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AN EMPIRICAL APPROACH TO PREDICTING CANNON TUBE EROSION RATE

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Watervliet Arsenal
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One difficulty in the wear prediction in new cannon systems is the uncertainty in its service life criteria. For tubes with low erosion rate, the service life is generally fatigue limited, and in tubes with high erosion rate the service life is limited by the accuracy of rounds fired. This accuracy in turn depends on the extent of erosion at the origin of rifling of a gun tube. Any correspondence in the bore enlargement and the accuracy of firing is non-existent. It varies from weapon to weapon, and within the weapon, it varies between
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different charges and different projectiles. It is this factor that has rendered earlier wear prediction equations unworkable. To circumvent this problem, equations have been developed that provide the wear rate of cannon from the internal ballistic data. This rate changes as rounds accumulate on a tube. Two equations have been developed that provide an upper and a lower limit for the wear rate of all cannon. The calculated results agree well with most cannon tubes. It is found that with the help of these equations, wear rate of totally new systems can be predicted to within about 25% of that observed in most cannon with very few exceptions.

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INTRODUCTION

One of the major problems associated with cannon is erosion of the bore, a problem that has attracted the attention of all classes of workers involved in the development of cannon systems. A somewhat related, but not so intense, problem is that of life expectancy of new cannon. In recent years, due to the high cost of test firing, the need for an educated guess of the wear life of a gun tube has become as urgent as the control of erosion itself. Among the newer cannon systems, such a need was realized when the life of a 155mm M185 tube fell short of the, then desired and hoped for, wear life of the M126 howitzer. This situation repeated itself in the development of the 155mm XM199 and in the 8 inch XM201 cannon tube. The need for a formula to predict wear life of gun tubes has thus become acute. In what follows, a method to alleviate the immediate problem is proposed, with a brief description of the earlier attempts at resolving the problem. It is suggested that the proposed formula for wear rate be considered interim in nature until the development of an analytical expression for such a purpose is realized by understanding the phenomena involved in the erosion of guns.

a. Background

Unlike the phenomenological and theoretical study of erosion in guns, the prediction of erosion has not been a very popular topic. The earliest attempt seems to be that of Nordheim, et al[1] during World War II, when the erosion rate in vents was calculated with a

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1. Nordheim, L.W., Soodak, H. & Nordheim, G., "Thermal Effects of Propellant Gases in Erosion Vents and Guns" NDRC Report #A-262 OSRD No. 3447.

fair degree of accuracy. This was the most analytical of all attempts that have been made to solve this problem thus far, the present included. Their method consisted of calculating the heat input in conjunction with the bore surface temperature of a vent as well as weight loss and diameter change in the vents, assuming that surface steel melting was the basic mechanism of erosion. These calculations agreed very well with the observed data. However, the method could not be extended to gun tubes primarily because of the lack of understanding of the mechanism of erosion in the gun tubes. In addition, calculations had shown that the bore surface temperatures in most cannon tubes do not reach the melting point of steel, thereby excluding the possibility of postulating general melting in all cannon.

b. Earlier Work

Later, several empirical methods were proposed by the Ballistic Research Labs (BRL) to estimate the wear rate as well as the erosion life of cannon tubes. The two terms may appear similar but are categorically different concepts. The former, that is, the wear or erosion rate, is the only term that can be discussed meaningfully. The latter term involves the criteria of condemnation of a gun tube that differ from weapon to weapon and hence, cannot be considered in any general consideration.

In 1951, Jones and Breitbart[2] proposed a method to calculate the wear rate in cannon. Although it was claimed to be analytical, in reality it was highly empirical as well as arbitrary. The method

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[2] Jones, R.N., & Breitbart, S., "A Thermal Theory for Erosion of Guns by Powder Gases", BRL Report #747, 1951.

assumed the existence of steel melting as the predominant factor in the erosion of gun tubes, without calculating the bore surface temperature. It was rather involved and did not produce good results when applied to the present weapons.

Later, Breitbart[3] developed a simpler formula from the detailed expression of wear rate, which was highly arbitrary and implied a decrease in wear rate with a rise in pressure above 28,000 psi. In addition, at pressures below 16,000 psi, the equation predicts a decrease in the diameter rather than an increase. Further, the method had the same drawbacks as the earlier detailed one, viz., a lack of agreement between the observed and the calculated data.

Recognizing the above, Frankel and Kruse[4] from BRL attempted a statistical approach to the problem. Apparently, the method was first applied on United Kingdom cannon. It consists of postulating an empirical expression for bore surface temperature of different cannon using the weight of propellant, the flame temperature and bore diameter, as follows:

$$\theta = \frac{T_0 - 300}{1.7 + 0.38\, d^{1/2} \left(\frac{d^2}{c}\right)} \quad 0.86 \qquad (1)$$

where T_0 is the flame temperature of the propellant

d - the bore diameter

c - the weight of propellant

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3. Breitbart, S., "A Simplified Method for Calculating Erosion in Guns" BRL Mem. Report No. 549, 1951.

4. Frankel, J. and Kruse, L., "A Method for Estimating the Service Life of a Gun or Howitzer", BRL Mem. Rpt. 1852 June 1967.

and θ is the rise in the bore temperature at the origin of rifling.

If w is the wear rate than $\ln\left(\frac{w}{\sqrt{d}}\right)$ is plotted against θ, and an expression is obtained for $\frac{w}{\sqrt{d}}$ with

$$\frac{w}{\sqrt{d}} = 9.09 \times 10^{-8} \; e^{0.00777} \tag{2}$$

A recalculation was proposed for weapons having θ greater than 600°C, resulting in a different value for $\frac{w}{\sqrt{d}}$, namely

$$\frac{w}{\sqrt{d}} = 8.48 \times 10^{-8} \; e^{0.00785} \tag{3}$$

The expressions were found by the authors to be unsatisfactory, particularly for howitzers. They considered total service life to be more important than the wear rate, notwithstanding the peril involved in such a venture. Therefore, they suggested a third expression to estimate the service life, namely:

$$L = K \; e^{a\theta} \tag{4}$$

where L is service life and K and a are constants determined statistically by plotting L against θ.

