706L 11/7
PICATINNY ARSENAL DOVER N J
A NEW ADDITIVE FOR REDUCING GUN EROSION. (U)
DESCRIPTIVE NOTE: TECHNICAL MEMO.,
MAY 67 23P PICARD,JEAN-PAUL ;WETTON, ROBERT G. ;TRASK,RUSSELL L. ;
REPT. NO. PA-TM-1781
PROJ: DA-1C014501A32C

AD-818 348 19/1
BALLISTIC RESEARCH LABS ABERDEEN PROVING GROUND MD
A METHOD FOR ESTIMATING THE SERVICE LIFE OF A GUN OR HOWITZER. (U)
DESCRIPTIVE NOTE: MEMORANDUM REPT.,
JUN 67 24P FRANKLE,JEROME M. ;KRUSE, LOREN R. ;
REPT. NO. BRL-MR-1852
PROJ: RDT/E-1P014501A33C

AD-818 624L 19/6
CORNELL AERONAUTICAL LAB INC BUFFALO N Y
DESIGN STUDIES OF THE XM140 BARREL. (U)
DESCRIPTIVE NOTE: TECHNICAL REPT.,
FEB 67 107P ADAMS,D. E. ;BROWN,W. R.
;MILLER,P. M. ;STERBUTZEL,G. A. ;VASSALLO,
F. A. ;
REPT. NO. CAL-GA-2324-W-1
CONTRACT: DAAF05-67-C-0018

AD-822 734 19/6 19/4
SPRINGFIELD ARMORY MASS
EROSION TEST ON 5.56MM RIFLE BARRELS - SMALL ARMS
WEAPON SYSTEMS STUDY (SAWS). (U)
DESCRIPTIVE NOTE: TECHNICAL REPT.,
JUN 67 51P JARRETT,W. J. ;
REPT. NO. SA-TR1-7024
PROJ: DA-1W523801A304
TASK: 1W523801A30408

AD-822 736 19/6
SPRINGFIELD ARMORY MASS
DEVELOPMENT OF A STELLITE-LINED, CHROMIUM-PLATED
BARREL FOR 5.56MM MACHINE GUN. (U)
DESCRIPTIVE NOTE: TECHNICAL REPT.,
JUN 67 45P JARRETT,W. J. ;
REPT. NO. SA-TR1-7025
PROJ: DA-1W523901A304
TASK: 1W523901A30408

AD-827 226 19/6
WATERVLIET ARSENAL N Y BENET LABS
UNPLATED TUBE EVALUATION PROGRAM FOR CANNON, 175MM
GUN, M113. (U)
DESCRIPTIVE NOTE: FINAL REPT.,
DEC 67 171P ROECK,DONALD M. ;
PROJ: FY66-66629
MONITOR: WVT 6750

AD-827 622L 19/1
ARMY WEAPONS COMMAND ROCK ISLAND ILL RESEARCH AND ENGINEERING DIV
DEVELOPMENT OF BOLT MECHANISMS FOR CASELESS AMMUNITION. (U)
DESCRIPTIVE NOTE: FINAL REPT. MAR-DEC 67,
JAN 68 64P WELLS,WARREN W. ;FRANTZ, JERRY W. ;
PROJ: DA-1-W-5-23801-A-353
MONITOR: RIA 68-55

AD-828 566L 19/6 19/1
TRW INC PORT CLINTON OHIO ORDNANCE DEVELOPMENT CENTER
CONCEPT AND FEASIBILITY STUDY FOR AN AUTOMATIC WEAPON CAPABLE OF REPETITIVE FIRE OF CASELESS AMMUNITION. VOLUME I. (U)
DESCRIPTIVE NOTE: FINAL TECHNICAL REPT. 24 JUL 67-2 FEB 68.
MAR 68 190P
CONTRACT: DAAF01-68-C-0009

AD-829 302L 19/6 5/9 14/2
ARMY INFANTRY BOARD FORT BENNING GA
PRODUCT IMPROVEMENT TEST OF BLANK FIRING ATTACHMENT (BFA) M12 (MODIFIED) FOR M14 RIFLE. (U)
DESCRIPTIVE NOTE: FINAL REPT.,
NOV 67 32P HORTON,GERALD M. ;
REPT. NO. USAIB-3175
PROJ: USATECOM-8-7-0020-02

