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PREDICTION OF EROSION FROM HEAT TRANSFER MEASUREMENTS

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A review is made of existing empirical models for predicting erosion rates of large caliber guns. All the empirical models are based on a correlation between calculated bore surface temperature and the measured wear rate. This prompted an investigation into correlating measured total heat input with the erosion rate. A correlation was obtained even for rounds with different wear-reducing additives. Such rounds have nearly identical interior ballistics but differ in the amount of heat transferred to the barrel and the erosion rate. (Cont'd)

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20. Abstract (Cont'd)

It was also determined that by including muzzle velocity, a correlation for a number of large caliber guns was obtained. The empirical formula is

$$W = C\,Q^{18.9}\,V^{3.5}$$

where

W = erosion rate, μm/rd, x10^4,
Q = heat input per unit area, J/mm^2,
V = muzzle velocity, m/s,
and C = a constant equal to 1.50x10^{-11} for the units quoted above.

Below a critical heat input of approximately 0.8 J/mm^2, the empirical formula underestimates the observed erosion rate. This suggests the erosion mechanism for guns with such low heat inputs may change. The erosion rate for such guns is less than 0.0001 mm/rd. Wear-limited guns of current interest have heat inputs above the threshold values of 0.8 J/mm^2.

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I. INTRODUCTION

New Army propelling charges, developed to extend the range of howitzers, surprisingly exacted a price of high barrel erosion. To avoid such an unpleasant surprise in future gun developments, research has been directed to understanding the erosion well enough to formulate models that can predict the erosion rate of a hypothetical gun design. If successful, the necessary trade-offs can be made before engineering development.

The major difficulty in estimating tube life resulted from the introduction of "Swedish" additive, a 45/55 percent by weight mixture of titanium dioxide and wax, which increased the wear life of the 105mm M68 tank cannon from 100 to 10,000 rounds.[1] The existing formula for standard propelling charge designs could not include the additive effect and a simple transfer from gun to gun was attempted. It was assumed the introduction of the additive in the new howitzers would similarly extend wear life to at least the 5,000-10,000 round fatigue limit of the new cannons. The liner, however, increased the wear life by only a factor of three, not the expected hundredfold improvement.[2]

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1. *R. P. Grepps, J. W. Harris, S. B. Parkoff, and G. Negaard, "Final Report of Product Improvement Test of Ammunition Additive Effect on M41 and M68 Gun Tube Life", Developement and Proof Services Report No. DPS-1520, December 1964.*

2. *J. R. Ward, "A New Initiative in Gun Barrel Wear and Erosion", Proceedings of the Tri-Service Gun Tube Wear and Erosion Symposium, March 1977.*

In an effort to learn the factors controlling the efficiency of the wear-reducing liners, heat transfer measurements have been used[3-8]. This report summarizes how such heat transfer data have been correlated with measured known erosion rates. In addition, a short review is made of existing empirical methods to predict erosion or tube life. Such methods are still useful, since they require parameters which can be estimated from interior ballistic calculations rather than experimental measurements of heat transfer to barrels.

II. EXISTING MODELS

The earliest model[9], developed by Jones[10] in 1911, predicted the accuracy life of a gun barrel by computing the heat transferred to the barrel up to maximum chamber pressure. Jones's formula is

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3. *T. L. Brosseau and J. R. Ward, "Reduction of Heat Transfer to Gun Barrels by Wear-Reducing Additives", BRL Memorandum Report No. 2464, March 1975.* AD #B003850L

4. *F. A. Vassallo, "Heating and Erosion Sensing Techniques Applied to the Eight-Inch Howitzer", 12th JANNAF Combustion Meeting, Vol 1, CPIA Publication 273, December 1975.*

5. *F. A. Vassallo, "An Evaluation of Heat Transfer and Erosion in the 155mm M185 Cannon", Calspan Technical Report No. VL-5337-D-1, July 1976.*

6. *T. L. Brosseau and J. R. Ward, "Reduction of Heat Transfer in 105mm Tank Gun by Wear-Reducing Additives", BRL Memorandum Report No. 2698, November 1976.* AD #B015308L

7. *J. R. Ward and T. L. Brosseau, "Effect of Wear-Reducing Additives on Heat Transfer into the 155mm M185 Cannon, "BRL Memorandum Report No. 2730, February 1977.* AD #A037374

8. *T. L. Brosseau and J. R. Ward, "Measurement of Heat Input into the 105mm M68 Wear-Reducing Additives", BRL Technical Report ARBRL-TR-02056, April 1978.* AD #A056368

9. *J. S. Burlew, "The Erosion of Guns Part Two: The Characteristics Of Gun Erosion", NDRC Report No. A-91, October 1942.*

10. *H. J. Jones, "The Erosion of Gun Tubes and Heat Phenomena in the Bore of a Gun", Engineer, III, 294, 317, 380, 399 (1911).*

$$N = \frac{A}{V^2 d\ (d-2)\ (P)^{1.7}}, \qquad (1)$$

where N = tube life,
V = muzzle velocity,
d = bore diameter,
P = maximum chamber pressure,
A = constant.