C. Discussion of Earlier Work

The la[illegible] formula cannot be used as a predictive equation since the cond[illegible]ation criteria in a cannon system are generally not determined in advance of substantial test firing. Furthermore, the larger cannon are often condemned on the basis of fatigue life if the erosion life is long enough and, hence, under those conditions, the bore surface temperature rise is a meaningless quantity. This aspect of the authors' calculations becomes obvious when the estimated service life of the 105mm M2A1 howitzer of 20,000 rounds and that of the 155mm M1A1 of 15,000 rounds are considered as compared to the actual service life of [illegible] rounds for the 105mm M2A1 and 7500 rounds for the 155mm M1A1.

There are three main objections to Frankel and Krause's first two expressions. In the first place, the prediction of a single value of wear rate is almost as bad as the prediction of total service life, because generally, the wear rate changes during the life of a single gun tube and, if the wear rate considered is obtained by dividing the total erosion by total rounds, then the prediction can only be made for the same condemnation limits. The second objection concerns the criteria of condemnation used in arriving at these expressions. Table I in the BRL Memo Report #1853,[5] provides the wear rate and the service lives of the cannon considered. Below is a sample taken for wear rate and service life from that report with a column of total wear (the product of Wear Rate x Service Life) added for comparison:

Gun	Wear Rate	Service Life	Total Wear
90mm M1	5.32×10^{-5}"/rd.	2,800 rounds	.149"
90mm M3	7.45×10^{-5}	2,060	.149"
90mm M41	28.14×10^{-5}	700	.197"

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[5] "Hypervelocity Guns and the Control of Gun Erosion" Summary Technical Report of Division I, NDRC Volume 1, OSRD #6, Washington, D.C.1946

Gun	Wear Rate	Service Life	Total Wear
105mm M68	75×10^{-5}	100	.075"
175mm M113	50×10^{-5}	400	.200"
8" How. M2	2.5×10^{-5}	6,000	.150"
8" Gun M1	51.43×10^{-5}	700	.360"

Present weapons do not seem to have similar condemnation limits. Hence, the use of an expression which is developed on these data as a predictive expression for newer weapons, will be incorrect.

The third objection concerns the very nature of the equations. In the first place, the values of θ suggested are grossly misleading. For example, the value for 105mm M2A1 How. is 400°C at the origin of rifling. This implies that the tube should not even develop any type of heat affected zone. The fact is that the howitzers develop white layers near the origin of rifling. Further, the maximum temperature indicated in their report for any cannon is 1141°C. It is a fact that melting is observed in some cannon indicating much higher temperatures.

NEW APPROACH

These are the reasons the determination of life estimation equations for gun tubes was left without any concrete starting point. The only course left was to start anew on the problem. In the following sections, a new approach is proposed which, though empirical, still maintains the influences of the ballistic parameters in the same order as is known to exist through experience.

a. Theoretical Considerations

To develop a precise method for predicting the erosion in an analytical fashion from theoretical calculations requires additional investigative efforts in the fundamentals of gun erosion. Even then a statistical step will be needed to bridge the final gap of the observed phenomena and the theoretical calculations. The theoretical work would consider calculations of bore surface temperatures, heat input, as well as ballistic parameters such as velocity and projectile engraving forces. A statistical relationship could then be developed for erosion rate in presently existing weapons. This should provide the unknown relating constants between erosion and ballistics that might be applied universally to all weapons. In the absence of such exact data, one has to look for simpler means. In the following sections, such a method is developed.

The ballistic factors that an engineer must consider are the quantity of charge, the pressure, the muzzle velocity and the weight of the projectile. These are not totally independent variables of interior ballistics. They are the apparent influences to which any cannon is subjected. Further, they are functionally related to each other. It would be a mistake to consider these parameters as the complete list of factors giving rise to erosion. In fact, in an exact calculation, these variables will be involved implicitly along with other propellant and cannon-material properties.

Nevertheless, an examination of the erosion rates of different cannon indicates that higher rates of erosion are generally associated with higher muzzle velocity, higher pressure and higher quantitites of charge.

The last factor could be misleading, however, when comparing different caliber cannon. For example, a 105mm M68 heat round has a charge weight of about 11-1/2 lbs. as compared to a weight of 13 lbs. in a 155mm M126 Zone 7 charge. It is well known that the wear rate in the M68 tube is about 400 times as high as in an M126 tube. As a first approximation, therefore, a better choice for incorporation into a wear equation should be the loading density, or perhaps density based on the complete burn out volume of the charge. As the latter involves either some complex calculations or assumptions that may vary from cannon to cannon and charge to charge, for simplicity, therefore loading density is a fair approximation. Pressure, per se, does not seem to have as high an influence on erosion as other factors such as velocity or loading density. The pressure does affect wear indirectly, though, by affecting the velocity and density of combustion gases. One of the most significant factors is the muzzle velocity (MV). In some cases, it has been observed that a difference of 300 fps in MV increases the erosion rate by a factor of 4 to 5. Another important, though not very obvious, factor affecting wear, is the duration of heating during a firing cycle. A rough approximation of this factor is the length of travel divided by the mean velocity (i.e., the muzzle velocity divided by 2).

Once the relative importance of erosion influencing factors is determined, the next step is to correlate them with the erosion rate. To do so in a direct manner would be time consuming, and would not add any extra confidence in the end results. If we examine the existing information on the erosion of different weapons, it is observed that cannon can be classified in three categories of severity of erosion. The first is comprised of howitzers with muzzle velocity under 2000 fps and using M1 propellant. These tubes apparently have such low erosion rates that they are condemned on the basis of fatigue. The second contains weapons having M.V. between 2000 fps and 3000 fps and a bore size less than 8 inches. These weapons have moderately high erosion rates and are condemned due to their erosion. The third is comprised of cannon having M.V. greater than 3000 fps or bore size larger than 8 inch. These cannon wear at extremely high rates and the nature of erosion is such that melting of the bore surface may be quite prominent.

b. First Equation

With these observations in mind, it is, therefore, suggested that the wear data over the whole life of one of the cannon in the second classification be used as the starting point, i.e., consider the erosion of one of the cannon as the standard and relate the other tubes through the ratio of their ballistic parameters. The ratios of the factors involved are weighted according to their importance. As a first approximation, the following is suggested:

$$W_2 = W_1 \cdot \frac{\Delta_2}{\Delta_1} \cdot \left(\frac{P_2}{P_1}\right)^{1/2} \cdot \frac{L_2/V_2}{L_1/V_1} \cdot \left(\frac{V_2}{V_1}\right)^3 \qquad (5)$$

$$\text{or } W_2 = W_1 \cdot \frac{\Delta_2}{\Delta_1} \cdot \frac{P_2}{P_1}^{1/2} \cdot \frac{L_2}{L_1} \cdot \frac{V_2}{V_1}^{2} \qquad (6)$$

where, W is the erosion rate,

Δ is the loading density,

P is the maximum pressure,

V is the muzzle velocity,

and L is the length of travel

The subscript 1 refers to the standard cannon (in this case, the 155mm Howitzer M185) and the subscript 2 refers to the unknown cannon.