AD-830 296 19/1
ARMY MATERIEL COMMAND WASHINGTON D C
ENGINEERING DESIGN HANDBOOK. AMMUNITION SERIES. SECTION IV. DESIGN FOR PROJECTION. (U)
JUL 64 198P
REPT. NO. AMC-PAM-706-247

AD-830 297 19/6
ARMY MATERIEL COMMAND WASHINGTON D C
ENGINEERING DESIGN HANDBOOK: GUNS SERIES, GUN TUBES. (U)
FEB 64 113P
REPT. NO. AMC-PAM-706-252

AD-836 994 19/6 14/2
WATERVLIET ARSENAL N Y BENET LABS
TUBE LIFE CRITERIA PROGRAM FOR CANNON, 175MM GUN, M113. (U)
DESCRIPTIVE NOTE: FINAL TECHNICAL REPT.,
JUN 68 148P ROECK, DONALD M. ;
MONITOR: WVT 6818

AD-840 121L 19/6 19/1
YUMA PROVING GROUND ARIZ
EROSION TESTING OF 175-MM UNPLATED BARRELS, (U)
MAR 67 89P PENDLETON, LEO ;
REPT. NO. YPG-FIRING-6537
PROJ: USATECOM-230069
TASK: 23006933

AD-841 434L 19/6
WATERVLIET ARSENAL N Y QUALITY ASSURANCE OFFICE
ANALYSIS OF CONDEMNATION MODES FOR 90MM TANK GUN, (U)
SEP 68 21P BARRON, M. Z. ;

AD-844 327L 19/1 19/6
PICATINNY ARSENAL DOVER N J FELTMAN RESEARCH LABS
A COMPARISON OF TALC AND TITANIUM-DIOXIDE AS EROSION REDUCERS. (U)
DESCRIPTIVE NOTE: TECHNICAL MEMO.,
OCT 68 14P SILVESTRO, GAYTON ;
PROJ: DA-1-W-014501-A-32-C
MONITOR: PA TM-1859

AD-844 875L 19/6 19/1
ARMY INFANTRY BOARD FORT BENNING GA
SERVICE TEST OF BLANK FIRING ATTACHMENT, XM15 AND CARTRIDGE, 5.56-MM, BLANK XM200. (U)
DESCRIPTIVE NOTE: FINAL REPT. 3 APR-6 MAY 68,
JUN 68 59P CONNOLLY,ROBERT B. ;
REPT. NO. USAIB-3107
PROJ: USATECOM-84025002

AD-847 291 19/6
NAVAL WEAPONS LAB DAHLGREN VA
EVALUATION OF 5 INCH 54 CALIBER LIGHTWEIGHT MOUNT, MARK 45 MOD 0. (U)
DESCRIPTIVE NOTE: TECHNICAL REPT.,
NOV 68 58P NEWTON,H. A. ;
REPT. NO. NWL-TR-2219
PROJ: ORD-083007/090-1/W-1320001

AD-847 697L 19/1 19/6
FRANKFORD ARSENAL PHILADELPHIA PA AMMUNITION DEVELOPMENT AND ENGINEERING LABS
INVESTIGATION OF 5.56MM, CARTRIDGE LOT LC-12387 IN STANDARD 5.56MM, M16A1 RIFLES. (U)
DESCRIPTIVE NOTE: TECHNICAL NOTE,
DEC 68 28P GRANDY,ANDREW J. ;
MONITOR: FA TN-1131

AD-847 714 19/4 19/6
BALLISTIC RESEARCH LABS ABERDEEN PROVING GROUND MD
MEASUREMENT AND ANALYSIS OF PRESSURES AND STRAINS IN A 175MM GUN TUBE. (U)
DESCRIPTIVE NOTE: MEMORANDUM REPT.,
DEC 68 52P HURBAN,JOHN M. ;
REPT. NO. BRL-MR-1951
PROJ: RDT/E-1-T-061102-A-33-C