The Navy predicted tube life by Schulyer's 1928 scheme in which the erosion rate was estimated from[11]

$$\log E = \log A - 1.54 \log \ell - 16.4 \log d + 12.0 \log V + 6.0 \log M, \qquad (2)$$

where E = wear measured one inch forward of the origin of rifling,
ℓ = projectile travel,
d = bore diameter,
V = muzzle velocity,
M = projectile weight,
A = empirical constant.

Schulyer's formula was combined with an empirical expression relating wear to tube life as follows

$$N = 0.1080\ d^{2/3}/E. \qquad (3)$$

The Navy modified Schulyer's formula since some experimental data suggested the erosion rate was independent of projectile weight at constant muzzle velocity. The Navy formula for barrel life was then modified in 1939 to

$$\log N = 6.35 + 0.03\ \ell - 0.82 \log d - 0.001611\ V\ (2M/d^3)^{1/2}.$$

In 1939 Kent[12] devised a formula that, unlike the Navy formula, included the maximum chamber pressure. Kent's formula for predicting tube life is

$$N = 10.26 \times 10^{19}\ d^{3.575}\ K^{-1.705}\ P^{-1.761}, \qquad (4)$$

where N = accuracy life,
d = bore diameter,
K = muzzle velocity,
P = maximum chamber pressure.

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[11] *G. L. Schulyer, "Erosion, A General Formula for, in U. S. Navy Guns", Bur. Ordnance Memo. S72-4/11/77, December 1928.*

[12] *R. H. Kent, "A Formula for the Accuracy Life of a Gun", BRL Report No. 133, March 1939.* AD #491792

When Burlew[9] applied the various schemes to a number of guns, he concluded that none was adequate. Kent's model consistently predicted high. The Navy formula only worked well for guns over 5-inch caliber; it underestimated wear life of smaller caliber anti-aircraft guns.

Despite the extensive work during World War II, no further progress was made in empirical formulas for erosion. However, calculated heat transfer to the bore surface[13-15] became the basis for the later empirical formulas.

Jones and Breitbart[16-18] used Nordheim's[14] methodology to compute the heat transferred to the gun barrel as a function of time. They came to the following expression

$$W = K\left(\frac{\Delta\ell}{R}\right)^2 \left[\frac{P^2-(16{,}000)^2}{P^3}\right], \qquad (5)$$

where W = wear rate,

Δ = density of loading,
ℓ = projectile travel,
R = expansion ratio,
P = maximum chamber pressure,
K = empirical constant.

The empirical constant was found from fitting wear data to equation (5). It was found that a single value of K would not fit data for both guns and howitzers.

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13. *J. O. Hirschfelder, W. Garten, and O. Hougen, "Heat Conduction, Gas Flow, and Heat Transfer in Guns", National Defense Research Committee Report A-87, August 1942.*

14. *L. W. Nordheim, H. Soodak, and G. Nordheim, "Thermal Effects of Propellant Gases in Erosion Vents and Guns", National Defense Research Committee Report A-262, March 1944.*

15. *J. Corner, Theory of the Interior Ballistics of Guns, Wiley and Sons, Inc., New York, 1950.*

16. *R. N. Jones and S. Breitbart, "On the Estimation of Gun Life", BRL Memorandum Report No. 497, October 1949.* AD #802139

17. *R. N. Jones and S. Breitbart, "A Thermal Theory for Erosion of Guns by Powder Gases", BRL No. 747, January 1951.* AD #801741

18. *S. Breitbart, "A Simplified Method for Calculating Erosion in Guns", BRL Memorandum Report No. 549, June 1951.* AD #802073

The next empirical scheme was devised by Riel[19] to estimate effective full charge (EFC) factors for new hypervelocity guns such as the 105mm M68 tank cannon. Using firing data collected at Aberdeen Proving Ground, Riel concluded the EFC factor could be computed relative to that of a standard round by

$$\mathrm{EFC} = (P/P_o)^{0.4}\,(C/C_o)^{2}\,(V/V_o)\,(K/K_o), \tag{6}$$

where EFC = equivalent full charge factor,
P = chamber pressure,
C = charge weight,
V = muzzle velocity,
K = specific energy of propellant.

The subscript refers to the standard charge and projectile which is assigned an EFC of unity. Riel's formula was generally used to estimate useful life of low-zone charges when data was available for the most erosive round. Holwager[20] prepared the latest revised list of EFC factors based on calculations with Riel's formula.