To calculate the wear life of a tube, first calculate the average erosion rate of the standard tube at different stages of its erosion life, in terms of discrete percentages of diameter change due to erosion. Ten points (i.e. diameter changes) were selected on the graph of the diameter against the rounds fired on the 155mm M185. For each point, the observed cumulative diameter change was converted to percent of bore diameter. At these points, the cumulative diameter change was divided by the rounds fired to provide W_1 (standard).

Using equation (6), W_2 was then calculated for a series of cannon tubes for each percentage diameter change. The percentage diameter changes were then converted into the actual diameter changes for the cannon in question. The diameter changes were divided by the appropriate W_2, giving the number of rounds against a certain diameter change.

Equation (6) can thus be used to calculate the wear rate at the origin of rifling, for other artillery and tank cannon if the charges consist of M6 propellant without any coolant additive as in the M185.

To carry out a correction for propellant and additive, there are certain difficulties that must be stated first. In the cannon tubes of interest, the most common propellants are the M1, M6 and M30 or M30E1. M1 and M6 are both single base but M6 is about 200°C hotter whereas M30 or M30E1 are triple base and are about 350°C hotter than M6. The problem one is faced with is the total lack of any current comparative study of these three propellants from the erosion point of view. Hence, to arrive at any corrective factors, earlier studies had to be used. Two such studies are available; one conducted under the National Defense Research Committee[5] and the other a British Study[6]. Although these studies compared different propellants than those in general use presently, considering the temperature ranges only, the following corrective factors can be obtained:

Propellant factor (PF) for M30 and M30E1 = 2.5 x M6. That is, M30 and M30E1 propellants are 2.5 times as erosive as M6. Also the PF between M6 and M1 propellants is such that erosion for M6 is 3 times greater than for M1.

PF (M30 and M30E1) = 2.5 x M6

PF (M6) = 3 x M1

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[5] "Hypervelocity Guns and The Control of Gun Erosion" Summary Technical Report of Division I, NDRC Volume 1, OSRD #6, Washington, D.C. 1946.

[6] Abram, H.H. Williams, T., Allen, K.F., "Examination of Six Q.F. 17 Pr. Gun Barrels Used in Ballistic and Erosion Trials of Propellants of Various Composition and Flame Temperature", Armament Research Establishment Metallurgy Report 8/54, AD #31516 Woolwich, U.K. March 1954.

In the suggested equation, the wear rate, W_2, calculated from W_1 is to be multiplied by 2.5 if the propellant used is M30 or M30E1, and W_2 is to be divided by 3 if the propellant used is M1, since the basic data were developed for M6 propellant.

The Coolant Factor (CF) from the scanty previous data is taken to be 3, i.e., if the charge utilized a titanium dioxide jacket, then W_2 should be divided by 3. If no coolant was used, CF = 1. Therefore, the final form of the erosion equation is

$$W_2 = W_1 \cdot \frac{\Delta_2}{\Delta_1} \cdot \frac{P_2{}^{1/2}}{P_1} \cdot \frac{L_2}{L_1} \cdot \frac{V_2{}^2}{V_1} \cdot (PF) \cdot (CF) \qquad (7)$$

which can be combined to yield

$$W_2 = W_1 \cdot K \cdot \Delta_2 \cdot (P_2)^{1/2} \cdot L_2 \cdot (V_2)^2 \cdot (PF) \cdot (CF) \qquad (8)$$

where $K = (\Delta_1 \cdot (P_1)^{1/2} \cdot L_1 \times V_1{}^2)^{-1}$

c. Discussion

Considering the data calculated, the very first question to be considered is the wear limits assumed. As far as the calculations are considered, the terminal change of diameter does not necessarily represent the service life of the tube. The terminal values shown in these data represent a fixed percentage of their original nominal bore diameters. Only in the case of the 155mm M185 does it appear to be the limit for total service life. On the question of total service life, as stated earlier, due to varied criteria of condemnation, at this stage, it is impossible to prescribe a wear limit and thus service life of a particular design in terms of rounds fired. In general, the 105mm tubes have a wear limit of about 0.08 inch, and the 155mm tubes from 0.070 to 0.153 inches. In addition, in the 105mm M137 and the 155mm M126 howitzers, the condemnation limit due to fatigue is reached before the wear limit is reached. For the 175mm tube, the limit has been 0.2 inches and for the 8 inch XM201, it is not yet established, but indications are that it may be between 0.13 and 0.15 inches.

Data were calculated using the ballistic data from Table 1 and Equation 8. They are shown in Table 2 and Figures 1 and 2. The data for the 105mm M137 and for the 105mm M126 with Z7 charges are indicative of the general trend for cannon with very low rates of erosion. The wear data for the M126 XM119 charge are not established and this round was abandoned. Nevertheless, the calculated figures agree reasonably well with the scanty firing data reported. For the two inch XM201 rounds, although the wear limits are not yet established, the calculated rate seems to be fairly close to the initial reported firing data.

d. Second Equation

The firing data that indicated a large departure from those calculated were the 105mm XM205, the 155mm XM199 and the 175mm M113. To overcome these differences, equation 3 can be changed to enhance the effect of muzzle velocity. The new equation becomes

$$W_2 = W_1 \quad K^1 \; (\Delta_2) \quad (P_2{}^{1/2}) \quad (L_2/V_2) \quad (e^{\,2V_2}) \quad (PF) \quad (CF) \qquad (9)$$

where $K^1 = \dfrac{1}{(\Delta_1) \quad (P_1)^{1/2} \quad (L_1/V_1) \quad (e^{\,2V_1})}$