AD-848 172L 19/6
MATERIEL TEST DIRECTORATE ABERDEEN PROVING GROUND MD
ENGINEER DESIGN TEST OF M139 GUN (LAND STRIPPING). (U)
DESCRIPTIVE NOTE: FINAL LETTER REPT.,
FEB 69 30P KEELE,ERIC ;
REPT. NO. APG-MT-3114
PROJ: USATECOM-14612026

AD-848 819L 19/1 19/6
ARMY INFANTRY BOARD FORT BENNING GA
PRODUCT IMPROVEMENT TEST OF STEEL CASES FOR 7.62-MM CARTRIDGES. (U)
DESCRIPTIVE NOTE: FINAL REPT.,
DEC 68 33P KNAUER,WILLIAM M. ;WIGHT, ROBERT K. ;
REPT. NO. USAIB-3226
PROJ: USATECOM-87000402

AD-850 424L 19/6 19/3
ARMY ARMOR AND ENGINEER BOARD FORT KNOX KY
INSPECTION COMPARISON TEST OF MACHINE GUN, 7.62MM: FIXED, M73E1. (U)
DESCRIPTIVE NOTE: FINAL REPT.,
APR 69 32P DIESTEL,JOACHIM ;STERRETT, DALE E. ;
PROJ: USATECOM-14613034

AD-851 365 11/6 19/6 13/8
AC ELECTRONICS-DEFENSE RESEARCH LABS SANTA BARBARA CALIF
STUDY TO INCREASE GUN BARREL LIFE BY PLATING THE BORE WITH TUNGSTEN. (U)
DESCRIPTIVE NOTE: FINAL TECHNICAL REPT. 24 JAN-22 OCT 68,
OCT 68 53P GEHRING,J. W. ;MEYER,K. H. ;
REPT. NO. AC-DRL-TR68-57
CONTRACT: F08635-68-C-0044
MONITOR: AFATL TR-68-124

AD-854 575L 19/4 13/8
IIT RESEARCH INST CHICAGO ILL
THE ROLE OF TITANIUM DIOXIDE IN THE REDUCTION OF GUN BARREL EROSION. (U)
DESCRIPTIVE NOTE: TECHNICAL SUMMARY REPT. 6 MAY 66-6 AUG 68,
FEB 69 94P REMALY,ROBERT ;STANLEY, THOMAS ;
REPT. NO. IITRI-C6090-8
CONTRACT: DA-28-017-AMC-3189(A)

AD-856 633L 19/6
YUMA PROVING GROUND ARIZ
ENGINEERING TEST OF INTERIM TUBE LIFE TEST OF 155-MM, SP, M109E1, XM185 CANNON, SERIAL NO. 1 AND 2. (U)
DESCRIPTIVE NOTE: FIRING REPT. 25 JUL 68-24 JUN 69,
JUL 69 213P BUSSELL,KENDALL K. ;
REPT. NO. YPG-FIRING-9513
PROJ: USATECOM-23002787

AD-857 054 19/6
ABERDEEN RESEARCH AND DEVELOPMENT CENTER ABERDEEN PROVING GROUND MD
OPERATION RESEARCH CRITERIA FOR ACCURACY LIFE OF GUN TUBES, 175MM, M113E1. (U)
DESCRIPTIVE NOTE: TECHNICAL MEMO.,
JUL 69 41P BRUNO,O. P. ;KNISS,JAMES R. ;GERARD,S. ;
REPT. NO. ARDC-TM-8

AD-859 269 19/5 19/6
BALLISTIC RESEARCH LABS ABERDEEN PROVING GROUND MD
STANDARD CONDITIONS FOR CANNON ARTILLERY FIRING TABLES. (U)
DESCRIPTIVE NOTE: MEMORANDUM REPT.,
AUG 69 22P MCCOY,DONALD H. ;
REPT. NO. BRL-MR-2002
PROJ: RDT/E-1-T-562603-A-287