In the meantime, United Kingdom (U. K.) investigators were devising a formula for predicting the erosion rate based on work done on World War II by Hicks and Thornhill[15] who reported that the maximum temperature rise at the commencement of rifling could be determined by:

$$\Theta = \frac{T_o - 300}{1.7 + 0.38 d^{1/2} \left(\frac{d^2}{c}\right)^{0.86}}, \tag{7}$$

where Θ = maximum temperature rise at the commencement of rifling,
T_o = adiabatic propellant flame temperature,
d = bore diameter,
c = charge mass.

The U. K. investigators found the wear rate could be correlated to Θ by

$$\frac{W}{\sqrt{d}} = a e^{b\Theta}, \tag{8}$$

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[19] *R. Riel, "An Empirical Method for Predicting Equivalent Full Charge (EFC) Factors for Artillery Ammunition", DPS Report No. 217, July 1961.*

[20] *D. D. Holwager, "Tables of EFC Factors and Percent Remaining Life for Gun, Howitzer, and Recoiless Rifle Tubes", DPS Report No. 813, January 1963.*

where W = wear/round,
d = bore diameter,
Θ = maximum temperature rise at commencement of rifling, equation (7),
a, b = constants.

In 1967 Frankle and Kruse[21] applied equation (8) to a number of Army cannons where they discovered that it provided a reasonable fit to the wear data. Table I illustrates the agreement. The constants, a and b, were determined from a least-squares fit of log $(W/\sqrt{d})$ vs Θ using data in Table II. Frankle and Kruse noted that equation (8) provided a better match to the data than did Jones and Breitbart's formula (equation 5).

Frankle and Kruse also extended the U. K. expression to compute service life by replacing the term, $W/\sqrt{d}$, by, L, the service life. Again, the constants, a and b, were determined from a least-squares fit of log L vs Θ through the available data. Table III summarizes the agreement. After trying Kent's formula (equation 4) and variations of Riel's method (equation 6) Frankle and Kruse adopted the U. K. formula for estimating service life because it gave the best fit to the data listed in Table II.

It is interesting to note that the formula overestimated the service life of the M68 tank cannon by almost a factor of four. The service life is based on firing the M392 APDS projectile, while the service life for the other cannons is based on firing standard, full-bore projectiles with metal rotating bands. The high estimate of service life for the M68 cannon may reflect that the discarding-sabot round, the M392, cannot tolerate as much barrel erosion as standard, metal-banded projectiles.

A major deficiency in the empirical models is their inability to account for the presence of wear-reducing additives. Effectiveness varied from gun to gun and different additives yielded different service life increases in the same gun. A review[22] of such data on wear-reducing additives summarizes these points. Rosenberger[23] tried to modify the Frankle-Kruse formula by introducing an improvement factor, IF, to account for the presence of the TiO_2-wax liner. From a summary of

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[21] *J. M. Frankle and L. R. Kruse, "A Method for Estimating the Service Life of a Gun or Howitzer", BRL Report No. 1852, June 1967.*
AD #A021389

[22] *A. C. Alkidas, M. Summerfield, and J. R. Ward, "A Survey of Wear-Reducing Additives and of the Mechanisms Proposed to Explain Their Wear-Reducing Action", BRL Memorandum Report No. 2603, March 1976.*
AD #B010280L

[23] *W. F. Rosenberger, "Method for Predicting Wear in Cannon Tubes Firing Ammunition with Titanium Dioxide Wear Reducing Additive", Watervliet Arsenal Technical Memorandum 1-21-73, June 1973.*

TABLE I. COMPARISON OF OBSERVED AND CALCULATED WEAR*/**

Cannon	Θ,K	$W/\sqrt{d}$, obs, $mm^{1/2}$, $x10^5$	$W/\sqrt{d}$, calc, $mm^{1/2}$, $x10^5$	W calc/W obs
37mm Gun, M1A2	713	14.82	11.60	0.78
37mm Gun, M3	946	42.34	70.94	1.68
37mm Gun, M4	507	9.89	2.35	0.24
75mm Gun, M3	567	1.26	3.75	2.98
75mm Gun, M35	720	12.41	12.29	0.99
76mm Gun, M1	743	8.73	14.63	1.68
76mm Gun, M48	979	83.13	91.74	1.10
90mm Gun, M1	804	14.24	24.02	1.65
90mm Gun, M3	833	19.95	29.64	1.49
90mm Gun, M41	1003	75.34	110.50	1.47
105mm How, M2A1	400	0.87	1.02	1.18
105mm Gun, M68	1000	185.91	107.82	0.58
120mm Gun, M1	919	111.59	57.50	0.52
120mm Gun, M58	1141	232.47	332.72	1.39
155mm How, M1A1	535	1.63	2.91	1.78
155mm Gun, M2	815	32.06	25.62	0.80
175mm Gun, M113	888	96.00	45.23	0.47
8in How, M2	549	4.46	32.56	0.73
8in Gun, M1	919	91.64	57.50	0.63
240mm How, M1	765	16.08	17.41	1.08

*Table II in reference 21 converted to metric units.