TABLE 1. BALLISTIC DATA

Weapon/Charge	Bore	W Wt. of Charge (Lbs.)	C Chamber Volume (Cu. in)	L Length of travel (In. x 10^2)	P Pressure (KSI)	V Muzzle Velocity (1000 ft/sec)	CF Coolant Factor	PF Propellant Factor	Propellant
M185/M119	155mm	20.4	1150	2.80	30.2	2.245	1	1	M6
M137/M67 Z7	105mm	2.8	153	1.10	36.7	1.621	1	1/3	M1
XM205	105mm	4.4	153	1.40	45.	2.170	1-1/3	2.5	M30A1
M68/Heat	105mm	11.5	369	1.86	60.5	3.850	1	2.5	M30
M126/M4A1 Z7	155mm	13.2	804	1.16	36.4	1.841	1	1/3	M1
M126/XM119	155mm	17.5	804	1.16	48.2	2.245	1	2.5	M30A1
XM199/XM123 Z8	155mm	26.6	1150	2.00	46.0	2.655	1/3	2.5	M30A1
M2 Gun/M119	155mm	30.9	1596	2.33	45.3	2.800	1	1	M6
M113/M86A2 Z3	175mm	57.2	2898	3.52	47.2	3.000	1/3	1	M6
XM201/Z9	8 Inch	43.6	1950	2.74	39.6	2.530	1/3	2.5	M30A1
Z8	8 Inch	38.0	1950	2.74	32.5	2.300	1/3	2.5	M30A1

TABLE 2. CALCULATED DATA (EQUATION 8)

155MM M185 Charge M119

No. of Rds.	Erosion in Inches
391	0.045
812	0.070
1217	0.088
1600	0.100
2000	0.110
2388	0.117
2801	0.121
3198	0.126
3542	0.130
4000	0.135

105MM M137 Charge M137 Z7

No. of Rds.	Erosion in Inches
2416	0.030
5015	0.047
7521	0.060
9886	0.068
12358	0.075
14754	0.079
17307	0.082
19760	0.085
21887	0.088
24716	0.091

105MM XM205

No. of Rds.	Erosion in Inches
247	0.030
513	0.047
770	0.060
1012	0.068
1265	0.075
1510	0.079
1771	0.082
2022	0.085
2240	0.088
2530	0.091

105MM M68 Heat-T

No. of Rds.	Erosion in Inches
16	0.030
32	0.047
48	0.060
64	0.068
79	0.075
95	0.079
111	0.082
127	0.085
141	0.088
159	0.091

155MM M126 M4A1 Charge Z7

No. of Rds.	Erosion in Inches
2960	0.045
6144	0.070
9204	0.088
12112	0.100
15140	0.110
18075	0.117
21203	0.121
24208	0.126
26814	0.130
30279	0.135

155MM M126 XM119 Z8

No. of Rds.	Erosion in Inches
174	0.045
362	0.070
543	0.088
714	0.100
892	0.110
1065	0.117
1250	0.121
1427	0.126
1580	0.130
1785	0.135

TABLE 2. CALCULATED DATA (EQUATION 8)(cont)

155MM XM199 Charge XM123 Z8

No. of Rds.	Erosion in Inches
209	0.045
434	0.070
650	0.088
855	0.100
1068	0.110
1275	0.117
1496	0.121
1708	0.126
1892	0.130
2137	0.135

155MM M2 Gun M19 Normal

No. of Rds.	Erosion in Inches
162	0.045
335	0.070
503	0.088
661	0.100
827	0.110
987	0.117
1158	0.121
1322	0.126
1464	0.130
1653	0.135

175MM M113 M86A2 Z3

No. of Rds.	Erosion in Inches
303	0.051
628	0.079
942	0.099
1239	0.113
1548	0.124
1849	0.132
2169	0.137
2476	0.142
2742	0.147
3097	0.152

8 Inch XM201 Z9

No. of Rds.	Erosion in Inches
245	0.059
508	0.092
762	0.115
1002	0.131
1253	0.144
1496	0.153
1755	0.159
2003	0.165
2219	0.170
2506	0.177

8 Inch XM201 Z8

No. of Rds.	Erosion in Inches
375	0.059
779	0.092
1168	0.115
1536	0.131
1920	0.144
2292	0.153
2689	0.159
3070	0.165
3401	0.170
3840	0.177