List of Attendees

ATTENDEES

Blair, K. E.	Air Force Armament Lab, Eglin AFB, Fla.
Davis, Dale	" " " " " "
Ingram, 1LT J. D.	" " " " " "
Lefebvre, LTC B. R.	" " " " " "
Lindsay, LTC J. T.	" " " " " "
Beeuwkes, Dr. R.	Army Materials & Mechanics Research Center, Watertown, Mass.
Levy, Milton	" " " " "
Crenshaw, Dr. C. M.	U. S. Army Materiel Command, Washington, D. C.
Kosting, Dr. P.	" " " " "
Nagor, Dr. J. K.	Army Research Office, Durham, N. C.
Chick, MAJ E. E.	" " " Washington, D. C.
Ebihara, Dr. W. T.	U. S. Army Weapons Command, Rock Island, Ill.
Gruner, F. R.	" " " " " "
Hammer, Dr. A.	" " " " " "
Bannister, E. L.	Ballistic Research Laboratories, APG, Md.
Frankle, J. M.	" " " "
Freedman, E.	" " " "
Gay, Herman	" " " "
Tag, D. K.	" " " "
Dickey, C. M.	Frankford Arsenal, Philadelphia, Pa.
Gisser, Dr. H.	" " "
Kowalick, Dr. J. F.	" " "
Levy, M. E.	" " "

ATTENDEES (Cont)

Nardi, A. V.	Frankford Arsenal, Philadelphia, Pa.
Petronio, Dr. M.	" " "
Suga, A. M.	" " "
Eig, Merrill	Picatinny Arsenal, Dover, N. J.
Gray, W. R.	" " "
Hassmann, Harry	" " "
Picard, Dr. J. P.	" " "
Trask, R. L.	" " "
Young, J. P.	National Bureau of Standards, Washington, D. C.
Ayer, D. E.	Naval Ordnance Station, Indian Head, Md.
Warlick, G. L.	" " " " "
Thielbahr, W. H.	Naval Weapons Center, China Lake, Calif.
Churchill, F. F.	Naval Weapons Laboratory, Dahlgren, Va.
Fishman, S. G.	" " " "
Francis, J. A.	" " " "
Logan, J. D.	" " " "
Poudrier, G. L.	" " " "
Williams, L. M.	" " " "
Gehring, J. W.	AC Electronics, Div. of General Motors, Goleta, Cal.
Meyer, K. H.	" " " " " "
Harlow, R. A.	Aeronutronic Div, Philco-Ford, Newport Beach, Calif.
Brown, W. K.	Cornell Aeronautical Lab of Cornell University, Buffalo, N. Y.
Vassallo, F. A.	" " " " "
Hanafee, J.	Franklin Institute Research Labs, Philadelphia, Pa.

ATTENDEES (Cont)

O'Shea, Dr. R. P.	IIT Research Institute, Chicago, Ill.
Watmough, Thomas	" " " "
Bihun, R. G.	TRW Inc., Port Clinton, Ohio
Wakefield, G. F.	Texas Instruments, Inc., Dallas, Texas
O'Keefe, Dr. T.	University of Missouri (Rolla), Rolla, Mo.
Tooke, R. C.	" " "
Bedard, J. R.	Defence Research Establishment Valcartier Courcellette, P.Q., Canada
Roberts, A. K.	" " " "
Hollingum, S. W.	Ministry of Defence-Royal Armament R & D Establishment, Fort Halstead, Sevenoaks, Kent, England
Taylor, Mrs. Doris	" " " "
Ahmad, Dr. I.	Watervliet Arsenal, Watervliet, N. Y.
Brown, MAJ W. T.	" "
Colangelo, Dr. V.	" "
Corey, D. H.	" "
Cox, Joseph	" "
Davidson, Dr. T. E.	" "
Greco, V. P.	" "
Greeson, E. O.	" "
Imam, Dr. Rauf	" "
Methe, Paul	" "
Montgomery, Dr R. S.	" "
Netzer, Paul	" "
Newman, L.	" "

ATTENDEES (Cont)

Rummel, P. K.	Watervliet Arsenal,	Watervliet, N. Y.
Saegusa, Dr. F.	"	"
Sautter, Dr. F. K.	"	"
Schmiedeshoff, Dr. F. W.	"	"
Slawsky, M. L.	"	"
Thierry, R.	"	"
Walden, Dr. J. A.	"	"
Weigle, Dr. R. E.	"	"