**Calculated with equation (8) with $a = 9.09x10^{-8}$ $in^{1/2}$ and $b = 0.00777\ K^{-1}$; to convert equation (8) to metric units, $a = 4.58x10^{-7} mm^{1/2}$.

TABLE II. WEAR, SERVICE, AND INTERIOR BALLISTIC DATA FOR U.S. ARMY GUNS AND HOWITZERS*

Gun or Howitzer	Wt. of Propellant Charge, kg	Type of Propellant	Adiabatic Flame Temp. of Propellant, K	Avg. Wear Per Round, mm, $x10^4$	Service Life (Rounds)
37mm Gun, M1A2	0.128	M2	3372	9.02	2000
37mm Gun, M3	.250	M5	3294	25.76	700
37mm Gun, M4	.070	M2	3372	6.02	3000
75mm Gun, M3	.902	M6	2583	1.09	4700
75mm Gun, M35	1.535	M6	2583	10.74	1300
76mm Gun, M1	1.734	M6	2583	7.62	3000
76mm Gun, M48	2.421	M17	2974	7.26	350
90mm Gun, M1	3.309	M6	2583	13.51	2800
90mm Gun, M3	3.688	M6	2583	18.92	2000
90mm Gun, M41	4.014	M17	2974	71.48	700
105mm How, M2A1	1.283	M1	2433	0.89	20,000
105mm Gun, M68	5.483	M30	3040	190.5	100
120mm Gun M1	10.603	M6	2583	121.5	500
120mm Gun, M58	13.350	M17	2974	254.0	250
155mm How, M1A1	5.982	M1	2433	2.03	15,000
155mm Gun, M68	13.999	M6	2583	39.90	700
175mm Gun, M113	25.202	M6	2583	127.0	400
8in How, M2	12.723	M1	2433	6.35	6000
8in Gun, M1	14.851	M6	2583	130.6	700
240mm How, M1	36.174	M6	2583	24.89	2000

**Table I in reference 21 converted to metric units.*

TABLE III. COMPARISON OF OBSERVED AND CALCULATED SERVICE LIFE*/**

Gun or Howitzer	Θ,K	L_{obs}, rounds	L_{calc}, rounds	L_{calc}/L_{obs}
37mm Gun, M1A2	713	2000	2234	1.12
37mm Gun, M3	946	700	527	0.75
37mm Gun, M4	507	3000	7960	2.65
75mm Gun, M3	567	4700	5489	1.17
75mm Gun, M35	720	1300	2132	1.64
76mm Gun, M1	743	3000	1856	0.62
76mm Gun, M48	979	350	430	1.23
90mm Gun, M1	804	2800	1271	0.45
90mm Gum, M3	833	2000	1057	0.53
90mm Gun, M41	1003	700	370	0.53
105mm How, M2A1	400	20,000	15,451	0.78
105mm Gun, M68	1000	100	378	3.78
120mm Gun, M1	919	500	623	1.25
120mm Gun, M58	1141	250	158	0.63
155mm How, M1A1	535	15,000	6727	0.45
155mm Gun, M2	815	700	1188	1.70
175mm Gun, M113	888	400	755	1.89
8in How, M2	549	6000	6149	1.02
8in Gun, M1	919	700	623	0.89
240mm How, M1	765	2000	1616	0.81

**Table IV in reference 21.*

***Calculated from equation (8) with $a = 1.84x10^5$ rounds and $b = -0.00619\ K^{-1}$.*

erosion data illustrated in Table IV, Rosenberger concluded that the improvement factor could be correlated to muzzle velocity. A regression analysis produced the following expression as an estimate of the improvement factor

$$\ln (IF) = b_0 + b_1 V + b_2 V^3, \tag{9}$$

where $b_0 = 3.22$,
$b_1 = -0.132 \times 10^{-2}$,
$b_2 = 0.688 \times 10^{-10}$.

When Rosenberger noted that the improvement factor predicted at the lower velocities was lower than three, he suggested that an improvement factor of 2.7 be used for weapons with a muzzle velocity below 2500 ft/s (820m/s).

Although Rosenberger's analysis fits the data in Table IV, the method of predicting improvement factors may be limited. Recent experiments have illustrated how the additive's effectiveness depends on positioning in the cartridge case. Removing the flaps on the additive in the M392A2 APDS projectile reduced the service life from 10,000 to 1,000 rounds[2]. Furthermore, the improvement factor for the TiO_2-wax additive in the 60mm medium-caliber, automatic, anti-armor cannon was only three[24], although the muzzle velocity is similar to that for the APDS projectile fired from the M68 tank cannon.