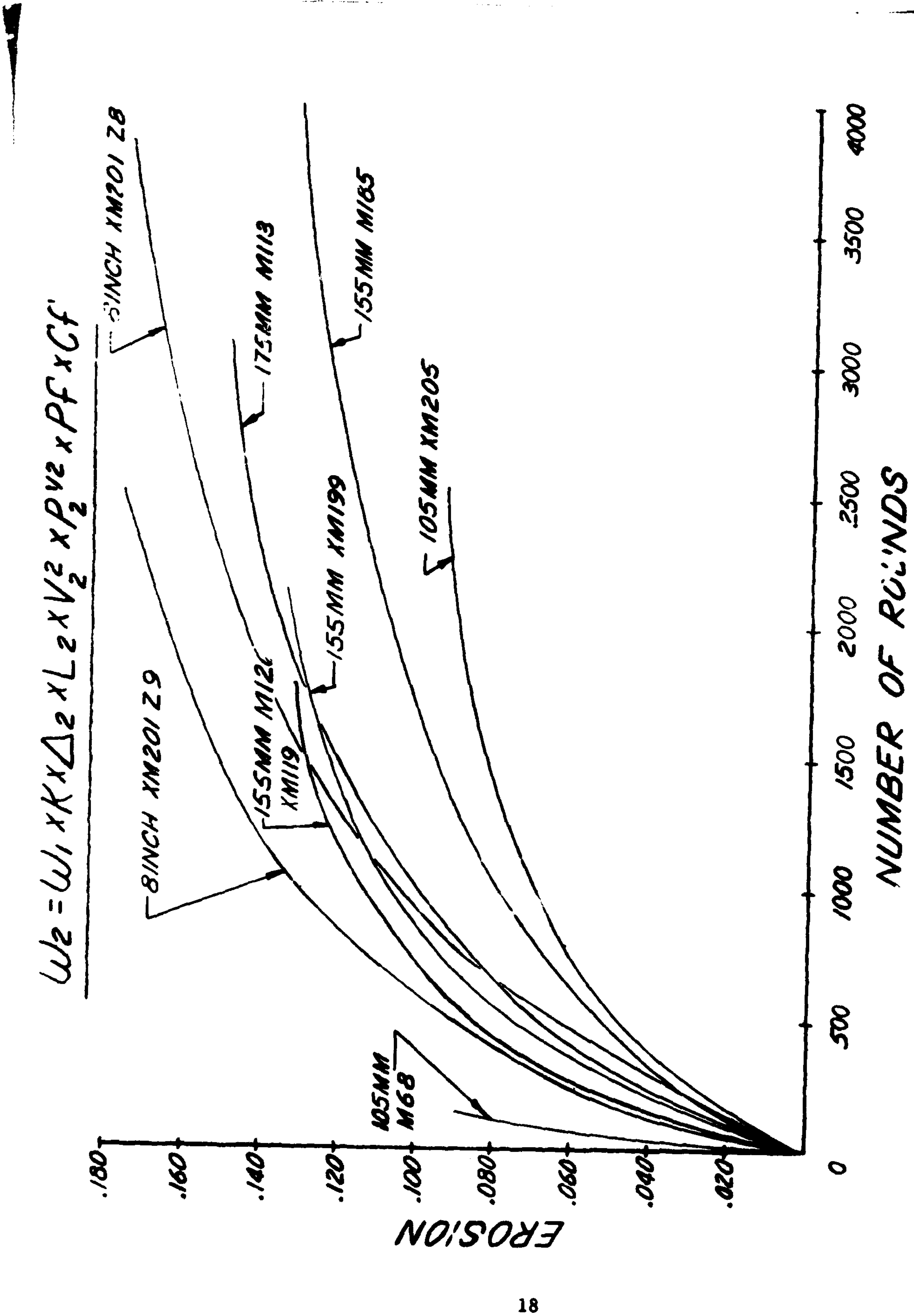

Figure 1. Erosion Life Curves (Calculated)(Equation 8)

$$W_2 = W_1 \times K \times \Delta_2 \times L_2 \times V_2^2 \times P_2^{1/2} \times Pf \times Cf$$

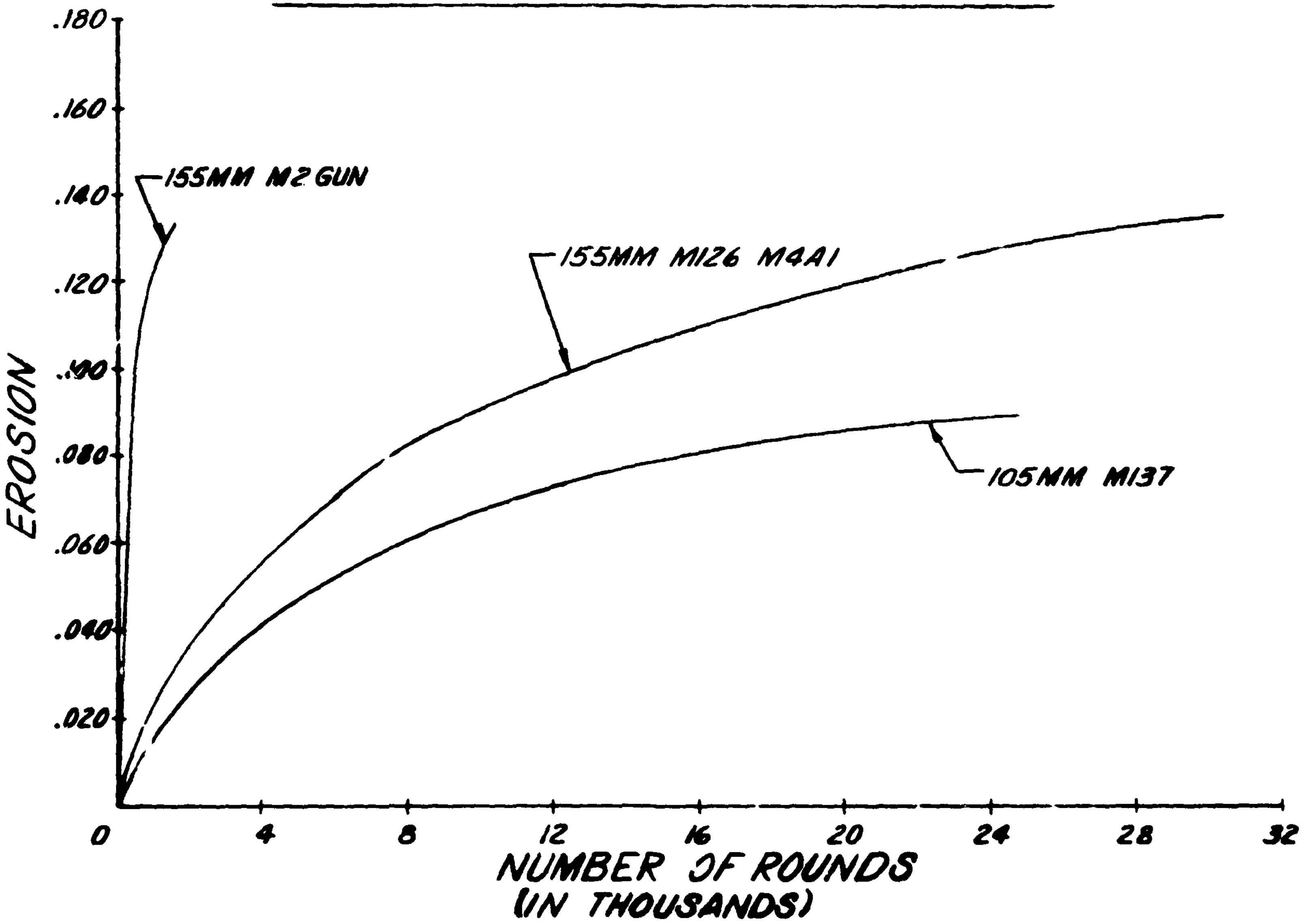

Figure 2. Erosion Life Curves (Calculated) (Equation 8)

e. Discussion

This equation was used to calculate the data in Table 3 and Figures 3-5. The results obtained are compared to the best available firing data in Table 4. The comparison indicates that the number of rounds for equivalent wear are higher for the M137 and the M126 over that of the first equation. For the XM205, the change is minor, i.e., a slight increase in rounds for a given amount of wear. All the others show a decrease in the number of rounds for a given amount of wear. For the XM199, at a diameter increase of 0.150 inches, the corresponding number of rounds are 2000 as against 3200 from the first equation and is much closer to the observed value of 2300 rounds. For the XM201, Zone 9, the value is about 1200 rounds at a diameter change of 0.15 inch whereas for Zone 8, the corresponding number of rounds is about 2200. Although no wear limit has been established as yet, indications are that for Zone 9, the wear limit will be about 0.15 inches. The results of firing of one plated XM201 tube shows the number of Zone 9 rounds against this erosion is about 1500. Similarly, for Zone 8, from firing data of two tubes*, the number of rounds fired for the same wear is 2500. The calculated value with equation (9) is not at all in agreement with the observed value of M68 Heat round where the calculated value is much lower. In fact, the calculated value from equation (8) is closer to the observed value. In the case of the M113 tube, the calculated value using equation (9) is not as high as in equation (8), but is still

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*One of the two tubes was chrome plated and the other unplated. At 2500 rounds the two tubes had eroded to about the same extent - 0.15".

TABLE 3. CALCULATED DATA (EQUATION 9)

155mm M185 Charge M119

No. of Rds.	Erosion in Inches
391	0.045
812	0.070
1217	0.088
1600	0.100
2000	0.110
2388	0.117
2801	0.121
3198	0.126
3542	0.130
4000	0.135

105mm M137 Charge M67 Z7

No. of Rds.	Erosion in Inches
3168	0.030
6576	0.047
0962	0.060
12964	0.068
16205	0.075
19347	0.079
22694	0.082
25911	0.085
28701	0.088
32410	0.091

105mm XM205

No. of Rds.	Erosion in Inches
259	0.030
539	0.047
808	0.060
1062	0.068
1327	0.075
1584	0.079
1859	0.082
2122	0.085
2350	0.088
2654	0.091

105MM M68 Charge, Heat T.

No. of Rds.	Erosion in Inches
3	0.030
7	0.047
10	0.060
13	0.068
16	0.075
19	0.079
23	0.082
26	0.085
29	0.088
32	0.091

155MM M126 Charge M4A1 Z7

No. of Rds.	Erosion in Inches
3661	0.045
7601	0.070
11399	0.088
14984	0.100
18730	0.110
22361	0.117
26231	0.121
29949	0.126
33173	0.130
37460	0.135

155MM M126 Charge XM119 Z8

No. of Rds.	Erosion in Inches
174	0.045
362	0.070
543	0.088
714	0.100
892	0.110
1065	0.117
1250	0.121
1427	0.126
1580	0.130
1785	0.135

TABLE 3. CALCULATED DATA (EQUATION 9)(cont)

155MM XM199 Charge XM123 Z8

No. of Rds.	Erosion in Inches
152	0.045
316	0.070
474	0.088
623	0.100
778	0.110
929	0.117
1090	0.121
1244	0.126
1378	0.130
1557	0.135

155mm M2 Gun M19 Normal

No. of Rds.	Erosion in Inches
103	0.045
214	0.070
322	0.088
423	0.100
529	0.110
631	0.117
740	0.121
845	0.126
936	0.130
1057	0.135

175MM M113 Charge M06A2 Z3

No. of Rds.	Erosion in Inches
160	0.051
331	0.079
497	0.099
653	0.113
816	0.124
975	0.132
1143	0.137
1305	0.142
1446	0.147
1633	0.152

8 Inch XM201 Z9

No. of Rds.	Erosion in Inches
198	0.059
412	0.092
617	0.115
811	0.131
1014	0.144
1211	0.153
1420	0.159
1622	0.165
1796	0.170
2028	0.177

8 Inch XM201 Z8

No. of Rds.	Erosion in Inches
362	0.059
751	0.092
1126	0.115
1489	0.131
1850	0.144
2208	0.153
2590	0.159
2957	0.165
3275	0.170
3699	0.177

TABLE 4. COMPARISON WITH FIRING DATA

	Observed Life Max. Wear in Inches at Rounds	Calculated Life Max. Wear in Inches at Rounds	
CANNON		EQUATION 8	EQUATION 9
105mm M137	Fatigue limited	.075/12500	.075/16000
105mm XM205	.04"/2000 (not yet established)	.075/1250	.075/1350
105mm M68 Heat	.075/125	.075/79	.075/16
155mm M126 Z7	.08"/7500 Fatigue limited	.080/8000	.080/9000
155mm M126 Z8	Not available	0.100/700	0.100/700
155mm XM199 Z8	.150/2300	0.150/3800	0.150/2100 extrapolated
155mm M2 Gun (Normal)	0.110/700	0.110/827	0.110/529
175mm M113	0.200/1200	0.200/> 4000 extrapolated	0.200/2400 extrapolated
8" XM201 Z9	0.15/1500 not yet established	0.15/1400	0.15/1200
8" XM201 Z8	0.1/2000 not yet established	0.15/2300	0.15/2200

$$W_2 = W_1 \times K \times \Delta_2 \times (L_2/V_2) \times (P_2)^{1/2} \times e^{2V_2} \times P_f' \times C_f'$$