The latest empirical model was devised by Smith and O'Brasky at the Naval Surface Weapons Center's Dahlgren Laboratory[25]. They noted that earlier bore surface temperature measurements[26,27] of a 5"/54 gun firing various propellants could be related to the known erosion rate by

$$W = Ae^{\alpha T_w}, \tag{10}$$

where W = erosion rate,
T_w = bore surface temperature,
A, α = contants.

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[24] *G. Samos, B. B. Grollman, and J. R. Ward, "Barrel Erosion Rate of a 60mm Gun", BRL Memorandum Report No. 02857, August 1978.* AD #A059804

[25] *C. S. Smith and J. S. O'Brasky, "A Procedure for Gun Barrel Erosion Life Estimation", Proceedings of the Triservice Symposium on Gun Tube Wear and Erosion, March 1977.*

[26] *C. W. Morris, "Bore Surface Temperature Phenomena in 5"/54 Guns", NWL Technical Report No. 2829, 1973.*

[27] *C. W. Morris, "Bore Surface Coolants in 5"/54 Guns", NWL Technical Report No. 3028, 1973.*

TABLE IV. EFFECTIVENESS OF WEAR-REDUCING ADDITIVES*

Weapon	Muzzle Velocity, m/s	Service Life	Service Life with Additive	Improvement factor
90mm M41 (AP)	914.4	700	2,100	3
90mm M41 (HEAT)	1204	240	3,000	12.5
105mm M68 (APDS)	1478	100	10,000	100
105mm M68 (HEAT)	1173	125	1,100	8.8
120mm M58 (HEAT)	1143	350	1,750	5
155mm M126 (ZONE 8)	684.3	700	2,100	3
175mm M113 (ZONE 3)	914.4	400	1,100	2.75

Constructed from Tables II and III in reference 23.

The Navy workers used Nordheim's[14] method for computing bore surface temperature. With a computerized version of Nordheim's equations, Smith and O'Brasky used multiple-regression techniques to find the functional dependence on charge weight, bore diameter, peak pressure, and propellant adiabatic flame temperature. Since Naval guns frequently fire bursts with a rate of a round per second, the effect of rate of fire was also included.

To account for the wear-reducing additive, Smith and O'Brasky reduced the adiabatic flame temperature by 500K. This came from experiments in which it appeared that rounds with talc-wax liners and M26 propellant were as erosive as rounds loaded with M6 propellant and no liner.[28] Smith and O'Brasky recognized that the wear-reducing liners were less efficient in Army bag charges, so a flame-temperature reduction of 300K was suggested for separately-loaded Army guns.

Smith-O'Brasky's model is outlined below.

1. Calculate cold wall temperature,

$$T_w = 1.096 \frac{(T_f - \Delta T_c - 600)}{d} (CP)^{1/2} , \qquad (11)$$

2. Calculate wall temperature from previous rounds during burst fire,

$$T_i = 0.4632 \, (T_f - \Delta T_c - 600) \, C^{0.75} \, (N-1)^{0.6} \, R^{0.5} / d^{1.5}, \qquad (12)$$

3. Compute wear rate,

$$W = 0.4216 \, \text{EXP} \, (0.0049 \, (T_w + T_i)), \qquad (13)$$

where W = wear rate mm/round, $\times 10^4$,
T_f = adiabatic propellant flame temperature, K,
ΔT_c = correction for additive, 500K for cased rounds, 300K for bag charges,
C = charge mass, kg,
P = peak chamber pressure, MPa,
d = bore diameter, mm,
R = effective firing rate, rounds/minute,
N = effective number of rounds fired.

For a single burst or a period of steady firing, R is the actual firing rate, and N is half the number of rounds fired. For multiple bursts, R is the firing rate in one burst. One can also use the average firing rate including time between bursts. N is then the number of rounds fired.

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[28] *M. C. Shamblen, "Overview of Erosion in U.S. Navy Guns", Proceedings of the Tri-Service Gun Tube Wear and Erosion Symposium, March 1977.*

For Army application T_i is typically zero, but special attention has been paid to the multiple-round aspect of the Smith-O'Brasky model, since two Army guns, a 75mm cannon and a 155mm self-propelled howitzer will fire short bursts. Smith and O'Brasky's model is the only tool available to estimate the impact of high firing rate on the erosion of these cannons.

From this review it is clear that attempts to estimate gun barrel erosion and gun barrel service life have been evolving since 1911. The principal advantage of these empirical techniques is that no experimental data are needed to make the estimate other than peak chamber pressure or muzzle velocity which can be estimated from interior ballistics predictions. The major barrier lies in the wear-reducing additives. The reduction in flame temperature suggested by Smith and O'Brasky gives an estimate of what erosion reduction one can expect from an additive, but their formula cannot account for differences in erosion seen among various additives. Although the heat transfer measurements at BRL and Calspan[3-8] can discern the differences between additives, the heat transfer measurements cannot predict what the erosion rate will be after a modification to the additive is made. Since the heat transfer measurements can detect the apparently subtle differences between the additives, the decision was made to try to correlate heat transfer measurements with erosion rates for rounds with additives. This was possible because only recently have rounds with TiO_2-wax additive been fired successively to find the minimum heat input that corresponds to the erosion rate measured in barrel service life tests[8]. The pertinent data are summarized in Table V.