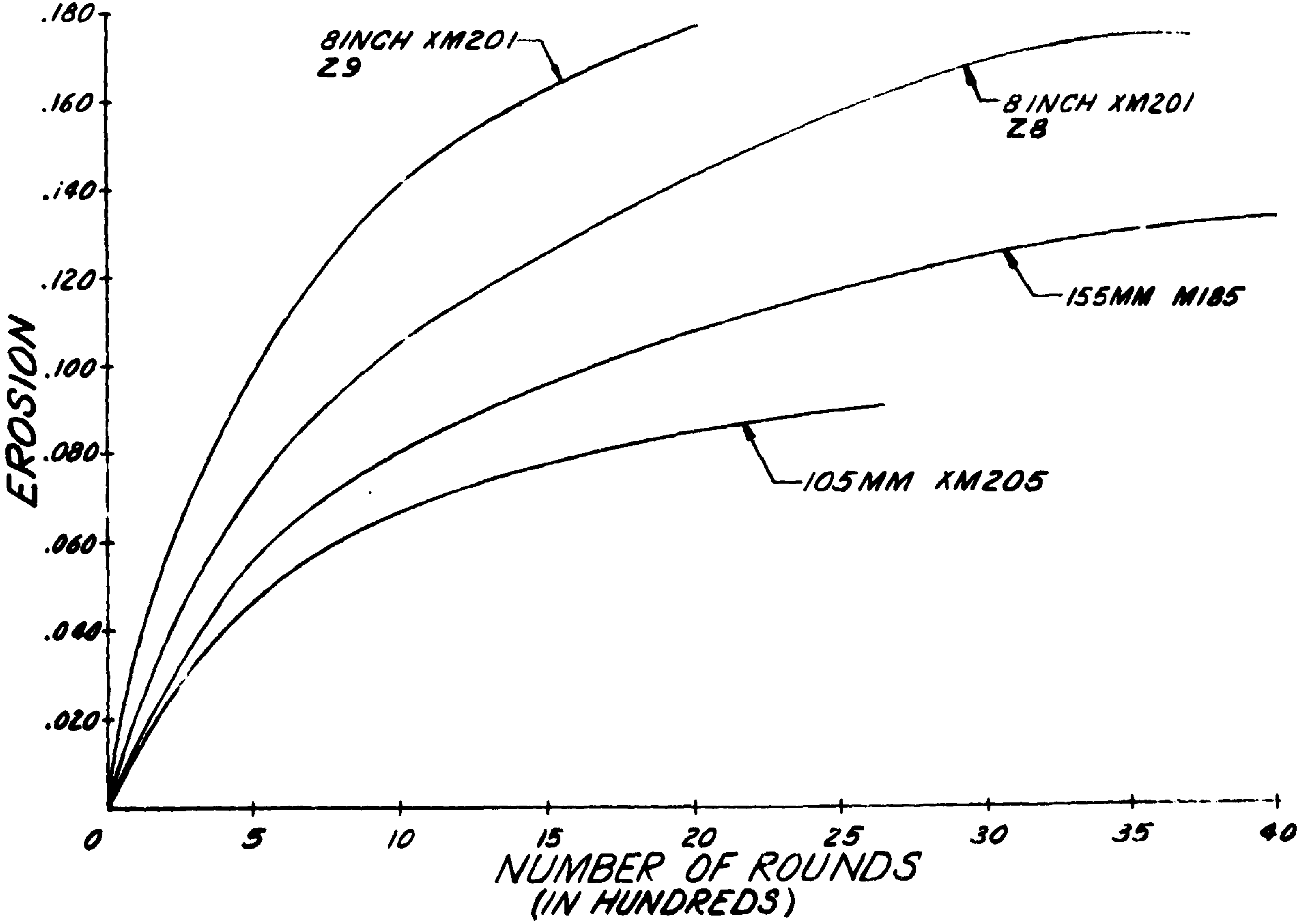

Figure 3. Erosion Life Curves (Calculated) (Equation 9)

$$W_2 = W_1 \times K \times \Delta_2 \times (L_2/V_2) \times (P_2)^{1/2} \times e^{2V_2} \times Pf' \times Cf$$

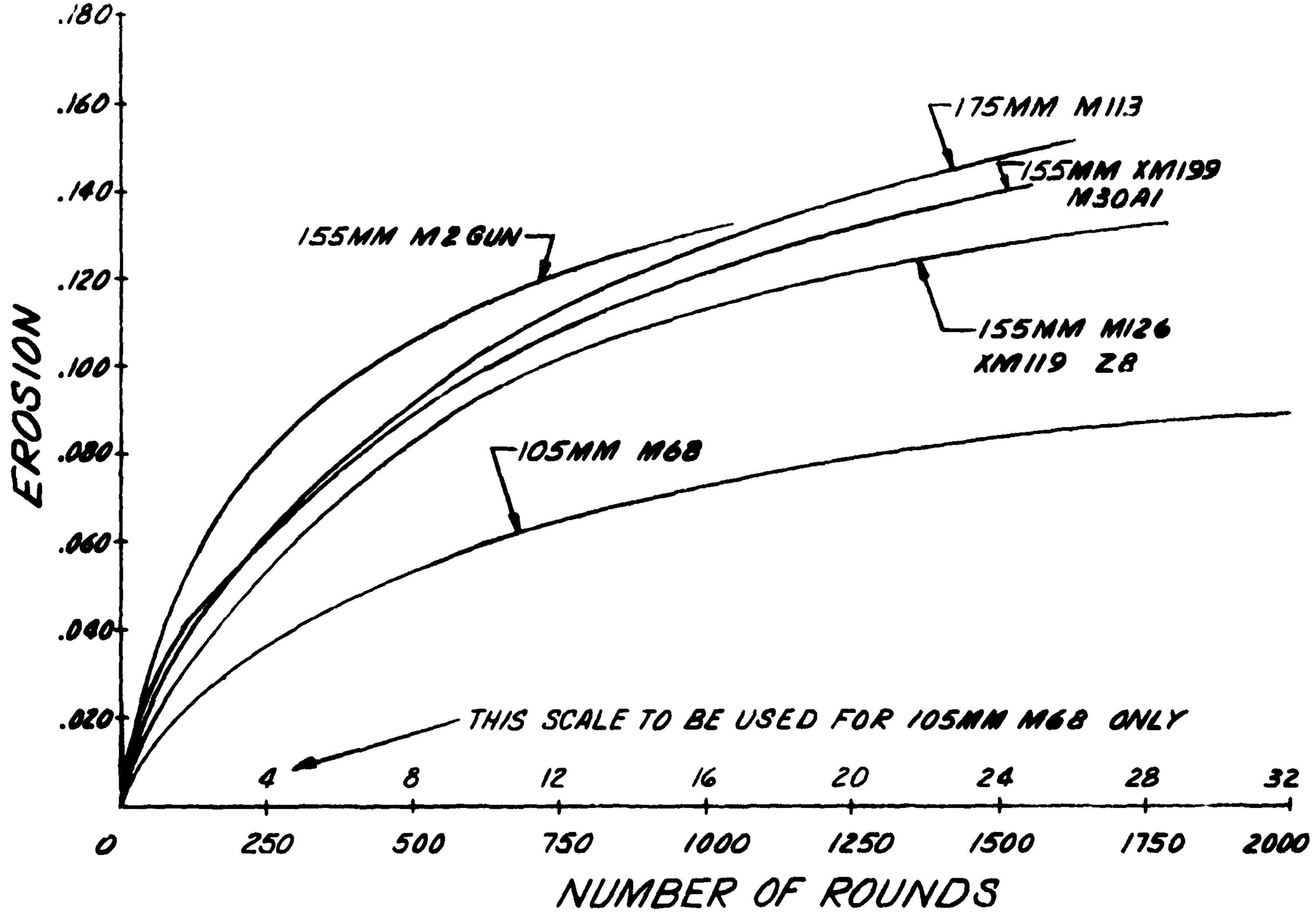

Figure 4. Erosion Life Curves (Calculated) (Equation 9)

$$W_2 = W_1 \times K \times \Delta_2 \times (L_2/V_2) \times (P_2)^{.12} \times e^{2V_2} \times Pf \times Cf$$