The results in Table V illustrate the strengths and weaknesses of assessing wear-reducing liners by measuring heat input. The advantage is that the relative efficency of the additive can be inferred from the measurement of heat input. This conclusion comes from the obvious correlation between decreasing heat input and lower wear rates. One sees, however, that only rounds with similar interior ballistics can be compared. For example, one would conclude polyurethane foam in the M392 round would have the same wear rate as the HEAT round with a TiO_2-wax liner (416 vs 412 J/mm^2). The other limitation is that a new additive which yields a heat input for which no corresponding wear data is available can only be ranked qualitatively against an existing additive design for which both heat input and erosion data are available.

To extend the utility of the heat transfer technique, an empirical analysis was made with the data in Table V to see if a general expression could be found to correlate heat input and erosion rate. It was thought that a correction for muzzle velocity was needed to extend the correlation to projectiles with different interior ballistics. It appeared from the M392 and M456 results that for a given level of heat input, the erosion is higher for the round with higher velocity. Intuitively this is not surprising, since the heating time is less for the higher velocity round; hence the flux will be higher. A calculation performed by Nordheim[14] gives a more quantitative basis for the idea that higher

TABLE V. HEAT TRANSFER AND EROSION IN 105mm M68 CANNON FIRING ROUNDS WITH ADDITIVES

Cartridge	Additive	Heat Input, J/mm^2	Erosion, μm/rd	Reference
M392A1	none	449	18	*
M392A2	polyurethane foam	416	4.1	**
M392A2	TiO_2/wax (flaps)	348	0.18	*
M456	none	471	15	***
M456A1	TiO_2/wax	412	1.8	*

**Reference 1.*

***R. Wolff, "Reduction of Gun Erosion-Part I. Laminar Coolant", Picatinny Arsenal Technical Report No. 3096, May 1963.*

****"Evaluation of Cannon Tubes", TM-9-1000-202-35, Department of the Army, November 1969.*

velocity rounds will give higher bore surface temperatures. Nordheim computed the heat input and maximum bore surface temperature for a 37mm gun firing a standard projectile, a projectile with one-half the original mass, and a projectile with one-fourth the original mass. The propellant mass was kept constant in all three instances; the assumption was made that the web size of the propellant had been adjusted to keep peak chamber pressure constant. The results of Nordheim's calculations are summarized in Table VI. The high-velocity, 168g projectile has the highest bore surface temperature.

In addition to the M68 tank cannon results in Table V, heat input and wear data were available from the 155mm M185 cannon experiments[7]. Since only single-shot heat input measurements were made in the M185 cannon, only wear data for the charges without the additive forming an insulating layer, i.e. the M119 charge, could be used. In order to use heat input from various guns, the heat input measured by Brosseau's technique is converted to unit area by dividing the heat input by the bore perimeter. The bore perimeter may be determined from cannon drawings or be found in Heppner's report.[29]

The wear-reducing liner was placed in the M456 HEAT round early in its development, so the wear data for the HEAT round without additive is estimated from firings made during safety tests, plate-penetration tests, and time-of-flight tests with rounds conditioned at various temperatures[30-31]. No wear test was ever done with the HEAT round without liner. The M456 cartridge without liner was not used in determining the correlation among heat transfer, muzzle velocity, and wear rate in the absence of such a wear test. The data used in the correlation are present in Table VII.

From a graphical analysis of the data in Table VIII, there appeared to be a correlation of the form

$$W = c^{-a} Q^{a} V^{b}, \tag{14}$$

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[29] *L. D. Heppner, "Special Study of Setback and Spin for Artillery, Mortar, Recoiless Rifle, and Tank Ammunition", DPS Report No. 2611, January 1968.*

[30] *L. Lawson, "Engineering Test of Cartridges, HEAT, 105mm, T384E2", DPS Report No. 275, July 1961.*

[31] *R. P. Angstadt, "Safety Certification and Combined Ordnance-User Test of Cartridge, HEAT-FS, 105mm, T384E4", DPS Report No. 497, May 1962.*

TABLE VI. HEAT INPUT AND MAXIMUM BORE TEMPERATURES FOR 37mm GUN BY NORDHEIM'S METHOD

Projectile Mass, g	Charge Mass, g	Muzzle Velocity, m/s	Maximum Bore Temperature, K	Heat Input J/mm^2
670	182	792	953	0.494
335	182	1,067	1,023	.469
168	182	1,417	1,093	.448