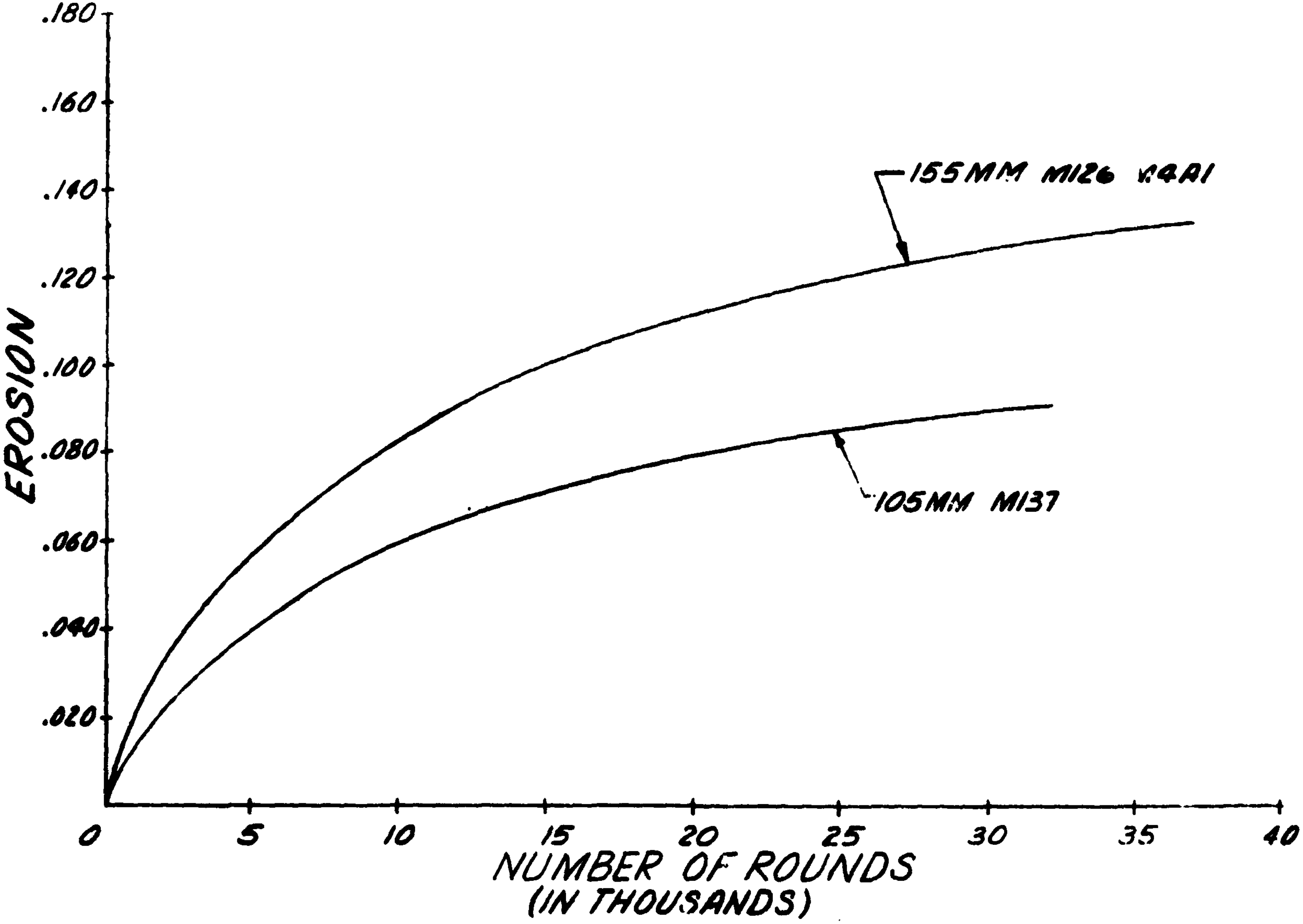

Figure 5. Erosion Life Curves (Calculated) (Equation 9)

about double the number of rounds actually observed.

There is a possible explanation for the discrepancy between actual and calculated values of the M113. The time factor for the firing cycle is included in the term L/V. The ratio obtained from this term between the standard gun (M185) and the M113 is about 7/9 i.e., 7ms length of cycle for the M185 and about 9ms for the M113. The data from the spin and setback tables indicates the time of cycle for Z3 M84 charge for M113 is about 21ms. The M185 is not listed in these tables. However, if the time cycle of the M126 XM119 charge is considered to be comparable with the M185, the time of cycle comes to about 9ms. Introducing this correction into the equation yields a value of about 1600 rounds for a wear of 0.2 inches. This is much closer to the observed value of 1200 rounds. On the same basis there will be a slight increase in the number of rounds of XM205 and M68 105mm cannon, but not enough to make the calculated values agree with the observed values.

f. Conclusion

Considering the overall performance, equation (9) seems to give a figure that is within 25% of the observed data, in the case of cannon that have a velocity below 2700 FPS, or better, where the ballistics are not drastically different from the standard tube, i.e., the M185. If the observed or properly calculated time for a firing cycle is introduced, a larger spectrum of weapons can be covered.

Another point to be noted is that the performance of the equation also depends implicitly on the similarity of projectile designs between the standard and any other system. It is possible that a correction for projectile engraving forces may improve the calculated results for the M68 heat round and the XM205 round, where the depth of rifling is only .030 as against 0.050 inches for the standard. But judging from the overall performance it may be stated that equation (9) provides a good estimate of erosion if used judiciously and can indicate, with some confidence, the nature of wear in a completely new cannon system.

In closing, this attempt should only be considered as a beginning of an investigation rather than as a final word. A considerable amount of verification and study is still needed.