TABLE VII. SUMMARY OF HEAT INPUTS AND EROSION RATES FOR ARMY GUNS

Cannon	Projectile	Cart. of Prop Charge	Additive	Muzzle Vel., m/s	Chamber Press., MPa	Heat Input*, J/mm^2	Erosion, μm/rd	Reference
105mm M68	M392E3	M392A1	none	1486	414	1.126	18	**
105mm M68	M392E3	M392A2	polyurethane	1486	414	1.043	4.1	***
105mm M68	M392E3	M392A2	TiO_2-wax	1486	414	0.873	0.18	**
105mm M68	M489	M490	TiO_2-wax	1174	410	1.033	1.8	**
155mm M185	M107	M119	none	684	206	1.103	0.8	†

Tank cannon results from reference 8; howitzer from reference 7.

***Reference 1.*

***R. O. Wolff, "Reduction of Gun Erosion-Part I Laminar Coolant", Picatinny Arsenal Technical Report No. 3069, April 1963.

†J. J. Read and J. P. Cherry, "Service Tests of 155mm Howitzer, Self-Propelled, Equipped with XM185 Tube", Field Artillery Board Report, January 1970.

TABLE VIII. COMPARISON BETWEEN EXPERIMENTAL WEAR RATES AND WEAR RATES CALCULATED WITH EMPIRICAL FORMULA

Round Description	Erosion, exptl, μm/rd	Erosion, calc, μm/rd
M392 (no additive)	18	18
M392 (polyurethane foam)	4.1	4.2
M392 (TiO_2-wax)	0.18	0.15
M456A1 (TiO_2-wax)	1.8	1.5
M119 charge	0.9	0.18

where W = wear rate, μm/rd,
Q = heat input, J/mm^2,
V = muzzle velocity, m/s,
c,a,b = constants.

To determine best-fit variables for c, a and b, a non-linear least-squares program[32] was used to fit the data in Table VII to equation (14). The calculated best-fit values of a, b, c turned out to be the following with the error expressed as the standard deviation

$$a = 18.9 \pm 0.5,$$
$$b = 3.5 \pm 0.08,$$
$$c = 3.74 \pm 0.2.$$

Table VIII compares the wear rates calculated with the best-fit values of a, b, and c in equation (14) with the experimental wear rates.

Figure 1 illustrates wear vs heat input along with the experimental values for the M392 projectiles, which show the range over which the empirical correlation applies.

To test the generality of the erosion formula, some calculations were made with guns for which both erosion data and heat inputs measured by other techniques were available[33,34]. The heat inputs measured by Bannister with a thermocouple mounted on the outside wall were revised upward. The correlation to Bannister's data was determined from a comparison between a 37mm round measured by both Bannister and Brosseau[35] using in-wall thermocouples.

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[32] *R. H. Moore and R. K. Ziegler, "The Solution of the General Least-Squares Problem with Special Reference to High-Speed Computers", Los Alamos Scientific Laboratory Report LA-2367, March 1960.*

[33] *E. L. Bannister, R. N. Jones, and D. W. Bagwell, "Heat Transfer, Barrel Temperatures and Thermal Strains in Guns", BRL Report No. 1192, February 1963.* AD #404467

[34] *F. A. Vassallo, "Heat Transfer and Erosion in the ARES 75mm High-Velocity Cannon", Calspan Technical Report No. VL-5645-D-1, October 1975.*

[35] *T. L. Brosseau, "An Experimental Method for Accurately Determining the Temperature Distribution in Gun Barrels", BRL Report No. 1740 September 1974.* AD #B000171L

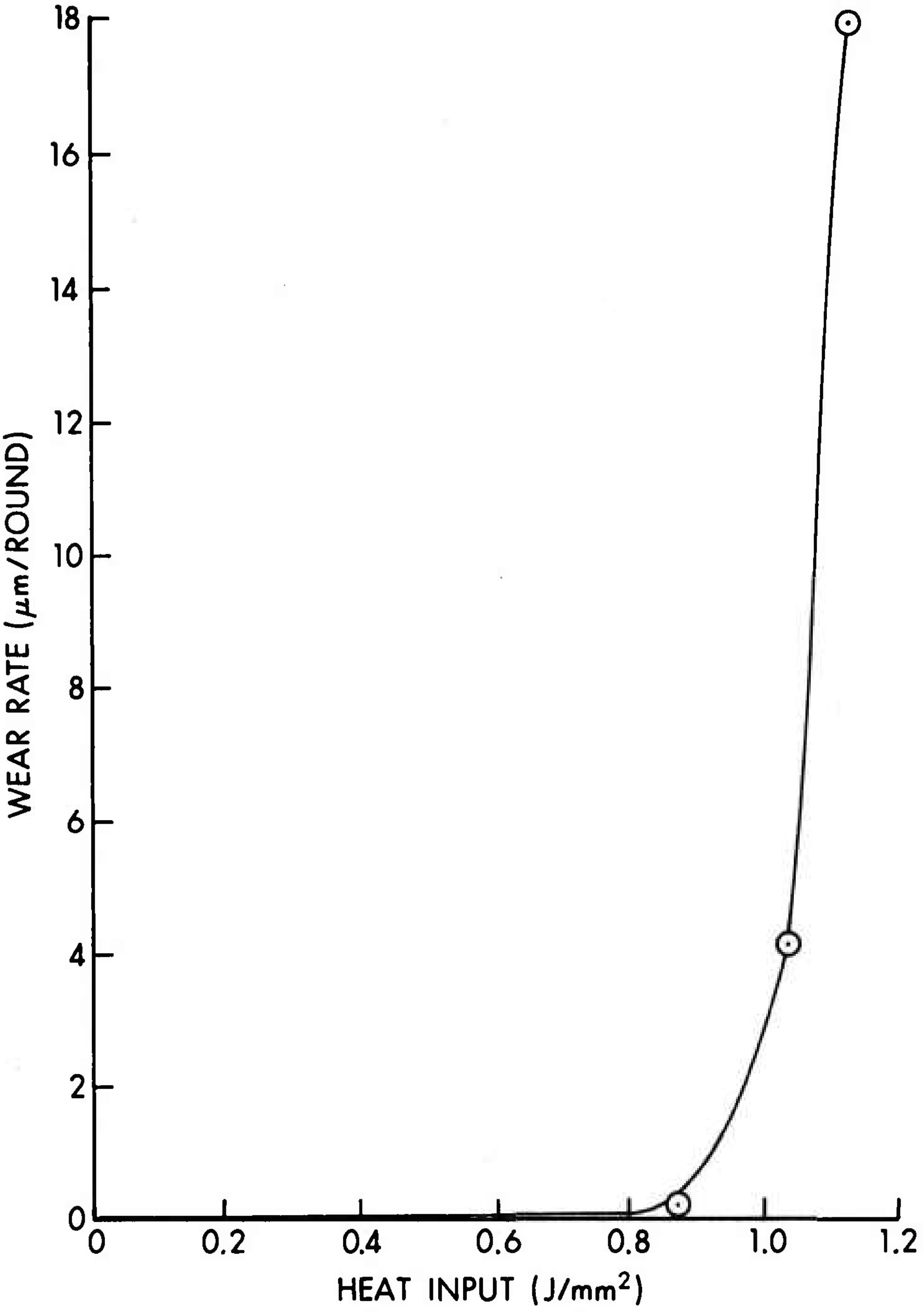

Figure 1. Wear rate *vs* heat input for M392 APDS projectiles.

The results of the computation are shown in Table IX. One sees reasonable agreement between computed and experimental wear for heat inputs above 0.8 J/mm^2. Equation (14) vastly underestimates erosion rates for the 20mm barrel[36]; it is likely equation (14) would overestimate erosion rates for guns with heat inputs above 1.2 J/mm^2.

Another problem with the strong dependence on heat input in equation (14) is that the wear for rounds which heat the barrel during ignition such as the base-ignited 155mm XM201 series of propelling charges will be overestimated. The heat accumulating in the barrel during ignition does not affect the wear, however, this heat is lumped together with the heat transferred convectively during projectile travel. The convective heating drives the bore surface temperature near the melting point.

III. CONCLUSION

An empirical expression has been devised that relates wear rate of a gun barrel as a function of heat input and muzzle velocity. Such an expression enables one to estimate the wear rate expected from various designs of wear-reducing liners for guns with heat inputs between 0.8 and 1.2 J/mm^2.

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[36] *R. Birkmire and A. Niiler, "Applications of the Radioisotope Wear Measurement Technique", BRL Report No. ARBRL-TR-02075, June 1978.* AD #A058307

TABLE IX. COMPARISON BETWEEN COMPUTED AND EXPERIMENTAL WEAR RATES

Gun	Projectile	Additive	Muzzle Velocity, m/s	Heat Input, J/mm^2	Erosion calc, μm/rd	Erosion exptl, μm/rd
20mm pressure barrel	M55	none	1055	0.322	3x10^{-10}	0.046
37mm M3	M51	none	884	1.17	6.4	6.6
37mm M3	M51	none	884	1.01	0.39	0.46
37mm M6	M51	none	884	1.115	2.5	2.5
75mm ARES	APFSDS*	none	1524	1.06	6.7	6.8
75mm ARES	APFSDS*	110g ablative	1524	0.903	0.3	0.25
105mm M68	M456 HEAT	none	1174	1.18	19.3	15.2

**Armor-piercing, fin-stabilized, discarding-sabot round in development.*

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